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Remote emission sensing compared with other methods to measure in-service conformity of light-duty vehicles

**On behalf of the Swedish Innovation Agency
and the Swedish Transport Administration**

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Acronyms

CARES	City Air Remote Emission Sensing
CO	Carbon oxide
CO2	Carbon dioxide
CONOX	Collaborationg On Nox Real Driving Emission Measurements
DPF	Diesel Particulate Filter
EFM	Exhaust Flow Meter
EGR	Exhaust Gas Recirculation
ERMES	European Research On Mobile Emission Sources
GTAA	Granting Type Approval Authorities
H2020	Horizon 2020
HBEFA	The Handbook Emission Factors For Road Transport
HC	Hydrocarbons
ICCT	International Council On Clean Transportation
ISC	In-Service Conformity
LCV	Light Commercial Vehicle
LDV	Light Duty Vehicle
LNT	Lean Nox Trap
MAW	Moving Average Window
NEDC	New European Driving Cycle
NO	Nitrogen oxide
NO2	Nitrogen dioxide
NOX	Nitrogen oxides
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
PEMS	Portable Emission Monitoring System
PM	Particulate Mass
PN	Particulate Number
PNSD	Particle Number Size Distributions
PSA	Peugeot-Citroen
PTI	Periodical Technical Inspections
RDE	Real Driving Emissions
RNM	Renault-Nissan-Mitsubishi
RSD	Remote Sensing Device
SCR	Selective Catalytic Reduction
SEMS	Simplified On-Board Emissions Monitoring Systems
uCARe	You Can Always Reduce Emissions Because You Care
VAG	Volkswagen Group
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
VSP	Vehicle Specific Power

Summary

The emission performance of light-duty vehicles was investigated based on various datasets from remote sensing, PEMS and chassis dynamometer measurements. The focus of the investigation was on NO_x and early Euro 6 (stage a and b) diesel vehicles, but both earlier and later diesel vehicle models, PM/PN emissions and petrol cars were also included. A methods comparison for assessing emission performance was based on three different datasets:

- Data collected from dedicated remote sensing measurements carried out in Sweden in 2018, used to recruit vehicles for further PEMS RDE tests and chassis dynamometer tests over the regulatory NEDC and WLTP driving cycles.
- A large remote sensing dataset from measurements carried out in six European countries over the period 2011-2020 retrieved from the CONOX database, which was compared with a large number of PEMS RDE data provided by the ERMES group and ICCT.
- Data collected by means of remote sensing, mini-PEMS and measurements from the roadside of size-resolved PN emissions in conjunction to a Swedish PTI-station in 2019.

In summary, the results of the analysis show:

- There was a good agreement between remote sensing and PEMS in terms of real-world NO_x emission reductions from Euro 5 to the various steps of Euro 6, i.e., both methods and the various datasets showed a 50% reduction for Euro 6ab and an 80% reduction for Euro 6c. Further reductions - about 90% when compared to Euro 5 - were observed for Euro 6d.
- For Euro 6ab light-duty diesel vehicles:
  - There was a good agreement in NO_x emissions between remote sensing and PEMS also when data were broken down on vehicle model level, and particularly on engine alliance level, with regression coefficients of ≈0.6 and ≈0.9, respectively.
  - Even on an individual vehicle level there was a fair agreement between remote sensing and PEMS, indicating that remote sensing is capable of identifying vehicles exceeding the Euro 6 RDE NO_x limit with a factor of three or more, with reasonably low estimated errors of omission and commission.
  - Both remote sensing and PEMS showed large variations - a factor of 30-40 between the highest and lowest emitting vehicles - in NO_x emissions between individual vehicles. High emissions were occasionally associated with certain engine families.
- For diesel LDV PM emissions the remote sensing data mirrors the evolution of the increasingly stricter emission standards from Euro 1 onwards, ultimately requiring all vehicles to be equipped with diesel particulate filters (DPFs) from Euro 5. Thus, the real-world emissions have been reduced by more than 90% since the introduction of DPFs.
- Already existing remote sensing technologies have a good potential to be used as stand-alone cost-effective methods for surveying the real driving emission performance of the in-use light-duty diesel vehicle fleet and could act as a useful supplement to in-use compliance programs, particularly to follow up compliance with the RDE legislation.
- Two types of remote sensing instruments and a mini-PEMS were used to measure real-world light-duty vehicle emissions of NO_x and PN at a PTI-station for the first time. The results indicate that screening for suspected high-emitters with remote sensing and confirmatory measurements with mini-PEMS can be a potential approach to enhance PTI emission testing, e.g., by incorporating NO_x and PN tests under real driving conditions.

Sammanfattning

Utsläppsprestanda för lätta fordon analyserades utifrån olika dataset från mätningar vid vägkanten med fjärranalys (remote sensing), ombord på fordon med PEMS, i chassidynamometer samt i anslutning till en kontrollbesiktningsstation. Fokus för analysen var utsläpp av NO_X från tidiga Euro 6 (a och b) dieselfordon, men äldre och nyare fordon (Euro 3-5 och Euro 6c/6d-temp/6d), partikelutsläpp och bensinbilar ingick också i analysen. En metodjämförelse för bedömning av utsläppsprestanda baserades på tre olika dataset:

- Data från dedikerade remote sensing-mätningar i Haninge år 2018 som utnyttjades för att rekrytera fordon till PEMS-mätningar samt till NEDC- och WLTP-prov.
- Ett stort dataset från remote sensing-mätningar utförda i sex europeiska länder 2011-2020, som jämfördes med ett stort antal PEMS-data tillhandahållna av ERMES och ICCT.
- Data från mätningar med remote sensing, mini-PEMS samt av enskilda fordons partikelutsläpp från vägkanten vid en kontrollbesiktningsstation i Göteborg år 2019.

Sammanfattningsvis visar resultaten från analysen:

- Det föreligger en god överensstämmelse mellan remote sensing och PEMS när det gäller verkliga utsläppsreduktioner av NO_X från Euro 5 till de olika stegen av Euro 6, dvs båda metoderna och de olika datamängderna visade en minskning för Euro 6ab på ca 50% och en minskning för Euro 6c på ca 80%. En ytterligare minskning - cirka 90% jämfört med Euro 5-nivån – kan observeras för Euro 6d.
- Avseende utsläpp av NO_X från lätta dieselfordon Euro 6ab:
    - Även när data delas upp på fordonsmodellnivå, och särskilt på motoralliansnivå, föreligger en god överensstämmelse mellan remote sensing och PEMS, med regressionskoefficienter på ≈0.6 respektive ≈0.9.
    - Även på fordonsindividnivå är överensstämmelsen mellan remote sensing och PEMS hyfsad, vilket tyder på att remote sensing kan identifiera fordon som överskrider Euro 6 RDE-gränsen med en faktor 3 eller mer, med rimligt låga uppskattade ”errors of commission” och ”errors of omission”.
    - Både remote sensing och PEMS visade mycket stora variationer i NO_X-utsläpp mellan enskilda fordon: En faktor 30-40 mellan de högst och lägst emitterande fordonen. I flera fall kan de högsta utsläppen tillskrivas vissa motorfamiljer.
- Avseende utsläpp av partiklar från lätta dieselfordon speglar resultaten från remote sensing-mätningarna utvecklingen av de allt strängare utsläppskraven från Euro 1 och framåt, vilka förutsätter användning av dieselpartikelfilter (DPF) fr o m Euro 5. Således har de verkliga partikelutsläppen minskat med mer än 90% sedan införandet av DPF.
- Befintlig remote sensing-teknik har goda möjligheter att användas som en fristående kostnadseffektiv metod för att övervaka utsläppsprestanda för den lätta dieselfordonsparken med avseende på NO_X och utgöra ett användbart komplement i hållbarhetsprovningen, särskilt för att följa upp efterlevnaden av RDE-lagstiftningen.
- Två olika remote sensing-instrument och en mini-PEMS användes för första gången för att mäta utsläpp av NO_X och PN vid en kontrollbesiktningsstation. Resultaten indikerar att screening av misstänkta högemitterare med remote sensing kombinerade med mätningar med mini-PEMS kan vara ett potentiellt tillvägagångssätt för att skärpa avgaskontrollen i den periodiska besiktningen, t. ex. genom att införliva NO_X- och PN-tester under verkliga körförhållanden.

1 Introduction

1.1 Background

Vehicle emission measurements are crucial for a comprehensive understanding of road traffic related air pollution and for effectively controlling the emissions through various policies - from the local to the international level. Today the main legislative elements in Europe for controlling vehicle emissions are: *type approval*, ensuring that newly designed engines meet the regulatory requirements before vehicles equipped with these engines are allowed to be sold on the market; *conformity of production*, ensuring that all manufactured engines meet the type approval specifications; and *in-service conformity*, representing the attempts to ensure that the targeted emissions performance is maintained also throughout the normal life of the vehicle under normal conditions of use (EC, 2007).

In the case of diesel vehicles, the strategies applied in Europe to control emissions of nitrogen oxides (NO_X, i.e. NO and NO_2) in the past have largely failed (Hooftman *et al.*, 2018), probably best exemplified by the dieselgate scandal revealed in 2015 (Thompson *et al.*, 2014). As a consequence, the NO_2 air quality standards set by the EU Air Quality Directive adopted more than ten years ago (EC, 2008) are still being violated in many large European cities and urban agglomerations (EEA, 2019). On top of that, many EU member states are facing problems to comply with the NO_X component of the National Emissions Ceiling Directive (EC, 2016). In Sweden, light-duty diesel vehicles accounted for 60% of the overall NO_X emissions from road transport in 2018 and 20% of the total national emissions (SEPA, 2020). Similar shares are seen in many other European countries.

To tackle these challenges new emission test procedures have been implemented in the EU regarding laboratory as well as real driving testing. The implementation has occurred stepwise within the Euro 6 legislation, the first step of which was entered into force in 2014. With the third step - Euro 6c - introduced in September 2017, the driving cycle applied for type approval testing was changed from the outdated NEDC (New European Driving Cycle), dating back to as far as the early 1990's, to the WLTP (Worldwide Harmonized Light Vehicles Test Procedure), a global test procedure considered much more representative for today's real world driving.

Along with Euro 6c, and complementing the WLTP, also RDE (Real Driving Emissions) testing was introduced in the EU emission legislation, accomplished by measuring the emissions over a specified real-world route with a portable emission monitoring system (PEMS) mounted onboard the vehicle. Both are established as type approval tests and procedures for light-duty vehicles (passenger cars and light commercial vehicles) under the Regulation (EU) 2018/1832 (EC, 2018). For Euro 6c the RDE test contained not to exceed limits for particle number (PN) and NOx emissions for monitoring only. For the next step – Euro 6d-temp – testing against temporary conformity factors was introduced. The conformity factor establishes the allowed discrepancy between the regulatory emission limit and the measured emissions in the RDE procedure. In the final Euro 6d step the conformity factor was lowered compared to the temporary factors. Table 1 presents emission limits for diesel passenger cars from Euro 1 to the Euro 6 standards, together with the introduction dates and the applied test cycles.

Table 1 EU emission standards for diesel passenger cars. Based on Dieselnet (2021) and Delphi Technologies (2020).

Emission standard	Date (type approval)	Test cycle	CO	HC+NOX	NOX	PM	PN
Euro 1	1992.07	Urban (40 sec idle) + EUDC cycle	2.72	0.97	-	0.14	
Euro 2	1996.01		1.0	0.7		0.08	
Euro 3	2000.01	Revised ECE + EUDC cycle	0.64	0.56	0.5	0.05	
Euro 4	2005.01		0.5	0.3	0.25	0.025	
Euro 5a	2009.09		0.5	0.23	0.18	0.005	
Euro 5b	2011.09		0.5	0.23	0.18	0.0045	6x10^{11}
Euro 6a*	-		0.5	0.17	0.08	0.0045	6x10^{11}
Euro 6b	2014.09		0.5	0.17	0.08	0.0045	6x10^{11}
Euro 6c	-	WLTC	0.5	0.17	0.08	0.0045	6x10^{11}
Euro 6d temp	2017.09	WLTC + RDE	0.5	0.17	0.08**	0.0045	6x10^{11}****
Euro 6d	2020.01		0.5	0.17	0.08***	0.0045	6*10^{11}****

*This level was not a mandatory level. Any cars with this class were approved and registered when previous level (Euro 5) were mandatory.
** Conformity factor for Euro 6d RDE = 2.1,
*** Conformity factor for Euro 6d RDE = 1.43,
**** Conformity factor for Euro 6d RDE = 1.5

Apart from introducing a new driving cycle and RDE (PEMS) testing for the type approval, the current RDE regulation also involves requirements on extensive in-service conformity (ISC) testing. This is to ensure that the real driving emissions are effectively limited during the normal life of the vehicles under normal conditions of use. The core test procedure applied for ISC testing is the same as for the type approval, plus some extra tests, such as evaporative testing and duration tests. The responsibility for carrying out the new ISC procedure is shared between the granting type approval authorities (GTAA) and the car manufacturers (OEM), and involves the following steps:

1. Information Gathering & Risk Assessment (GTAA)
2. ISC Testing (GTAA and/or OEM)
3. Compliance Assessment (GTAA + OEM)
4. Remedial Measures, if needed (GTAA + OEM)
5. Reporting (GTAA)

For the ISC Step 1, the RDE regulation states:

"The GTAA shall gather all relevant information on possible emission non-compliances relevant for deciding which ISC families to check in a particular year. The GTAA shall take into account in particular information indicating vehicle types with high emissions in real driving conditions. ***That information shall be obtained through the use of appropriate methods, which may include remote sensing, simplified on-board emissions monitoring systems (SEMS) and testing with PEMS****. The number and importance of exceedances observed during such testing may be used to prioritise ISC testing."*

In general, remote sensing can be considered as a complementary method to PEMS for RDE testing: It provides an emission snapshot of an individual vehicle, in contrast to the much more detailed characterization of the emission performance of an individual vehicle that PEMS provides. On the other hand, in one day, several thousands of vehicles can be measured with remote sensing, whereas normally only a few vehicles can be measured with PEMS. Thus, remote sensing has the capability to efficiently screen the emission performance of large light-duty vehicle fleets, e.g. for identification of suspicious high-emitting vehicles, as demonstrated in many recent studies (Bishop, 2019; Borken-Kleefeld *et al.*, 2018ab; Carslaw *et al.*, 2019; Chen *et al.*, 2019; Dallmann, *et al.*, 2018; Dallmann *et al.*, 2019; Davison *et al.*, 2020; Huang *et al.*, 2018; Pujadas *et al.*, 2017; Sjödin *et al.*, 2018; Tietge *et al.*, 2019).

Despite that a substantial number of real driving emission measurement studies have been conducted in the wake of "dieselgate", utilizing both remote sensing and PEMS, only a few studies have been reported in which the two have been combined. JRC found a good agreement for CO and NO_x fuel-specific emissions from a small set of individual light-duty vehicles, representing different vehicle types and emission standards, as measured by two commercial remote sensing instruments and PEMS (Gruening *et al.*, 2019). Further, it was concluded that several remote sensing measurements on the same vehicle, or on vehicles of the same type, need to be made to draw robust conclusions about the emission behaviour of the vehicle or vehicle type, respectively.

Similar observations were made in a recent Australian study involving two large Euro 4 and Euro 5 diesel cars, the NO to CO_2 emission ratios of which were measured repeatedly by a remote sensor and compared with measurements on a mobile transient chassis dynamometer operating over an Australian real-world drive cycle (Smit and Kennedy, 2020). The weighted correlation for the NO/CO_2 ratio between the methods were in the range 0.89-0.95 over a large vehicle power range.

In the CONOX project ("Study on comparing NO_x real driving emissions from Euro 5 and Euro 6 light-duty diesel vehicles as measured by remote sensing, PEMS and on chassis dynamometers"), a large amount of remote sensing and PEMS data for diesel passenger cars across Europe were compiled and analysed for the first time (Sjödin et al., 2018). The results showed a good agreement between the remote sensing and PEMS datasets with regard to fleet average NOx emissions, expressed as gram NO_x emitted per kg fuel burned, for both Euro 5 and Euro 6 diesel cars. In addition, a reasonable agreement between the two methods was also observed for Euro 5 diesel cars when the comparison was broken down on manufacturer and even on engine alliance level. For Euro 5, the average NO_x emissions by make varied from about 10 to about 30 g NO_x/kg fuel (roughly corresponding to 0.5-1.5 g NO_x/km). For the early Euro 6 diesel cars the variation was even larger.

Another component of ISC testing in the EU is roadworthiness testing or Periodical Technical Inspections (PTI). A new directive was entered into force in 2014 (EC, 2014), replacing its predecessor from 2009 (EC, 2009). Although the new directive implies a significant improvement in terms of emission testing compared to its predecessor, the minimum PTI emission testing required for all EU member states from 20 May 2018 involves still no more than an idle check of the exhaust tailpipe concentrations of CO and HC for gasoline cars, and a free acceleration opacity test for diesel cars. None of these can be considered as appropriate for an adequate diagnosis of the emission performance of modern cars when being driven on the road. However, member states are allowed to set higher test standards than those required by the new directive.

In a few member states, authorities have recently used remote sensing successfully in roadside inspections to capture NO_x high-emitting heavy-duty trucks equipped with SCR Selective Catalytic Reduction (SCR) systems (DEPA, 2018; Buhigas *et al.*, 2019). Typically, the emission control systems of these trucks were deliberately tampered with, e.g. by installing AdBlue emulators. The tampering meant that the reducing agent urea was not injected into the catalyst leaving the NO_x emissions untreated.

Regarding light-duty vehicles, there is little experience of enhanced roadworthiness emission testing in Europe. In a pilot study in Sweden, involving pre-Euro and Euro 1 gasoline cars, the efficiency of capturing cars in roadside inspections failing the Swedish PTI idle test increased by a factor of 2-3 when cars that were above a certain remote sensing cut-point were subject to an idle test at the roadside compared to when cars were pulled over by random (Sjödin, 1994). More recently, with the aim of investigating alternatives for the current PTI emission testing in Belgium, the NO_x emissions of Euro 5 and Euro 4 in-use light-duty diesel vehicles were measured in six variants of the IM240 test (US EPA, 2017), frequently used for emission testing in inspection & maintenance (I/M) programs in the USA (Hooftman *et al.*, 2018). Compared to the NEDC emission limits, the emissions of the diesel cars tested in the more realistic variants of the IM240 driving cycle were a factor of 6-16 higher. More recently, for passenger cars' NO_x and CO emissions, Buhigas et al., (2021) found a good correlation between emissions as measured by remote sensing and as measured by means of new instrumentation in a dynamometer emission test at a PTI station.

In contrast, there has been a quite extensive use of remote sensing in the US (see e.g. CARB, 2019; Virginia DMV, 2020; Colorado DPHE, 2020) as well as in Hong Kong, China (Huang *et al.*, 2018) to complement or support I/M programs and other dedicated emission control programs. These have been oriented towards "clean screening", i.e. when truly low-emitting vehicles are exempted from further emission testing, and/or for pinpointing the worst polluters (to be subject to more extensive testing, such as the IM240 test and follow-up repair actions).

1.2 Objectives

It is apparent that much more can be done when it comes to improving the in-service conformity testing of light-duty diesel vehicles in the EU. With this in mind, the objective of the present study was to demonstrate and evaluate the potential of remote sensing to be used as a complementary tool, when e.g. targeting high-emitting vehicles, as individuals and/or certain types of vehicles, both in in-use compliance programs, such as the one being operated in Sweden, and in periodical technical inspections. Basically, this objective involved a comparison of remote sensing with mainly PEMS to measure in-service emissions of NO_x from early Euro 6 light-duty diesel vehicles. However, the comparative study was extended also to some Euro 5 vehicles and particle (PM) emissions, since for many years to come Euro 5 and Euro 6 vehicles will be predominant in the Swedish light-duty fleet as well as in other national fleets across Europe. A secondary objective of the project was to evaluate the potential of remote sensing as a possible stand-alone and cost-effective method for surveying the real driving emission performance of the in-use light-duty diesel vehicle fleet.

1.3 The Swedish In-Use Compliance Program

The In-Use Compliance Program in Sweden, hosted by the Swedish Transport Agency, has been in operation since 2009. It consists of two separate sub-programs; one for light-duty vehicles and one for heavy-duty vehicles. For the light-duty program, about 70 individual in-use vehicles are recruited randomly from vehicle owners every year. The emission testing consists of chassis dynamometer testing over various legislative and non-legislative driving cycles as well as RDE testing by means of PEMS. Yearly reports (in English) on the results from the emission measurements are published on the Swedish Transport Agency's website[1].

The aim of the Swedish in-use compliance program is twofold: to check that the durability of exhaust aftertreatment systems complies with the legal requirements according to the EU legislation, and to make sure that vehicle manufacturers are aware that the emission performance of the Swedish in-use vehicle fleet is being monitored.

1.4 PTI emission testing in Sweden and EU

Every year about 6 million vehicle inspections are carried out within the Swedish PTI program. The regulations and general advice on these inspections are governed by the Swedish Transport Agency. Since 20 May 2018, the Swedish PTI program adheres to the minimum requirements for emission testing as given by Directive 2014/45/EU (EC, 2014). This means that for light-duty diesel vehicles the emission test is limited to an opacity measurement in the exhaust during a steady-state free acceleration phase only for vehicles that are younger than 20 years. In addition, the emission related error codes in the OBD (on-board diagnostics) system should be read off, but only in cases when the malfunction indicator lamp on the vehicle's dashboard is lit up.

The adaptation of the Swedish PTI emission testing requirements to Directive 2014/45/EU in 2018 resulted in that the share of diesel light-duty vehicles failing the emission test decreased from around 3% in 2017 to around 1% in 2019, according to estimates by the Swedish PTI bodies (Swetic, 2020).

In recent years, several studies have demonstrated that the free acceleration opacity test is not effective in identifying malfunctioning diesel particulate filters (DPF), being mandatory on light-duty diesel vehicles from Euro 5. Instead, measurements of particle number at idle has proven to be effective (Kadijk, et al., 2016; 2017; 2020); Jarosinski, W. and Wisniowski, 2021). Based on this research, a new PTI particle test has recently been developed by the international New Periodical Technical Inspection (NPTI) working group, involving Belgium, Germany, the Netherlands, Switzerland and the European Commission. The Netherlands will be the first country in Europe introducing this test from July 2022 (Government Gazette, 2021).

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[1] https://www.transportstyrelsen.se/sv/vagtrafik/Miljo/Luftkvaliet-i-tatorter/Avgaser/Hallbarhetsprovning-av-avgasrening/

2 Experimental

2.1 Remote sensing

2.1.1 Dedicated remote sensing measurements

Remote sensing measurements were carried out on 14 days in late May – early June and late August – early September 2018. The measurement site was located in Haninge, a suburb to Stockholm, Sweden. The instrument was placed about 40 meters after the exit of a roundabout at an almost flat road section, Figure 1. The road at which the measurement site was located is a commonly used commuting route for people working in Stockholm, passing the site when returning from work in the afternoons, giving the opportunity to catch a substantial number of repeat measurements on individual vehicles during the course of the measurement campaign.

The instrument used was an Opus AccuScan™ RSD5000, capable of measuring the raw exhaust concentrations of both NO and NO_2 (i.e., and their sum NO_X) besides CO, HC (total hydrocarbons), particulate matter (derived from an opacity measurement in the UV range) and CO_2.

Fixed (internal) gas cells calibration as well as audit calibrations of the instrument were made in regular intervals during each measurement day. The audit calibration was done by means of certified gas mixtures with known concentrations of NO, NO_2, CO, HC and CO_2. Since the measured emission rates are associated with the driving condition of the vehicle, the RSD5000 also measures speed and acceleration of each passing vehicle, which enables the possibility to express the driving condition as vehicle specific power (VSP), which is the engine power divided by the vehicle mass. The VSP calculations in this study are based on the method presented in Borken-Kleefeld *et al.* (2018a). Further, licence plate numbers were captured with a video camera connected to the RSD5000 instrument to retrieve vehicle information from the Swedish vehicle register, needed for the subsequent analysis.

Figure 1 **The remote sensing site and instrument set up.**

The aims of the remote sensing measurements in Haninge were to:

1. Carry out multiple measurements on as many light-duty diesel vehicles as possible, and from that data identify vehicles with suspiciously high emissions. These vehicles were prioritized when recruiting vehicles for the RDE and chassis dynamometer tests.
2. Gather as much measurement data as possible and use it together with data from other European measurement campaigns for analysis of e.g. average emissions on a vehicle model/engine family level for early Euro 6 diesel light-duty vehicles.

2.1.2 Complementary remote sensing and PEMS data

When using remote sensing data to estimate emission performance of vehicle models, Euro classes, etc., a large amount of data is key for estimating mean values with high certainty. To maximize the amount of analytical data, emissions measured within this study were complemented with data from the CONOx database which contains data from remote sensing measurement campaigns conducted in several European countries, (Borken-Kleefeld *et al.*, 2018b). When it comes to early Euro 6 vehicles, we have in this study chosen to present Euro 6a and Euro 6b vehicles as one category, Euro 6ab. We estimate that less than 5 % of the cars in this group are actual Euro 6a vehicles. To some extent there may be uncertainty in the specified Euro 6 step due to e.g. missing information in the national vehicle registers. Due to this there is a possibility that some vehicles labeled Euro 6b in the CONOx database are Euro 6c or Euro 6d-temp vehicles and vice versa. However, we assess that the number of misclassifications is relatively low.

A minimum of 200 measurements have been used as the lowest limit for analysed populations. This number is based on the analysis presented in Chen *et al.*, 2019. Only measurements where the vehicle specific power was in the range of 2 to 30 kW/t were included. Furthermore, only data for vehicles with valid measurements of both NO and NO_2 was analysed.

Also, data from PEMS measurements conducted within this study were complemented with data from PEMS measurements provided from the ICCT PEMS database (Baldino *et al.*, 2017) and the ERMES database (Keller, 2017). Only data from RDE compliant tests were included in the analyses.

2.1.3 uCARe Taxonomy for engine alliances

In many cases the same engine is used not only in different vehicle models of the same manufacturer, but also across different manufacturers. This creates links between vehicles that go beyond vehicle makes and model boundaries. In order to highlight these links and to properly and exclusively identify each specific engine the engine taxonomy developed and used within the EU H2020 project uCARe (uCARe, 2020ab), and also used within its H2020 sister project CARES, has been applied when analysing the remote sensing data. The uCARe taxonomy consists of five parameters applied to distinguish between different engines. The parameters are type of fuel, Euro standard, engine displacement, engine rated power and engine alliance code. For example, D_6_1969_110_VOLV is a 2 litre diesel Euro 6 engine with an engine power of 110 kW manufactured by Volvo. The engine is used in several different Volvo models, e.g., V60, V70 and V90. Another example is the D_6_1968_135_VAG engine which is a Volkswagen Group engine found among different makes and models, e.g., Audi A3, VW Tiguan, Seat Leon and Skoda Octavia among others.

2.1.4 Remote sensing and other real driving emission measurements at a PTI station

The second remote sensing measurement campaign within the study was carried out during five days in May 2019 at a PTI station in Göteborg, Sweden. During this campaign the remote sensing measurements were complemented with a simplified PEMS system for NOx measurements and with instrumentation for measuring particle emissions from the roadside. The aim was to measure NOx emissions and emitted number of particles (PN) from light-duty vehicles that were subject to PTI emission testing, to evaluate if:

1. vehicles that pass the PTI emission test could be identified as having poor emission performance due to e.g. a not well-functioning exhaust after-treatment system.
2. each method would be suitable as a complement to current testing.

The instruments used during the campaign were:

- An Opus AccuScan™ RSD5000.
- A TSI Engine Exhaust Particle Sizer Spectrometer EEPS 3090 (measuring the particle number size distribution (PNSD) in the range from 5.6-590 nm, distributed over 32 size channels) together with a Thermo Scientific CO_2 analyser.
- An ECM EZ-PEMS ("Mini-PEMS") measuring the tailpipe exhaust concentrations of NO_x and CO_2.

25 passenger cars and four light commercial vehicles were tested using the above-mentioned instrumentation. The vehicles were a mixture of those coming to the station for normal periodic inspection and a few that were retrieved from a nearby car rental. All vehicles were also tested using the standard procedure for emission testing used within the PTI. Technical information on the tested cars can be found in Appendix 4.

The RSD5000 and EEPS instruments were placed just outside the PTI station building. All vehicles were measured by the two instruments multiple times by circulating the building. The vehicles came to a halt about 5-10 meters upstream of the instrument set-up before they accelerated heavily past the instruments, thus all measurements were carried out with the engines at load. To minimize differences in testing conditions (speed and acceleration) for the different vehicles, one of the PTI staff was appointed to drive the vehicles past the instruments (for the majority of the vehicles). The used method for measuring particle emission was similar to the method previously described for measurements of exhaust plumes from public busses (Hallquist *et al.*, 2013), with the difference in that a thermo denuder not was used for the measurements at the PTI station.

The simplified PEMS was mounted on all the 29 tested vehicles to measure the NO_x emissions during a short route in the proximity of the PTI station. The length of test route was approximately 5 km and consisted of roads with a speed limit of 50 km/h. The average speed for the tested vehicles when driving the route was around 30 km/h, hence it can be considered as a short route in urban driving conditions. All tested vehicles were first warmed up by driving 3-5 laps around the PTI station. During the warm-up the vehicles passed the RSD5000 and the EEPS instrument multiple times, resulting in at least three consecutive measurements before the PEMS route was driven. This procedure was repeated after each completed PEMS route.

Whenever possible, data from the OBD of the vehicle was read during the PEMS measurements, which enabled calculations of the NOx emissions in grams per kilometre based on the measured exhaust concentrations. When data from the OBD was not available, the measured NOx concentration was ratioed to the CO_2 concentration also measured by the PEMS system. From this ratio, NOx emissions in g/km could roughly be estimated by applying data on CO_2/km for the vehicle model obtained from other sources.

The set-up for the roadside measurements and the Mini-PEMS are shown in Figure 2.

2.2 RDE tests and chassis dynamometer measurements

2.2.1 Approach for recruiting vehicles for RDE and chassis dynamometer testing

The results from the remote sensing measurements (of NOx) in Haninge were used for determining which specific vehicle individuals that were targeted for recruitment to PEMS and chassis dynamometer testing by AVL. Euro 6 vehicles with multiple passes showing high NOx emissions in the remote sensing measurements were given the highest priority to be recruited. Some Euro 6 vehicles with low to intermediate NOx emissions according to the remote sensing measurements were also recruited, enabling a comparison of not only vehicles with high NOx emissions, but also with low and intermediate emissions. Further, a few Euro 5 vehicles with high emissions in the remote sensing measurements were also recruited for the further testing by AVL.

Suspected high-emitters were defined as vehicles with at least two valid measurements (but preferably more) for which the average NO_x emission was above the 90th percentile for all vehicles of the same Euro standard measured at the Haninge site. Also, vehicles with only one valid measurement were defined as potential high-emitters if the measured NOx emission was above the 98th percentile. These high-emitter criteria were similar to those used by Buhigas et al., (2021). Low-emitters were defined as vehicles with several measurements close to zero. Intermediate emitters were defined as vehicles with several measurements and an average close to the Euro standard. Only data for vehicles passes within the VSP range 2-30 kW/t were considered in the analysis.

2.2.2 Tested vehicles

All vehicles that were recruited for the RDE and the chassis dynamometer tests were diesel powered Euro 5 or Euro 6 (b, c and d-temp) passenger cars or light commercial vehicles. The vehicles were manufactured between 2011 and 2019 and the mileage varied between approximately 20 km to 240,000 km. More detailed information regarding the tested vehicles can be found in Appendix 1. The time between the remote sensing measurements and the extended tests varied between approximately 2 months to half a year.

2.2.3 Test procedure

Based on the results from the remote sensing measurements in Haninge in all 30 light-duty diesel vehicles, the majority of them passenger cars, were recruited for extended PEMS and chassis dynamometer testing. RDE tests were conducted on all 30 vehicles, seven of which were also tested in the laboratory using the NEDC or the WLTP (some of the vehicles were tested using both NEDC and WLTP). The availability of the chassis dynamometer during the time that the recruited cars were available determined which vehicles that could undergo this test. Figure 3 gives a schematic overview of how the testing procedure was carried out.

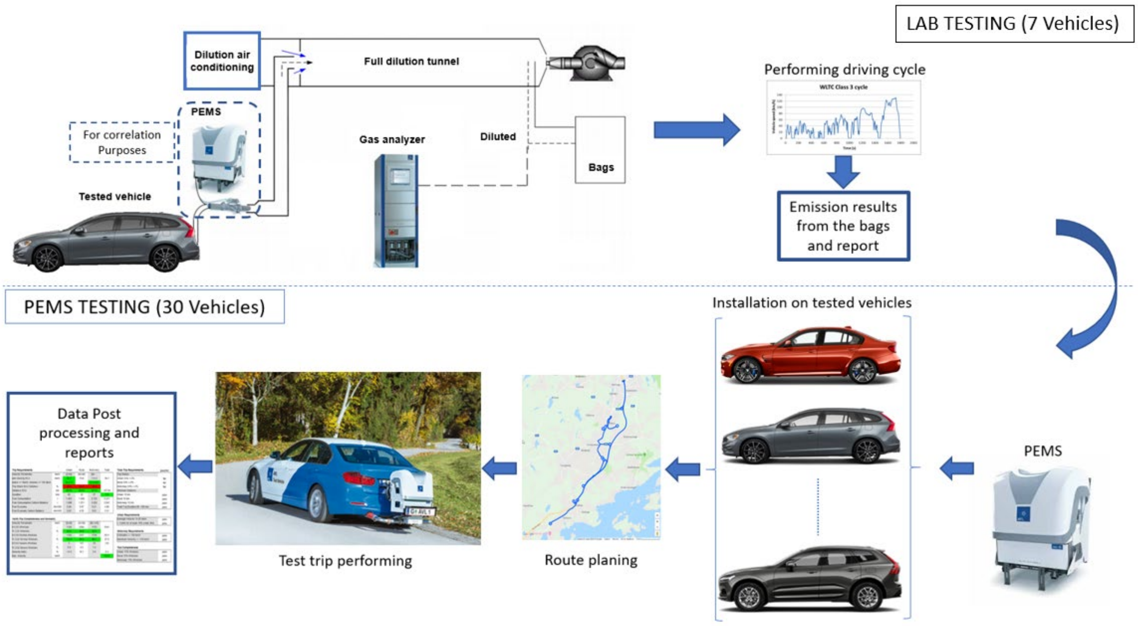

Figure 3 **Schematic overview of the RDE and laboratory measurements.**

The laboratory tests were conducted using a chassis dynamometer at the AVL MTC site in Haninge, Sweden. The exhaust gas was connected to a full dilution tunnel with a constant volume sampler. For the emission acquisition sampling bags were filled with the diluted exhaust and were analyzed at the end of the test. Also, diluted gas was measured with an AVL AMA i40. For PEMS and laboratory equipment correlation, an AVL M.O.V.E. PEMS was installed in the exhaust line together with an exhaust flow meter (EFM). Attention was given to leave large enough tube diameter before and after the EFM to ensure proper operation and to prevent any significant pressure drop. Appendix 1 gives an overview of the instruments used for the PEMS and laboratory tests.

The route used for the RDE tests was designed to follow the RDE regulations rules and was carried out in the Stockholm metropolitan area. The route was planned to cover different conditions of driving, respecting the driving shares stipulated by the EC regulation (1/3 in urban condition, 1/3 in rural condition and 1/3 in motorway condition) and stop time periods (EC, 2018). The route started and ended at the same location at the AVL MTC site in Haninge. Each trip lasted approximately 5600 seconds and the driving distance was around 75 km.

2.2.4 Data analysis

Data from the RDE tests was analyzed with and without treatment. Thus, results in g/km were calculated in terms of the whole trip but also separately for urban, rural and motorway. Raw data was used for comparison with the remote sensing data, however, the same data was applied to the Moving Average Window (MAW), the regulated procedure to analyze data for certification RDE tests, focused on trip validity. The MAW is a method which divides the trip into WLTP CO_2 mass integration subsets, then performs a normalization of the "subsets" results. More information can be found in the RDE regulation (EC, 2018).

Since most of the vehicles tested were early Euro 6 and some Euro 5, WLTP values are not available. Thus, to run the MAW analysis, WLTP CO_2 values were generated based on the RDE tests raw results and using a method for defining the WLTP values with errors between 7% and 15%. This method was developed by Duarte *et al.* (2015) and performs a characterization of the trip results in Vehicle Specific Power (VSP) time binning distribution.

That way, data analysis was performed comparing different results, such as laboratory, raw RDE and remote sensing results in terms of NOx. For easy comparison with remote sensing emissions measured during the RDE and laboratory tests were expressed as g NOx/kg fuel.

3 Results

3.1 Results overview of the remote sensing measurements in Haninge

In Figure 4, the average NOx emissions (in g/kg fuel) by Euro standard starting from Euro 4 are presented (the number of measurements (N) for vehicles prior to Euro 4 were too low to be included in the analysis). The trend from Euro 4 to Euro 6 is the same as observed in several previous studies (e.g. Sjödin *et al.*, 2017; Dallman *et al.*, 2018 and 2019). It can also be seen that there is a decrease from the early stages of Euro 6 (a and b) to Euro 6c and Euro 6 d-temp, also confirmed in another recent remote sensing study in Poland (Bernard *et al.*, 2020). Note though that the number of measurements on Euro 6 d-temp vehicles in the present study was comparatively low (N=115).

Both temperature and VSP have impact on NOX emissions from diesel passenger cars (see e.g. Grange et al (2019), Dallmann et al (2018) and Dallmann et al (2019)). All data from the site in Haninge were sampled during similar wether conditions with an average temperature of 22°C. The average measured VSP was 14 kW/t.

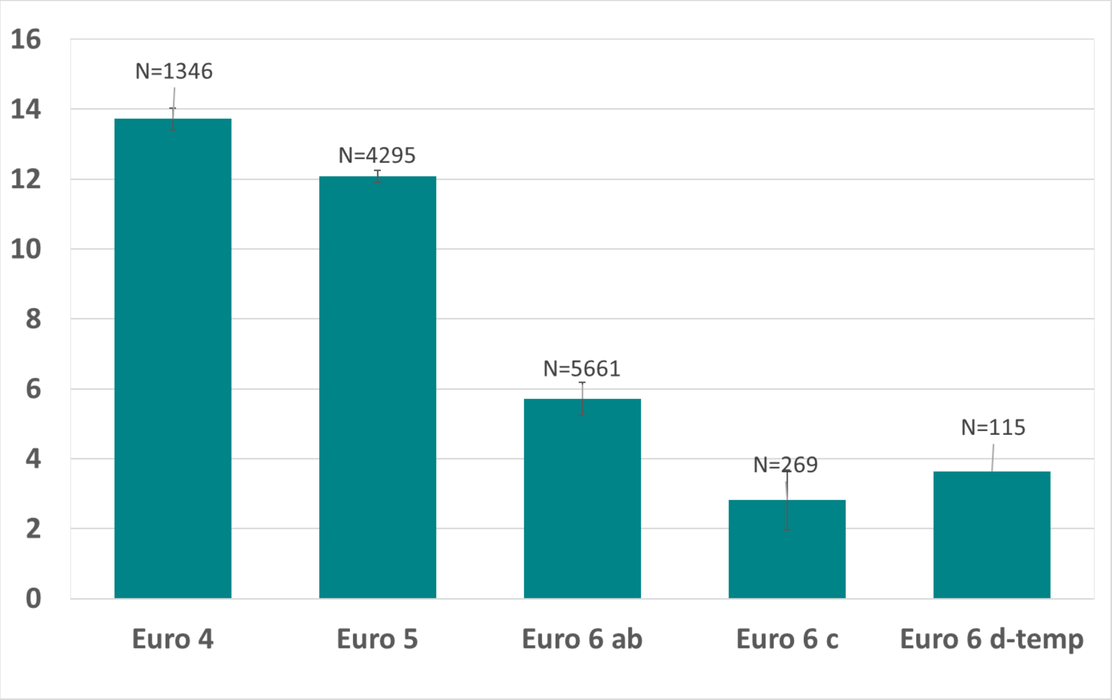

Figure 4 Average NOx emissions in g/kg fuel by Euro standard for diesel cars as measured by remote sensing in Haninge, Sweden 2018. N is the number of measurements. Error bars represent the standard error of the mean (95% CI).

The number of measurements per Euro standard, average VSP, average NOx emission, the 90th and 95th percentiles for NOx are presented in Table 2. Since the focus was on Euro 5 and Euro 6 vehicles, data for older vehicle categories are not presented in this table.

Table 2 **Number of valid NOx measurements, average VSP, average NOx emissions, the 90th percentiles and 95th percentiles for Euro 5 and Euro 6 light-duty diesel vehicles measured with remote sensing in Haninge. The averages are presented together with the standard error (95% CI).**

Vehicle category	Number of valid measurements	Average VSP (kW/t)	NOx average (g/kg)	NOx 90th percentile (g/kg)	NOx 95th percentile (g/kg)
PC Euro 5	4 295	14±0.2	12±0.3	27	34
PC Euro 6a,b	5 661	14±0.2	6±0.2	14	18
PC Euro 6c	269	14±0.7	3±0.5	7	11
PC Euro 6d-temp	115	13±1.0	4±0.9	9	13
LCV Euro 5	2 672	14±0.2	16±0.4	33	39
LCV Euro 6a,b	2 220	14±0.2	6±0.3	16	23

3.2 Recruiting of vehicles for RDE and chassis dynamometer tests

During the recruitment of vehicles for the RDE and chassis dynamometer tests it turned out that many of the contacted car owners (both private persons and companies) were unwilling to lend their cars for emission testing. This meant that several of the vehicles recruited were not those originally identified as the most prioritized, i.e. repeat high-emitters (see section 2.2.1). This also meant that some vehicles were not recruited based on the results from the remote sensing measurement per se, but rather to ensure the recruiting of the targeted number of Euro 6 diesel vehicle models most common on the Swedish market. Figure 5 shows the percentile distributions of the NOx emissions as measured by the remote sensor in Haninge, together with the average NOx emissions as measured by the remote sensor for the vehicles recruited for the RDE and chassis dynamometer tests. Most of the recruited vehicles had NOx emissions above the 75th percentile, but as can be seen some vehicles with low or intermediate emissions were also recruited. All Euro 6 vehicles presented in Figure 5 are Euro 6b. In addition to those, a few Euro 6d-temp and 6c vehicles were also recruited for RDE testing, but these were not measured by the remote sensor. Detailed information on the recruited vehicles can be found in Appendix 2. Note that the percentile distributions in the figures shows that some measured emissions are below zero. It is general praxis to keep negative values when evaluating remote sensing results since they still are considered to contain information and they should be interpreted as really low emissions close to zero. On the other side of the scale there are a few really high emission values, up to 180 g/kg fuel. Although such high results can be seen as less plausible, we have chosen to keep them in the figures as we have not been able to identify any obvious reason to suspect an incorrect measurement.

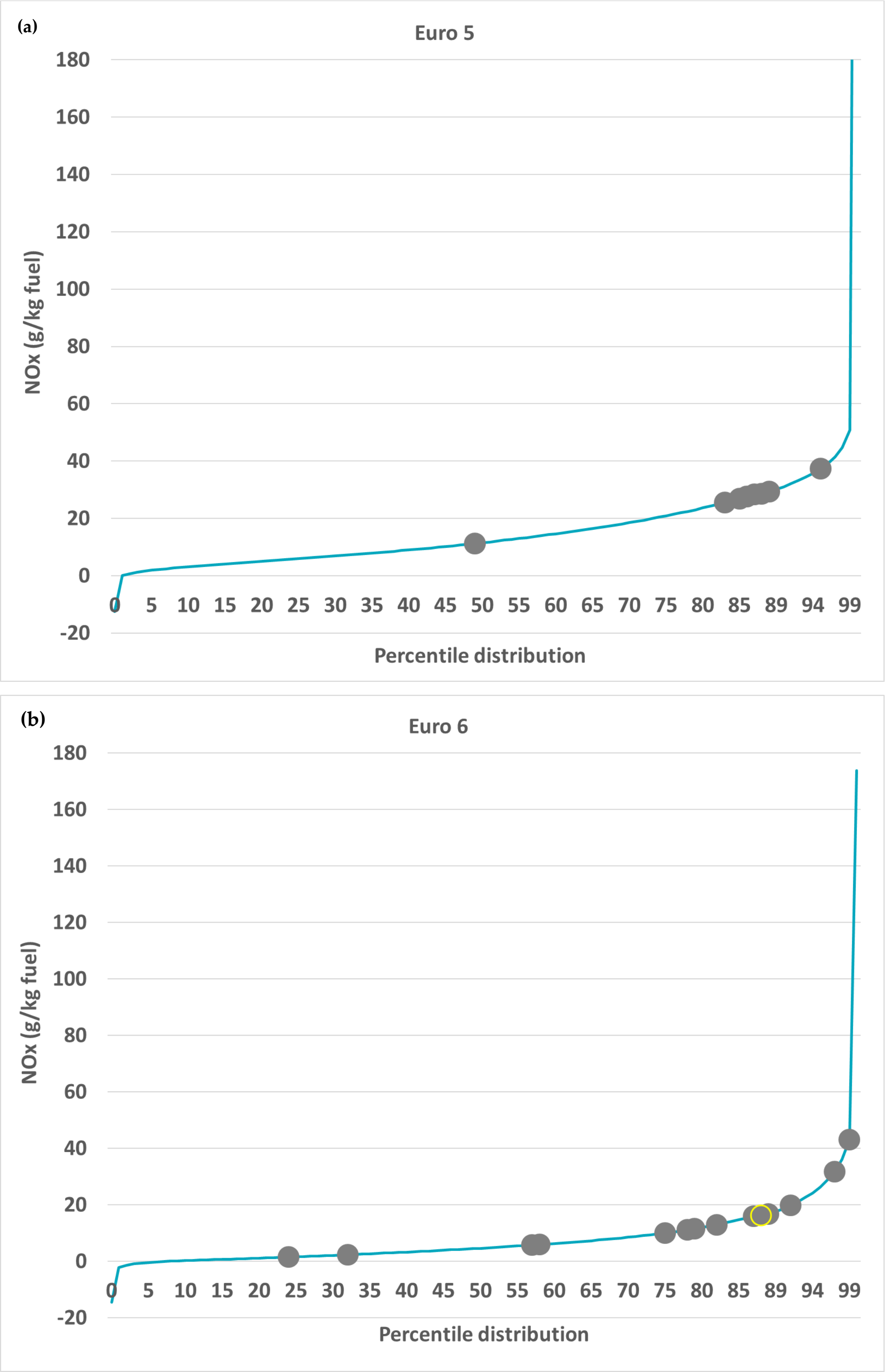

Figure 5 Percentile distributions of NOx emissions (in g/kg) for Euro 5 (a) and Euro 6 (b) light-duty diesel vehicles according to the remote sensing measurements in this study. Markers represent average NOx emissions from the remote sensing tests of vehicles recruited for further RDE tests and laboratory tests. The marker with yellow border is a light commercial vehicle, all others are passenger cars.

3.3 PEMS and chassis dynamometer tests

NOx and CO_2 emission factors were derived from the RDE tests that were conducted on seven Euro 5 passenger cars, 16 Euro 6b passenger cars, one Euro 6c passenger car, four Euro 6 d-temp passenger cars and one Euro 6b light commercial vehicle. Seven of these vehicles (four Euro 5 and three Euro 6 passenger cars) were also tested on a chassis dynamometer. All emission factors from the RDE, NEDC and WLTP tests are presented in Appendix 3. It is important to point out here that only vehicles certified as Euro 6d-temp and later must meet the requirements set for RDE testing.

Four of the tested Euro 5 cars were tested over the NEDC resulting in NOx emissions below or just slightly above the Euro 5 limit as presented in Figure 6. As expected, emissions in the RDE test were much higher than over the NEDC - for most vehicles about three times higher or even more. Two of the vehicles were also tested over the WLTC resulting in NOx emissions somewhere between the emissions measured over the NEDC and the RDE test.

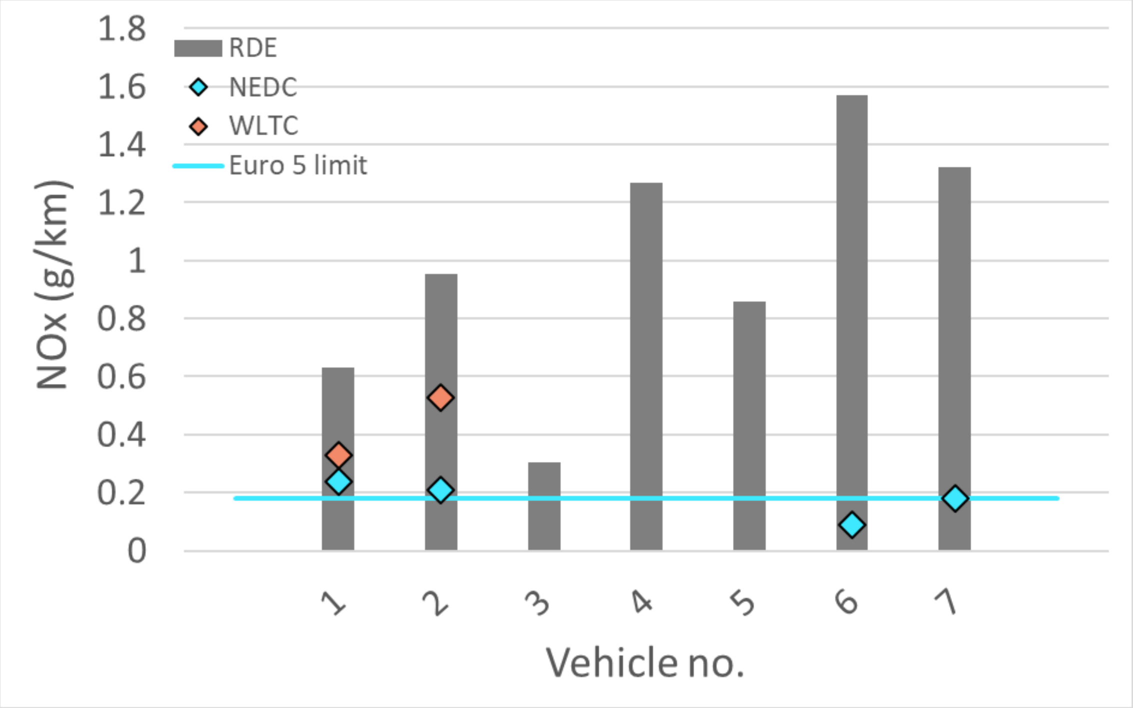

Figure 6 **NOx emissions (g/km) over the RDE, NEDC and WLTC for the tested Euro 5 diesel passenger cars.**

Figure 7 presents NOx emissions from the tested Euro 6 vehicles as measured over the NEDC, WLTC and RDE test. Vehicles no. 8-25 were certified as Euro 6b and vehicles no. 26-30 as Euro 6c or Euro 6d-temp. One of the three cars tested over the NEDC (vehicle no. 8) had emissions significantly above the Euro 6 limit. Note that this vehicle had lower emissions over the WLTC. The other two cars were close to the Euro 6 limit. All five Euro 6d-temp vehicles had emissions under the accepted limit (conformity factor=2.1), four of them were also well below the Euro 6d limit (conformity factor=1.43).

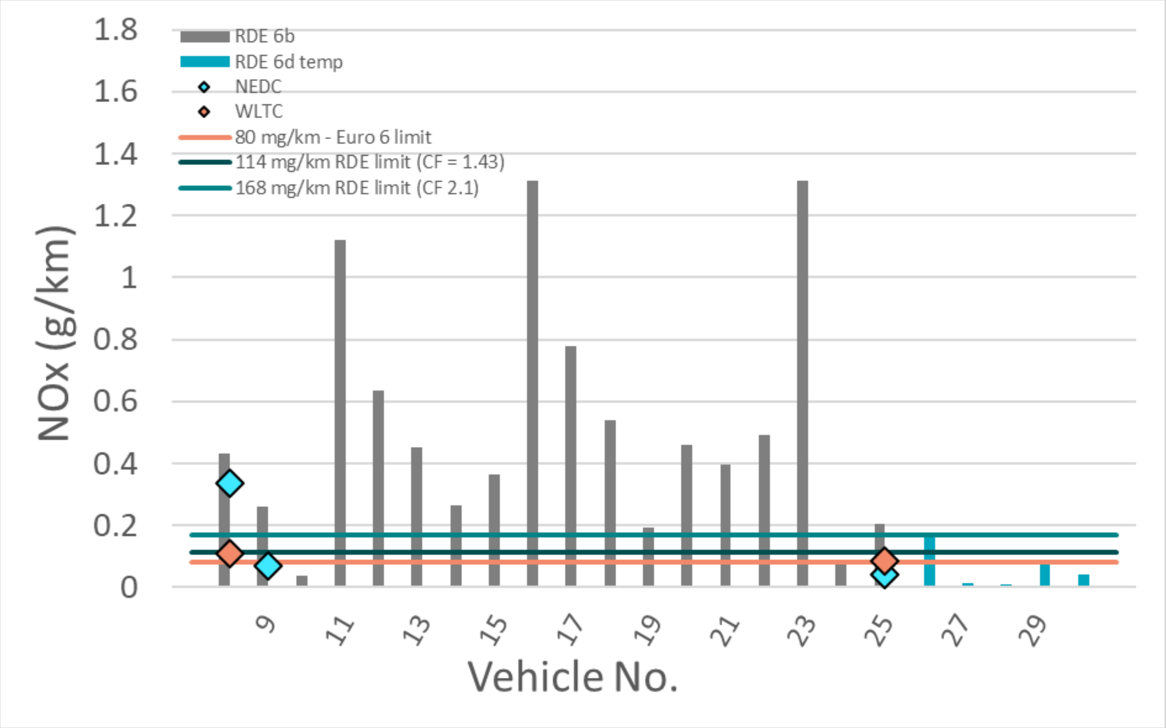

Figure 7 NOx emissions over the NEDC, WLTC and the RDE test for the tested Euro 6 diesel vehicles. Vehicle no. 12 is a light commercial vehicle (class II), all other vehicles are passenger cars.

The RDE measurements showed a stepwise decreasing trend in NOx emissions from Euro 5 to Euro 6 d-temp, Figure 8.

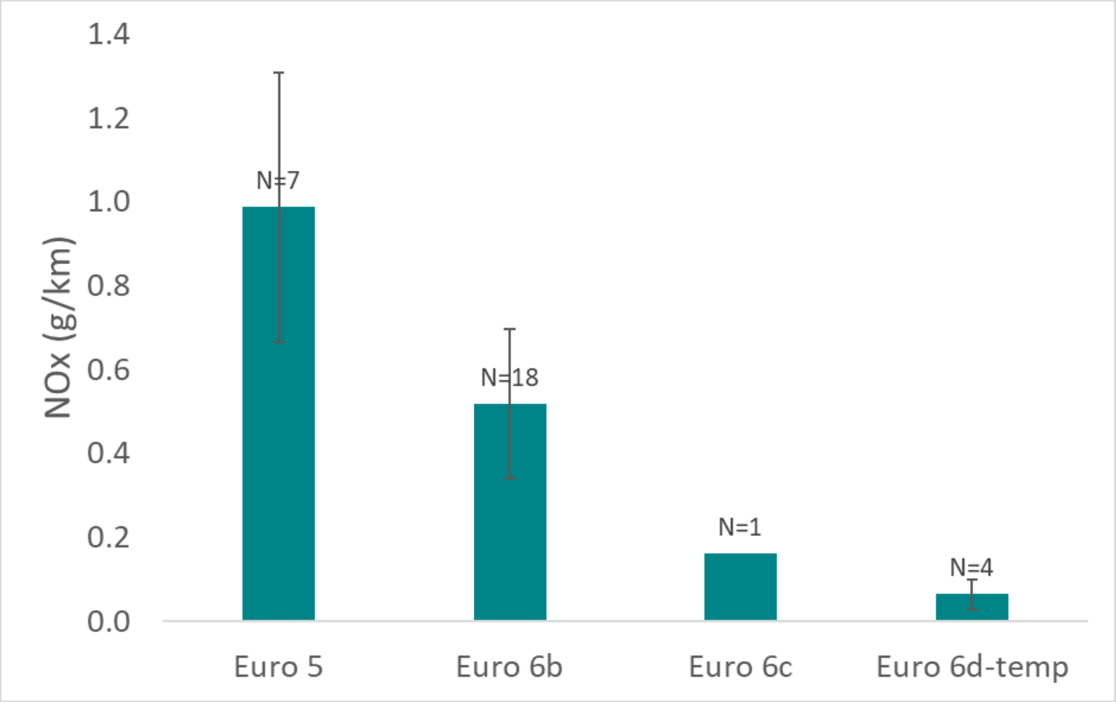

Figure 8 **Average NOx emissions (g/km) by Euro standard for the passenger cars measured in the RDE test. Error bars represents the standard error (95% CI).**

3.4 Remote sensing vs PEMS for NO_X emissions on individual vehicle level

22 of the 30 vehicles that were measured by PEMS were also measured by the remote sensor. Due to some of the recruitment problems described in chapter 3.2, seven vehicles in this sample were measured only once by the remote sensor, hence the remote sensing based assessment of the emission performance of each individual vehicle was not as robust as was initially hoped for. Nevertheless, a comparison of the NOx emissions (in g/kg fuel) as measured by the remote sensor and PEMS, respectively, is presented in Figure 9. For vehicles with three or more remote sensing measurements the two methods agrees quite well for the measurements close to 10g NO_X/kg fuel.

For vehicles number 10 and 20 a greater difference is seen but still the methods can be said to be consistent in that the measured emissions from both vehicles are in the lower to intermediate emission range compared to other Euro 6 vehicles. For vehicle number 11 low emissions were measured with remote sensing but the PEMS measurement showed over 20 gNOx/kg fuel. When the RDE test was conducted on that vehicle it was apparent that the SCR system for an unknown reason was not functioning. Since the emissions of this car as measured by the remote sensor were repeatedly low, the SCR seems to have been working properly a few months before the RDE tests were carried out. For vehicles only tested once or twice with remote sensing the agreement between the two methods is weaker as it can be expected since several remote sensing measurements generally are needed to get at robust estimate of the emissions.

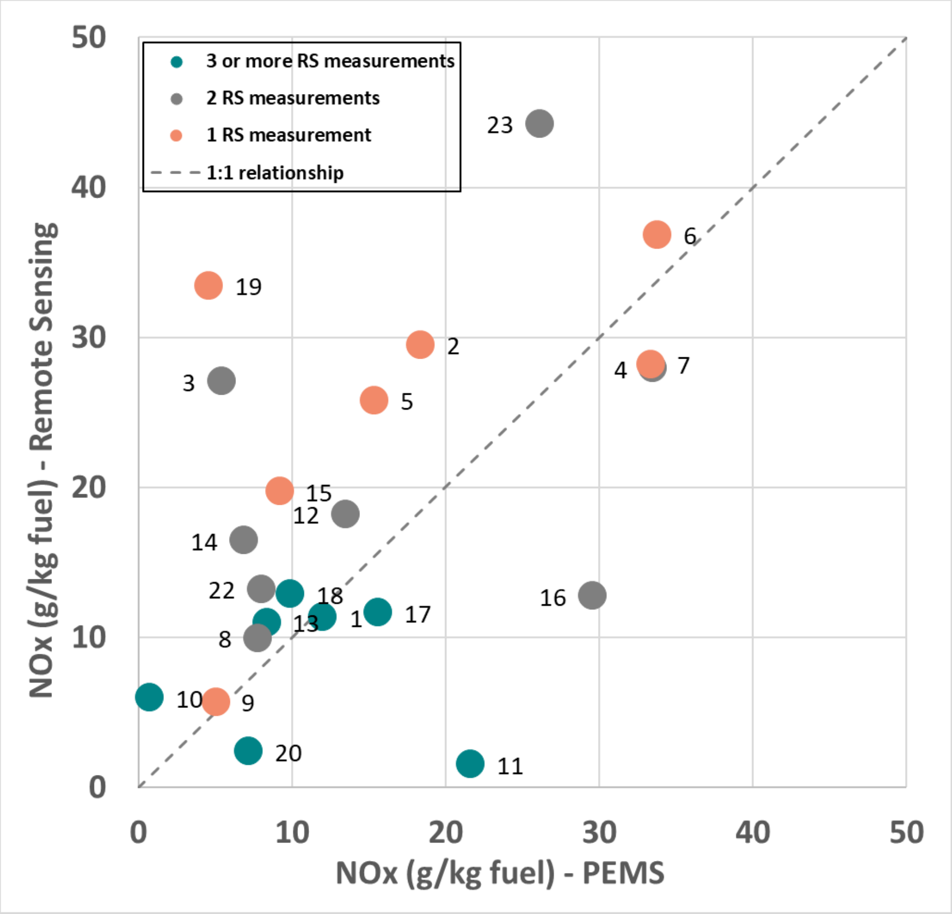

Figure 9 Average NOx emissions as measured by PEMS (RDE test) and by the remote sensor on the same vehicle individuals. Marker numbers represents vehicle id number, see further Appendix 2.

Figure 10 compares the results from the remote sensing and PEMS NOx measurements on the same vehicles that appear in Figure 9, grouped by Euro standard (Euro 5 and the different steps of Euro 6) and the two different emission control technologies applied to Euro 6ab vehicles – LNT and SCR. Since neither any Euro 6c nor Euro 6d-temp vehicles were recruited from the remote sensing measurements to be measured by PEMS (these were recruited by other means), a direct comparison between the two methods based on the same vehicle individuals for these two Euro categories was not feasible. Instead, an average for all remote sensing measurements on the Euro 6c and Euro 6d-temp vehicles, respectively, was used for the methods comparison.

Two interesting observations can be made from Figure 10. First, there is a reasonably good agreement between remote sensing and PEMS for all vehicle categories, except for Euro 6d-temp for which the NOx emissions according to the remote sensing measurements are substantially higher compared to the PEMS measurement. Second, both methods show a large scatter in emissions between individual vehicles. Normally this is often something that is said to characterize remote sensing data, which occasionally therefore are discredited, but this feature seems to characterize PEMS RDE data with regard to diesel LDV Euro 5 and 6 NOx emissions as well. In this sense, the use of remote sensing can be claimed to be a good complement to PEMS, since measuring a large number of vehicles with PEMS is often restricted by costs, whereas this is normally not the case for remote sensing.

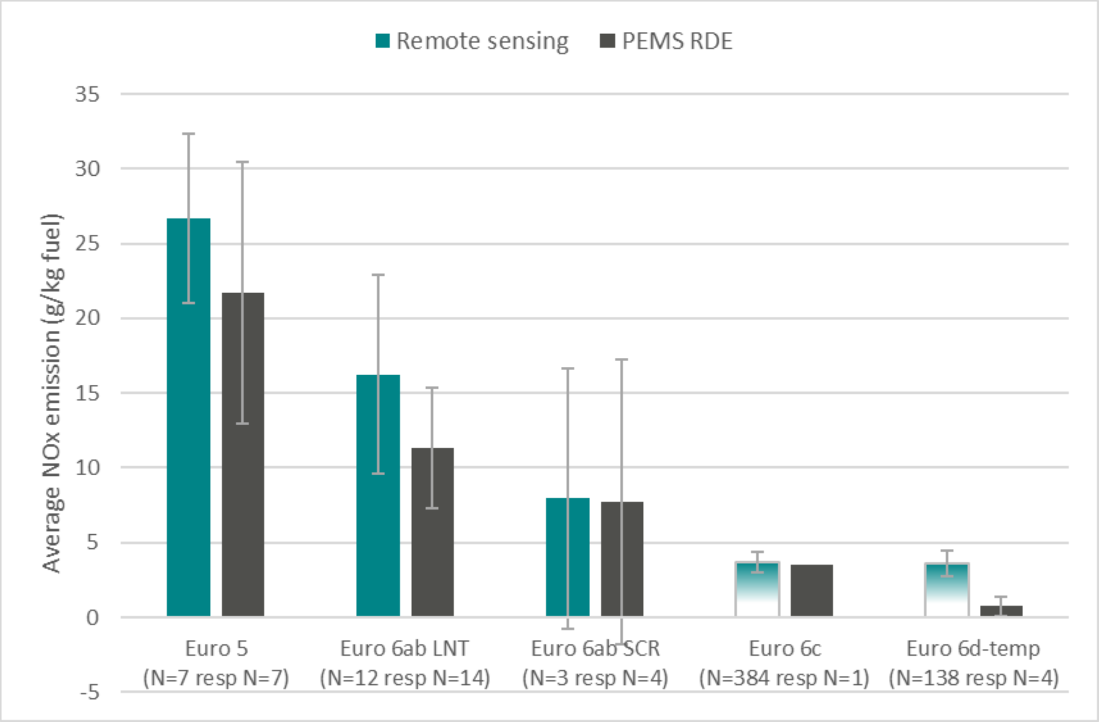

Figure 10 Average NOx emissions as measured by PEMS (RDE test) and remote sensing by Euro standard and Euro 6ab emission control technlogy. Note that the bars for remote sensing for Euro 6c and 6d-temp do not represent the same vehicles as for the PEMS measurements, see further explanation in the text.

3.5 Analysis of Euro 6 diesel LDV NOx emissions using extended datasets

The remote sensing results in this chapter are based on an analysis of data from the CONOX database described in chapter 2.1.2. Since the CONOX dataset is much larger than the dataset from the measurements conducted in Haninge, the average emissions by Euro class, vehicle make/model or engine alliance, could be estimated with a much higher certainty and at a more detailed level. The number of valid NO_X emission measurements on diesel light-duty vehicles by Euro standard in the remote sensing measurements used in the analysis is presented in Table 3.

As was also the case in the analysis of the data from the Haninge site (Figure 4 and Figure 8) vehicles certified for Euro 6 step c and later have lower average NO_X emissions than earlier Euro 6 vehicles, Figure 11 (a). The CONOX data also include some Euro 6d vehicles which were not present in the remote sensing data sampled in Haninge. The average NO_X emission for those vehicles is on the same level as Euro 6c and Euro 6d-temp. On model year level the Euro 6 vehicles exhibit a significant downward trend from model year 2015 and onwards, Figure 11 (b).

Table 3 **Number of valid remote sensing measurements for diesel passenger cars and light commercial vehicles included in the extended analysis of NO_X emissions on vehicle model/engine alliance level.**

Vehicle category	Emission standard	Number of valid NOx measurements
Passenger cars	Euro 5	78 325
	Euro 6a,b	63 459
	Euro 6 c	2 166
	Euro 6 d-temp	1 313
	Euro 6d	2 540
LCV	Euro 5	40 944
	Euro 6a,b	16 101
	Euro 6 c	376
	Euro 6 d-temp	43
	Euro 6d	54

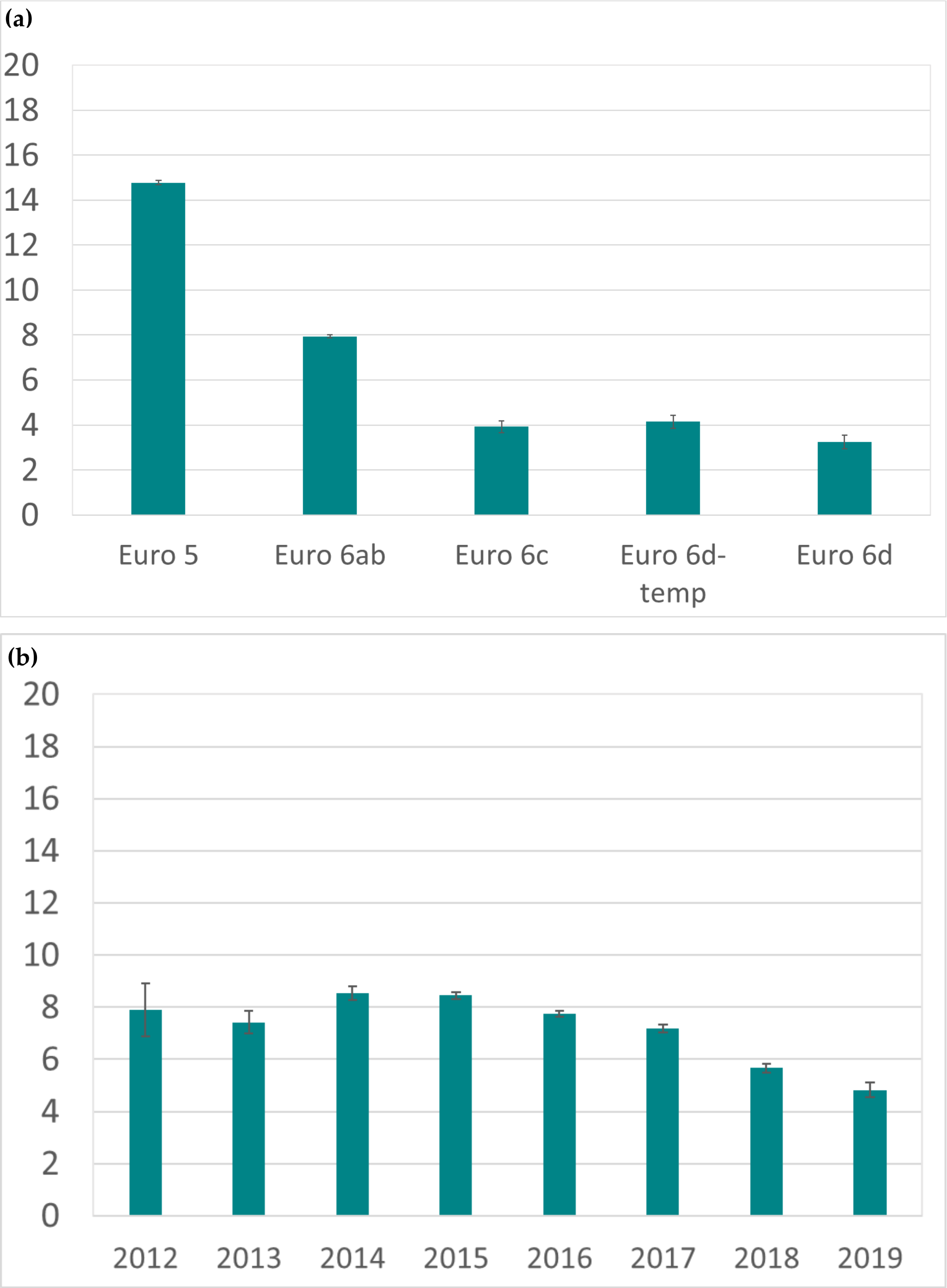

Figure 11 Average NOx emissions for diesel cars by Euro standard (a) and for Euro 6 diesel cars by model year (b), based on data from the CONOX remote sensing database. Error bars represent the standard error (95% CI).

3.5.1 NOx emissions from Euro 6 diesel LDVs by vehicle model as measured by remote sensing

Figures 12-14 present average NOx emissions for several different Euro 6ab diesel passenger car models (bars) for three different engine volume intervals <2 litres (Figure 12), 2 litres (Figure 13) and >2 litres (Figure 14). Also, average emissions for specific engine alliances according to the uCARe taxonomy (uCARe, 2020) are presented as lines. The engine power is included in the uCARe taxonomy, but it has not been considered in this analysis since the amount of data did not allow a comprehensive analysis on that level of detail. In the figures the average temperature and VSP are presented for an analysis of possible differences in emissions due to these parameters.

From the figures it can be seen that many vehicle models sharing the same engine have similar NOx emissions (in g per kg fuel), but there are also some exceptions. One example of the latter is the 2-litre engine from the Volkswagen group, where the models Golf, A3 and Octavia have higher NOx emissions than other models using the same engine. Some of the differences may be explained by the fact that there are differences in fuel consumption between different models and hence the difference in distance specific NOx emissions (in g/km) may not be as large but there may also be other explanations, e.g. different engine/aftertreatment calibration approaches to optimize NOx emission reductions and fuel economy (Bernard *et al*., 2019). It should be noted that the Golf, A3 and Octavia have low NOx emissions (as measured by remote sensing) compared to many other models, even though somewhat higher than other models sharing the same engine.

To investigate whether the difference in fuel consumption between the models using the Volkswagen group 2-litre engine could explain the difference in emissions when expressed as g/kg, the distance specific emissions (g/km) were estimated from the g/kg fuel emissions and by assuming a fuel consumption according to the NEDC test based on information from the EEA monitoring of CO_2 emissions from passenger cars (EEA 2020). To compensate for the divergence between the NEDC and real-world driving information from Tietge, 2019b was used. In Figure 15 (a) average NOx emissions in g/kg fuel are presented as box plots with percentiles. In Figure 15 (b) the estimated g/km emissions are presented. As can be seen, the difference in fuel consumption between the models does not seem to compensate for the lower fuel specific NOx average emission measured for the Golf, A3 and Octavia.

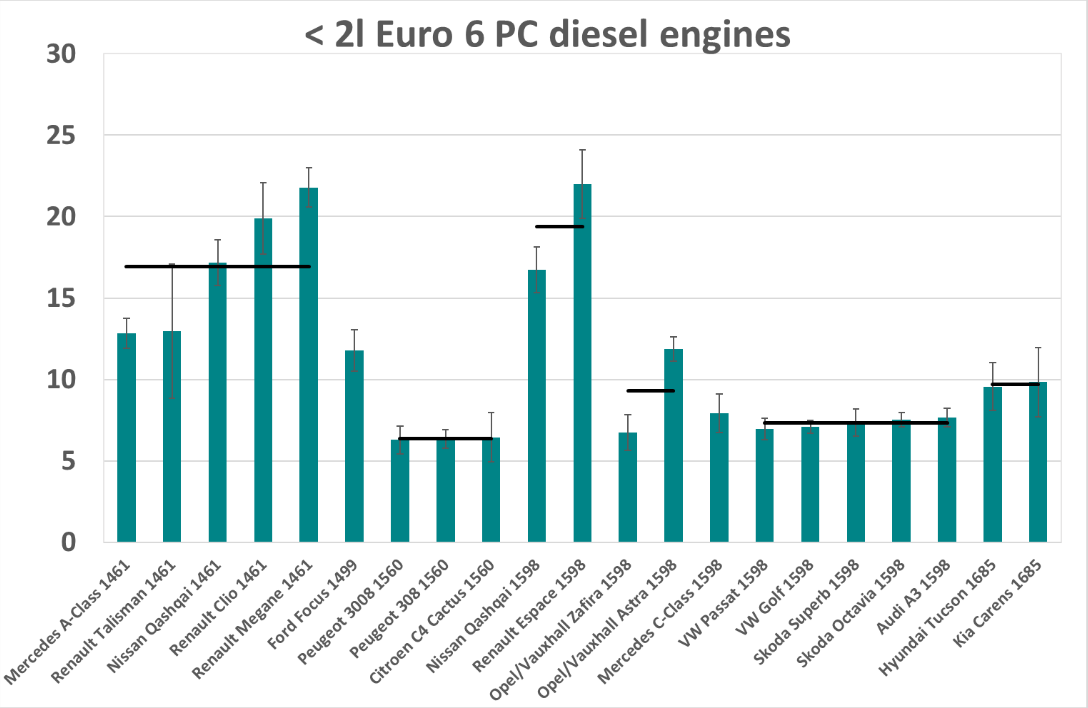

Figure 12 NOx emissions (g/kg fuel) for different Euro 6ab vehicle models (bars) with an engine displacement volume < 2 litres. Average NOx emissions (g/kg fuel) for vehicle models using the same engine are presented as black lines. Error bars represent the standard error (95% CI).

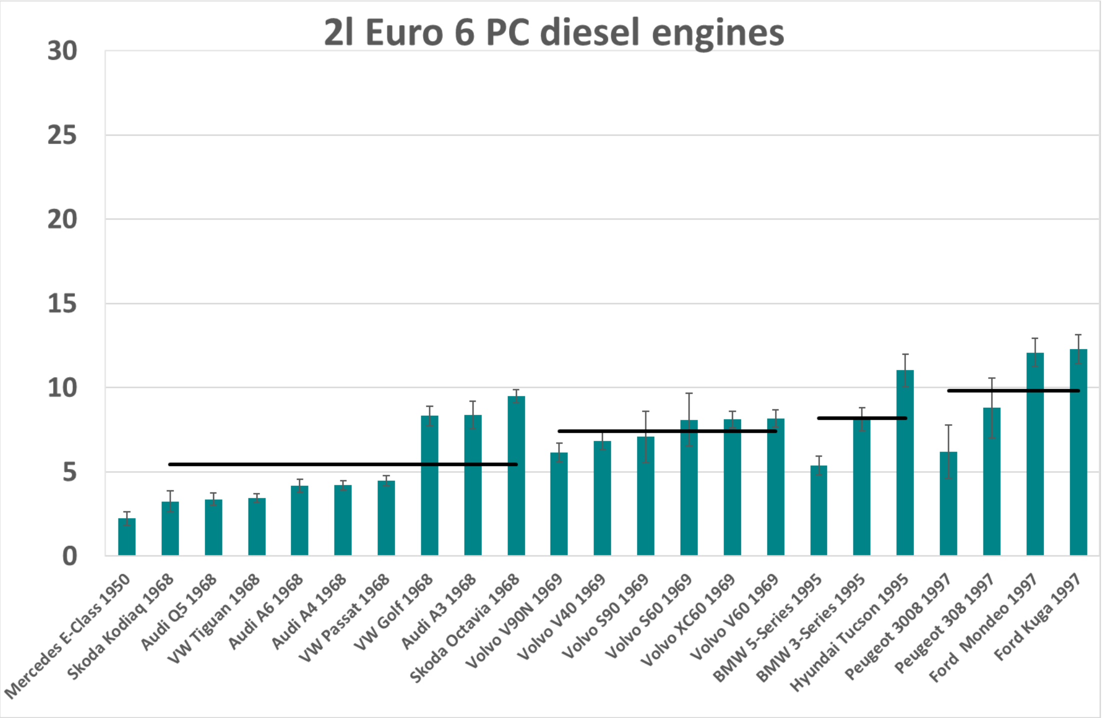

Figure 13 NOx emissions (g/kg fuel) for different Euro 6ab vehicle models (bars) with an engine displacement volume of 2 litres. Average NOx emissions (g/kg fuel) for vehicle models using the same engine are presented as black lines. Error bars represent the standard error (95% CI).

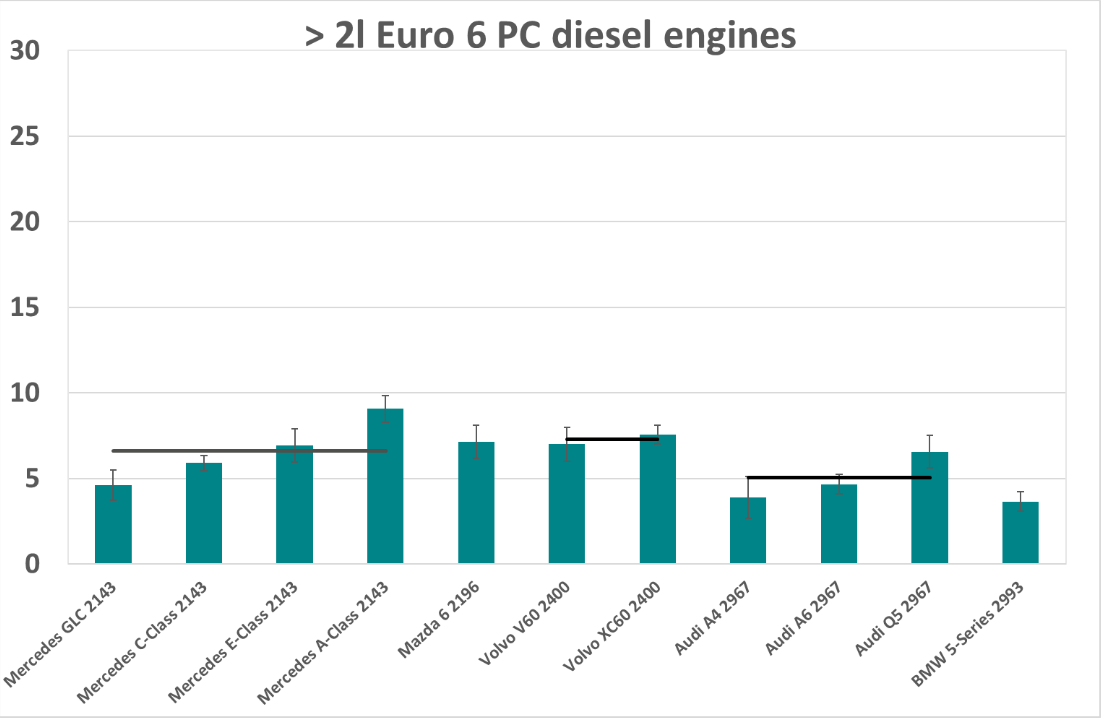

Figure 14 NOx emissions (g/kg fuel) for different Euro 6av vehicle models (bars) with an engine displacement volume > 2 litres. Average NOx emissions (g/kg fuel) for vehicle models using the same engine are presented as lack lines. Error bars represent the standard error (95% CI).

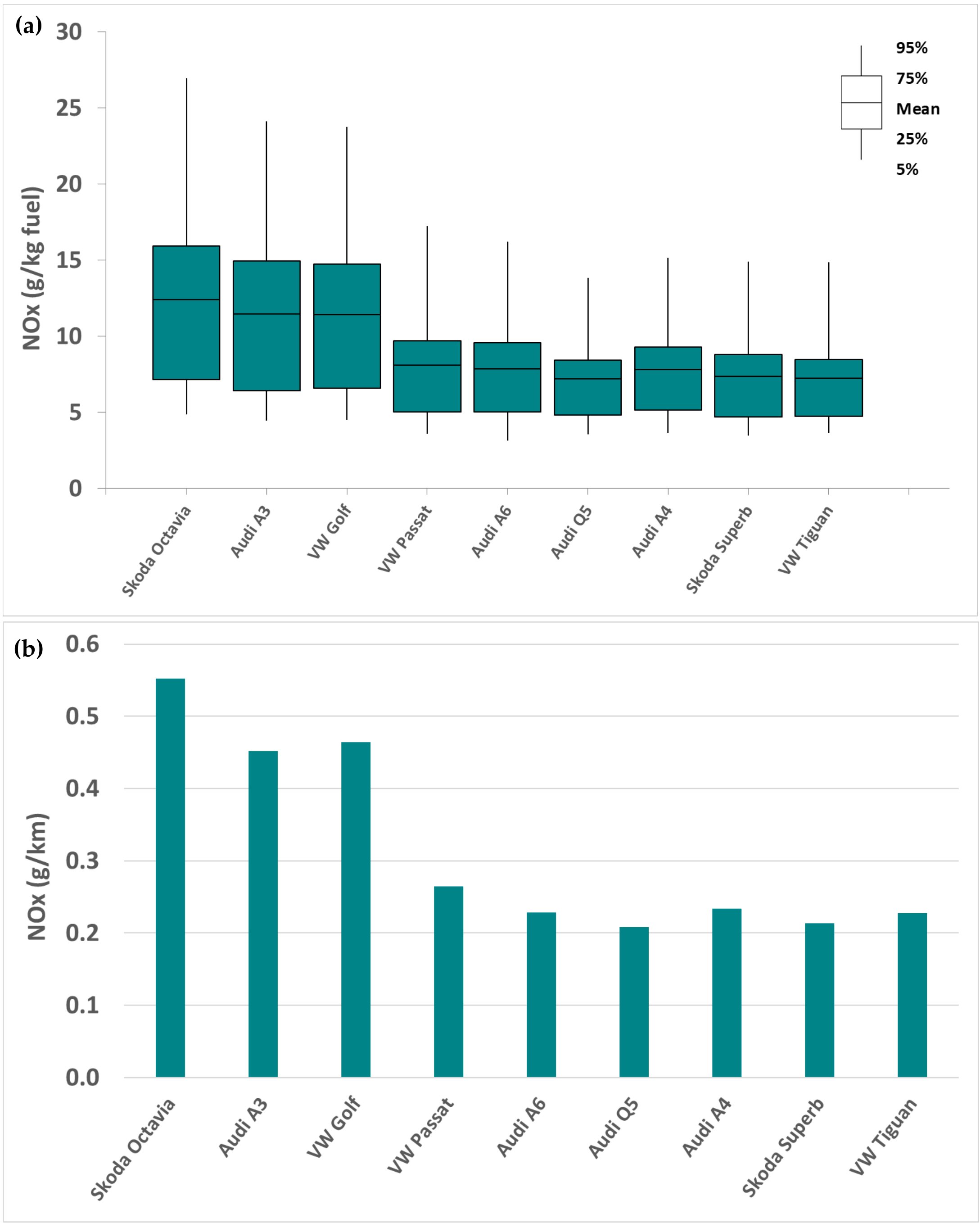

Figure 15 NOx emissions for models using the same 2l engine in g/kg fuel burnt (a) and g/km (b). Boxes and bars in (a) represent 5%, 25%, 75% and 95% percentiles.

3.5.2 Comparison between remote sensing and PEMS by make and model of Euro 6ab diesel cars

In this section average NOx emissions (in g/kg fuel) as measured by remote sensing on vehicle model level (Figure 16) and on engine alliance level (Figure 17) are compared with PEMS measurements conducted on the same vehicle models and engine families. For this comparison, as described in section 2.2.1, the PEMS data that were sampled in this study was complemented with data from the ICCT PEMS database (Baldino et al., 2017) and the ERMES database (Keller, 2017), whereas the remote sensing data sampled in this study was complemented with data from the CONOX database. In the overall dataset, the number of PEMS measurements on a single vehicle model ranges from one to five and the number of remote sensing measurements on a single vehicle model ranges from 600 to 12 000. The models included in the figures presented in this section are top selling models in Sweden and in the EU. For the PEMS measurements only RDE compliant tests are included.

In a similar analysis for Euro 5 diesel passenger cars, Borken-Kleefeld *et al.* (2018b) concluded that, despite the differences between the two methods (remote sensing and PEMS), the agreement is good since most of the differences are random and are averaged out if the sample size is sufficiently large. Our analysis (Figures 16 and 17) shows that the agreement between the two methods is good also for Euro 6ab diesel light-duty vehicles.

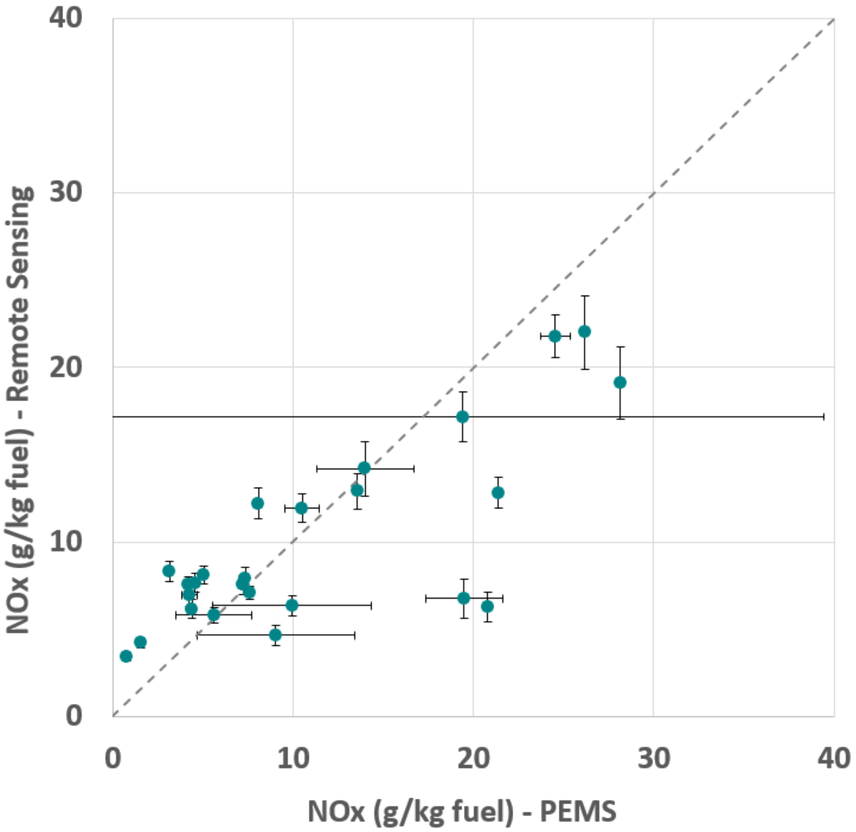

Figure 16 **Average NOx emissions for common Euro 6ab diesel light-duty vehicle models as measured by PEMS (RDE test) and by remote sensing. Remote sensing averages are based on data from the CONOX-database, PEMS measurements were conducted within this project and were obtained from the ICCT database (Baldino et al, 2017) and the ERMES database (Keller, 2017). Error bars represent the standard error (95% CI).**

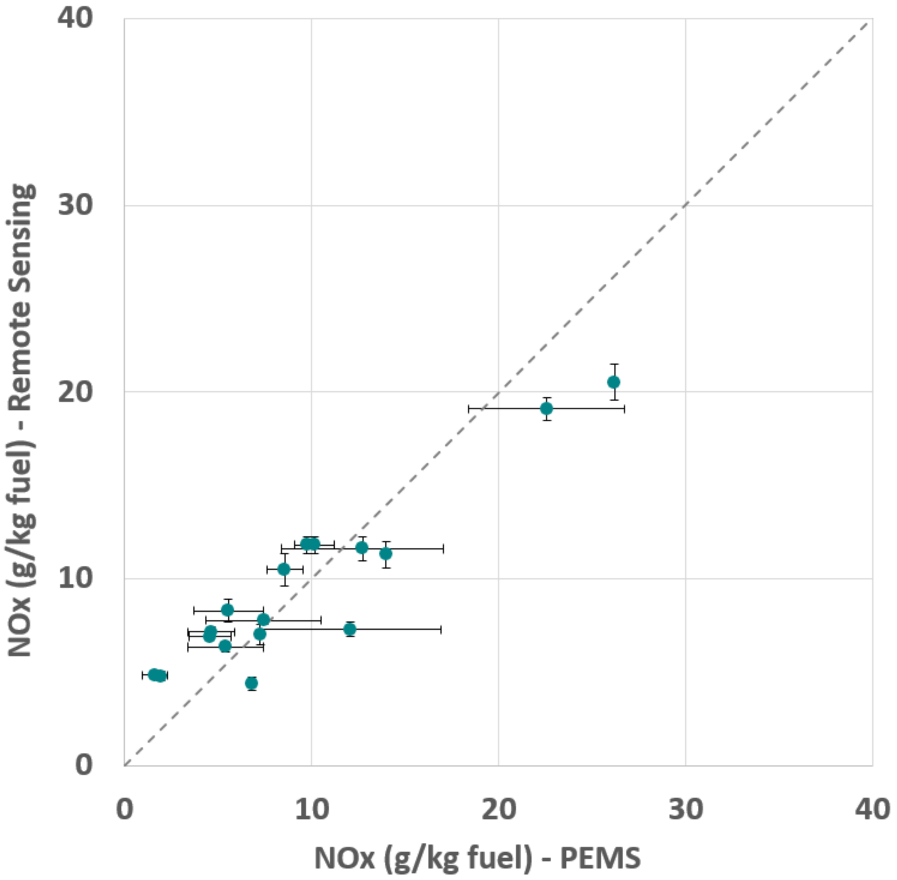

Figure 17 Average NOx emissions for common Euro 6 diesel engines (step a + step b) as measured by PEMS (RDE test) and by remote sensing. Remote sensing averages are based on data from the CONOx-database, PEMS measurements were conducted within this project and were obtained from the ICCT database (Baldino et al, 2017) and the ERMES database (Keller, 2017). Error bars represent the standard error (95% CI).

It can be seen by Figure 16 and 17 that the agreement between remote sensing and PEMS is somewhat better when vehicles are grouped by engine code (engine family) than when they are grouped by vehicle model. A simple regression analysis applied to Figure 16 and 17 yielded an R^2 value of 0.62 and 0.87, respectively.

3.6 Characterization of Euro 6 high-emitters

In this chapter the occurrence and emission behavior of high-emitting vehicles within the Euro 6 diesel LDV category with regard to NOx and PM emissions was explored, based on the data collected in the dedicated remote sensing measurements conducted in Haninge outside Stockholm in 2018. The focus of the analysis was on Euro 6ab since this was the by far most abundant Euro 6 category in the dataset. However, some analysis was also made for the smaller samples of the later Euro 6 categories 6c and 6d-temp (chapter 3.6.2). By the time the measurements were carried out, any Euro 6d vehicles had not yet penetrated the Swedish light-duty diesel vehicle fleet.

Valid NOx (NO and NO_2) and VSP measurements (in the range 2-30 kW/ton, records with lower and higher VSP values were discarded from the analysis) were obtained for 5193 unique Euro 6ab light-duty diesel vehicles (passenger cars and light commercial vehicles). Of these, 1576 unique vehicles were measured more than once. The distribution of the number of unique vehicles measured more than once over the number of repeat measurements is shown in Figure 18, i.e. 820 unique vehicles were measured twice, 329 vehicles were measured three times, etc. Similar statistics were achieved for the high-emitter analysis with regard to PM.

The high-emitter analysis was carried out on a subsample of the vehicles measured four times or more by the remote sensor, comprising 427 unique vehicles. The threshold of ≥4 repeat measurements for including vehicles in the analysis was arbitrary chosen to achieve a proper balance between a sufficiently high number of repeat measurements and a sufficiently high number of unique vehicles, as an attempt to optimize the robustness of the statistical analysis.

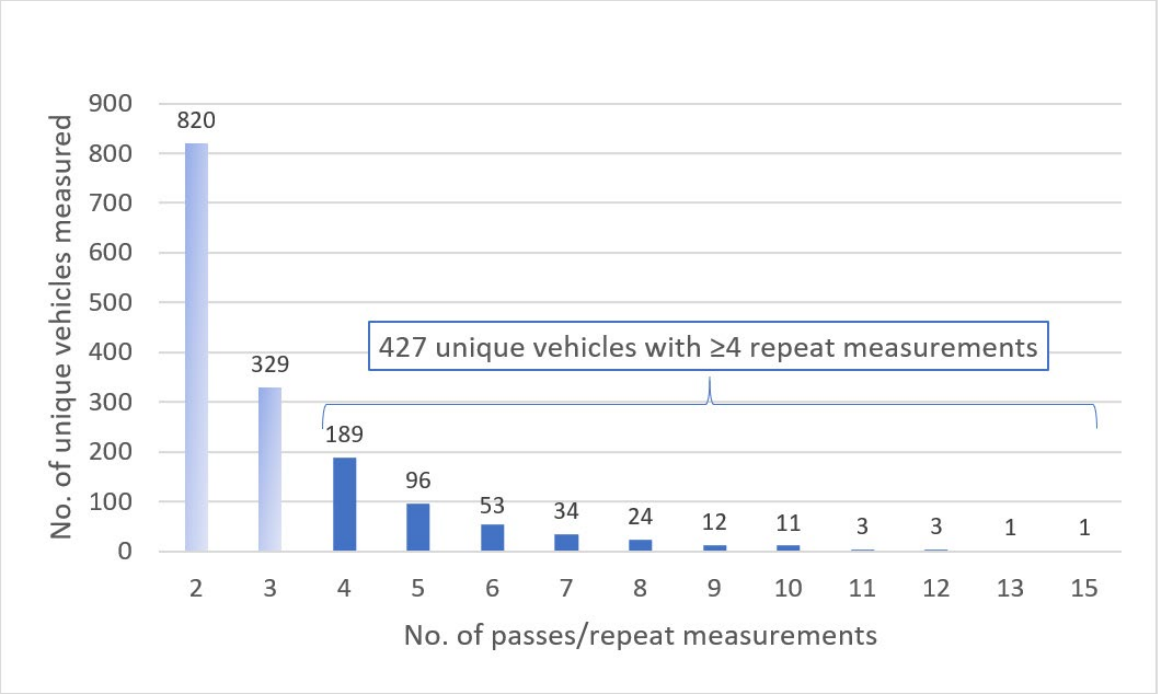

Figure 18 **Number of unique vehicles measured by the number of passes/repeat measurements of Euro 6ab light-duty diesel vehicles.**

3.6.1 Euro 6ab NO_X emissions

3.6.1.1 Influence of engine alliance and engine family

The average NO_x emission and average VSP by decile for the 427 unique Euro 6ab light-duty diesel vehicles measured more than four times by the remote sensor are presented in Figure 19. The NO_x emissions from the 10 % highest emitting fraction (the 10th decile) of the subsample were on average 18 times higher than the 10 % lowest emitting fraction (the 1st decile). On a g/kg fuel basis, the 10 % highest emitting vehicles (43 vehicles) accounted for about 30 % of the overall NO_x emissions from the 427 vehicles subsample. There was no statistically significant trend in the average VSP by decile, although a slight tendency of increasing VSP for the highest deciles was observed (see also chapter 3.6.1.2).

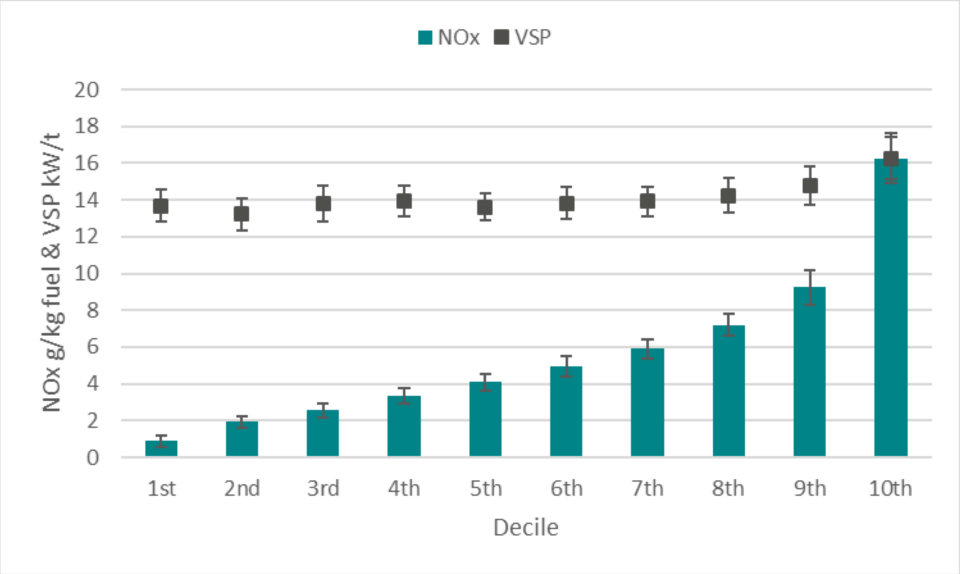

Figure 19 **Average NO_x emissions (in g/kg fuel) and VSP (in kW/t) by decile for the 427 unique Euro 6ab light-duty diesel vehicles measured four times or more by the remote sensor. Error bars represent the standard error (95% CI).**

An in-depth analysis on individual vehicle level was made by comparing the remote sensing data for the ten highest emitting vehicles, representing approximately the 2% highest emitting vehicles, with the ten lowest emitting vehicles, representing the 2% cleanest vehicles in the 427 vehicles subsample. It was found that the NO_x emissions from the ten highest emitting vehicles were on average about two orders of magnitude higher than the average emissions from the ten lowest emitting vehicles (Figure 20). The high-emitting vehicles exhibited a large variability in NO_x emissions between individual passes, at most ranging from 2 up to 60 g NO_x per kg fuel for a single vehicle, whereas the low-emitting vehicles appeared with consistently low emissions (none exceeding 4 g NO_x per kg fuel for a single pass) and a significant share of negative emission readings (revealing that the emission levels of the best performing diesel Euro 6ab LDVs were below or close to the noise level or detection limit of the remote sensing instrument). Of the overall 56 NO_x emission measurements on the highest emitting vehicles only two measurements (<4%) overlapped with the highest value recorded for the lowest emitting vehicles. Of the overall 47 NO_x emission measurements on the lowest emitting vehicles only six measurements (<13%) overlapped with the lowest value recorded for the highest emitting vehicles. These observations of characteristics of high- and low-emitters, respectively, as measured by remote sensing, are well in line with those made by Buhigas et al. (2021).

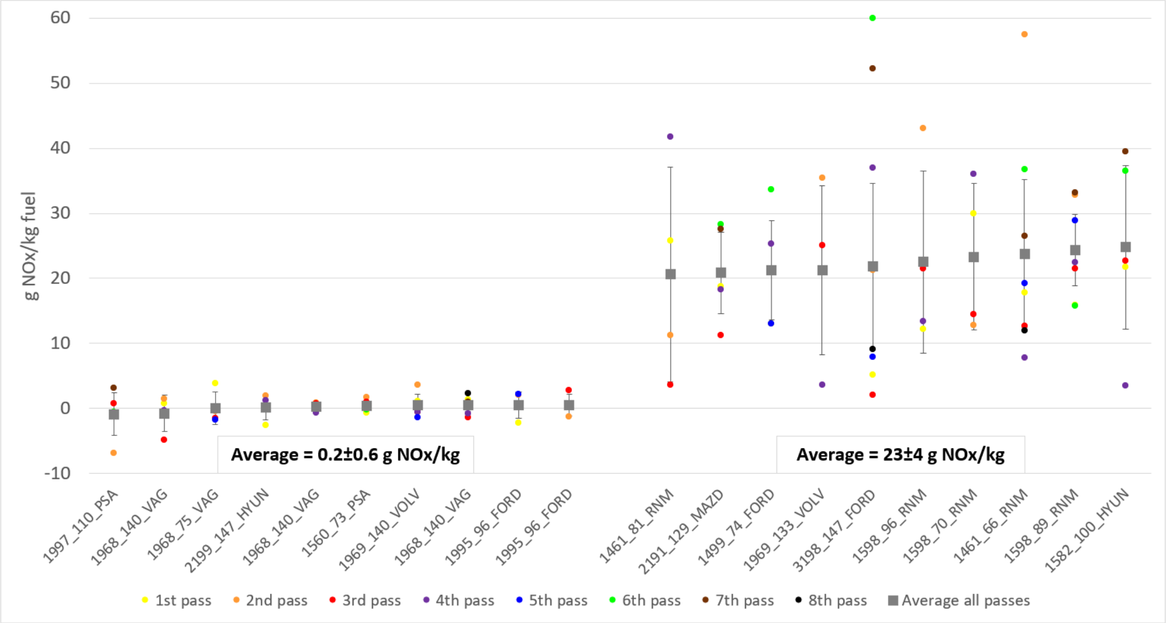

Figure 20 NOx emissions for the ten lowest emitting and the ten highest emitting diesel Euro 6ab light-duty vehicles measured by the remote sensor four times or more, rank ordered by increasing average NOx emissions. The uCARe taxonomy (see section 2.1.3) is used for labelling the vehicles on the x-axis. The labelling reads: [engine displacement in cm3]_[rated engine power in kW]_[engine alliance]. (Engine alliance PSA = Peugeot-Citroen and VAG = Volkswagen Group, RNM = Renault-Nissan-Mitsubishi).

As can be seen by Figure 20, some engine families were more frequently represented among the highest emitting vehicles than what could be expected from their market share in Sweden. For instance, the RNM (Renault-Nissan-Mitsubishi) alliance 1598 cm^3 engine made up only about 2% of all the Euro 6ab vehicles that passed the remote sensing site, whereas three vehicles with this engine appeared among the ten highest emitting vehicles measured by the remote sensor, implying a high-emitter overrepresentation by a factor of about 15. Similarly, the RNM alliance 1461 cm^3 engine made up only about 1% of the overall fleet, whereas it accounted for two of the ten highest emitting vehicles measured by the remote sensor, implying a high-emitter overrepresentation by a factor of about 20.

Conversely, the VAG (Volkswagen group) alliance 1968 cm^3 engine appeared with four vehicles among the ten lowest emitting vehicles (40%) while accounting for about 25% of the overall diesel Euro 6ab LDV fleet passing the remote sensing site. Thus, this engine appears to be overrepresented among the cleanest diesel Euro 6ab LDV engines.

Similar observations were also made when expanding the sample of high- and low-emitting vehicles by analyzing the 10% fraction of the highest and lowest emitting vehicles, respectively, in the 427 unique vehicles subsample measured four times or more by the remote sensor (i.e. the vehicles contained in the 10th and 1st decile, respectively, in Figure 19). For instance, the RNM alliance engines with capacities of 1461 cm^3 and 1598 cm^3, respectively, were overrepresented by a factor of about 10 among the 10% highest emitting vehicles. Other alliances and engine families that were clearly overrepresented among the 10% highest emitting vehicles were Ford with the 1499 cm^3 engine by a factor about 8, Hyundai with the 1582 cm^3 engine by a factor of about 5 and PSA with the 1560 and 1997 cm^3 engines by a factor of about 4 and 3, respectively. Despite its large market share, the VAG 1968 cm^3 engine was rarely observed among the 10% highest emitting vehicles. This engine was one of the most abundant among the 10% lowest emitting vehicles, overrepresented by a factor of 3-4.

The results of a further expansion of the remote sensing data sample for the Euro 6ab high-emitter characterization is visualized in Figure 21, in which the NOx emission percentile distributions for the engine families discussed above and some others of the most abundant Euro 6ab LDV diesel engine families in the remote sensing measurements are presented. The percentile distributions in Figure 21 are based on all measurements, i.e. on all early Euro 6 vehicles regardless of how many times they were measured by the remote sensor (8,740 valid measurements). It shows the same pattern as the analysis of the smaller subsamples, i.e. a large difference in NOx emission performance between various alliances and engine families, ranging from the cleanest VAG alliance 1968 cm^3 engine to the highest emitting RNM alliance 1461 cm^3 engine, with a span in the difference in emission performance between these two engine types of a factor about 3 for the highest percentiles and a factor of about 6 around the median. The difference in NOx emissions between the two engine types is visible over the whole percentile distribution range

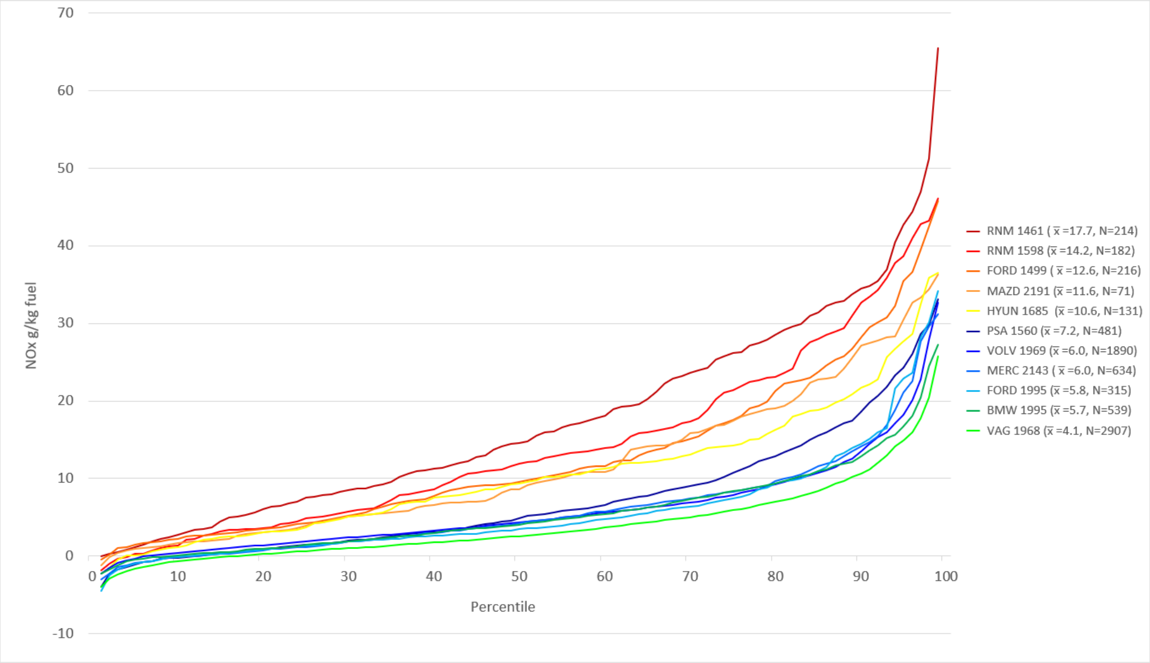

Figure 21 **Percentile distributions of NOx emissions in g/kg fuel for the most abundant early Euro 6 engine families in the remote sensing measurements. The four digits following the alliance code name denotes the engine displacement volume in cm^3, $\bar{x}$ the average NOx emission by engine family, and N the number of remote sensing measurements for each engine family.**

The high- (and low-) emitter patterns for various engine alliances and engine families observed in this section are consistent with the observations of the average NOx emission performances by vehicle model presented in chapter 3.5.1, and largely also with the results from previous studies on the real-world NOx emission performance of early Euro 6 light-duty diesel vehicles. Yang *et al.* (2015) measured the NOx emissions of 32 vehicles of various makes, vehicle segments and engine capacity, also with different NOx control technology (EGR, LNT, SCR), over the NEDC and version 2.0 of the more realistic WLTC. The RNM 1598 cm^3 engine and the Hyundai 1995 cm^3 engine were represented in the test sample and were among the highest emitting over the WLTC. Also, the VAG 1968 cm^3 engine, the BMW 1995 cm^3 engine and the MERC 2143 cm^3 engine were represented in the test sample and were among the lowest emitting over the WLTC. Bernard *et al.* (2019) carried out in-depth Euro 6 RDE (PEMS) testing on two Mercedes models (MB 180 and MB 200 with the 1598 cm^3 engine) and one Volkswagen model (Passat, engine capacity not specified but most likely 1968 cm^3). The Passat had much lower NOx emissions in the RDE test compared to the two Mercedes.

3.6.1.2 Influence of vehicle specific power (VSP)

For the same vehicle individuals appearing with their measured NOx emissions in Figure 20, the corresponding VSP data are presented in Figure 22. Although there was a large overlap (≈75%) with regard to individual VSP values between the two emitter categories, the average VSP for the ten highest emitting vehicles was about 50% higher than for the ten lowest emitting ones (Figure 22). Further, among the high-emitters the VSP value exceeded 20 kW/t for 46% of all passes, whereas for the low-emitters this occurred for only 4% of all passes. Conversely, the VSP value was lower than 10 kW/t for 28% of the low-emitter passes, but for only 13% of the high-emitter passes. Thus, broadly speaking, repeat NOx high-emitting Euro 6ab diesel light-duty vehicles according to the remote sensing measurements, with emissions expressed as g/kg fuel, appear to be associated with higher but also more variable VSP values than for low-emitting vehicles.

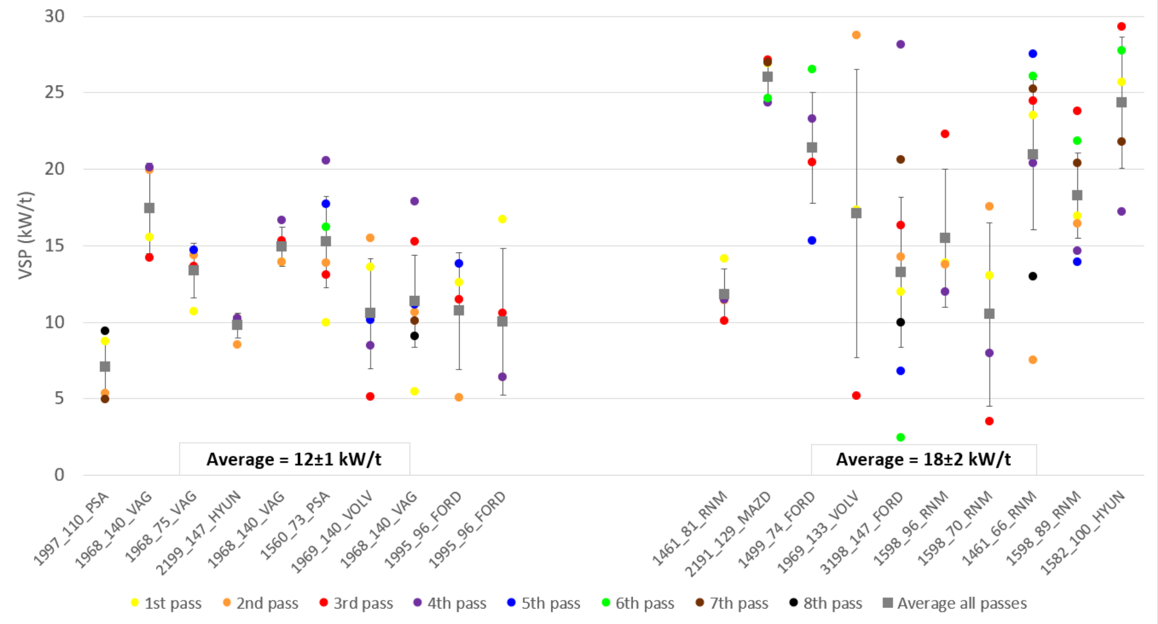

Figure 22 **Vehicle specific power (VSP) for the ten lowest emitting (left) and the ten highest emitting (right) diesel Euro 6ab light-duty vehicles measured by the remote sensor four times or more, presented in the same order as in Figure 19. For the labelling of vehicles on the x-axis, see caption for Figure 19.**

However, since these observations were based on a very small sample of vehicles (10 + 10 unique vehicles) further investigations on the influence of VSP on NOx emissions as measured by remote sensing were made, the results of which are presented in Figures 22 and 23.

Figure 23 displays NOx emissions versus VSP as measured by remote sensing in Haninge in 2018 for the 10% highest emitting Euro 6ab light-duty diesel vehicles from two datasets. The first dataset contains the vehicles that were measured four times or more by the remote sensor, whereas the second dataset contains the vehicles that were measured only once by the remote sensor. As can be seen by Figure 23, the two datasets result in different NOx vs VSP profiles. While the data based on multiple remote sensing measurements on each individual vehicle results in a rather clear dependence of NOx emissions on VSP, with a factor of about two higher average NOx emissions for VSP in the 25-30 kW/t range than for the 5-10 kW/t range, NOx emissions for the high-emitters measured only once by the remote sensor were on average consistently around 25 g/kg fuel independent of the VSP. This is most likely explained by the first dataset containing a number of emission events (i.e. 238 events) produced by only 43 unique high-emitting vehicles from multiple passes, and the second dataset containing a similar number of emission events (i.e. 362) produced by as many as 362 unique vehicles. Thus, the first dataset can be considered as more homogeneous than the second one and as better catching the emission behavior of actual high-emitting vehicles, while the second dataset is more biased towards reflecting high-emission events rather than the actual emission performances of high-emitting vehicles.

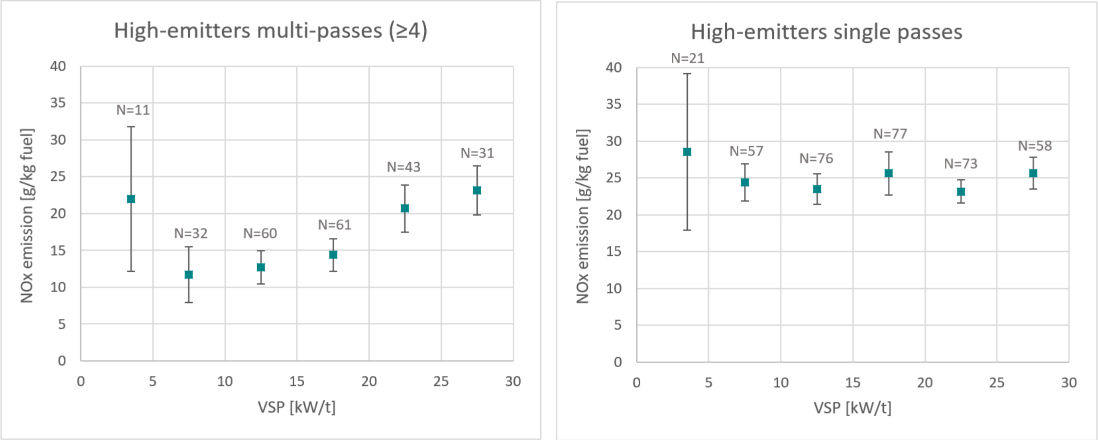

Figure 23 **Average NOx emissions vs VSP (as averaged over six VSP bins: 2-5, 5-10, 10-15, 15-20, 20-25 and 25-30 kW/t, respectively) for two subsamples of the Euro 6ab light-duty diesel vehicles measured by remote sensing in Haninge 2018. *Left:* The 43 unique vehicles contained in the 10th decile (i.e. the 10% highest emitters) with regard to the distribution of NOx emissions of the *vehicles measured four times or more* by the remote sensor as in Figure 18 (a total of 238 passes/measurements). *Right:* The 362 unique vehicles contained in the corresponding 10th decile of the *vehicles measured only once* by the remote sensor.**

The observed dependence of NOx emissions - expressed in the typical remote sensing unit g/kg fuel - on VSP for high-emitting vehicles in the two previous figures was confirmed by an analysis of a much larger dataset derived from the CONOX remote sensing database. In this analysis the NOx emission dependence on VSP of the RNM alliance 1461 cm^3 capacity engine was compared to that of the VAG alliance 1968 cm^3 capacity engine, the former representing one of the worst performing (highest emitting) Euro 6ab diesel engines and the latter one of the best performing (lowest emitting) with regard to NOx emissions as shown in this study. There were 5,205 valid data records for the RNM alliance engine and 14,574 valid data records for the VAG alliance engine retrieved from the CONOX database. The results are presented in Figure 24.

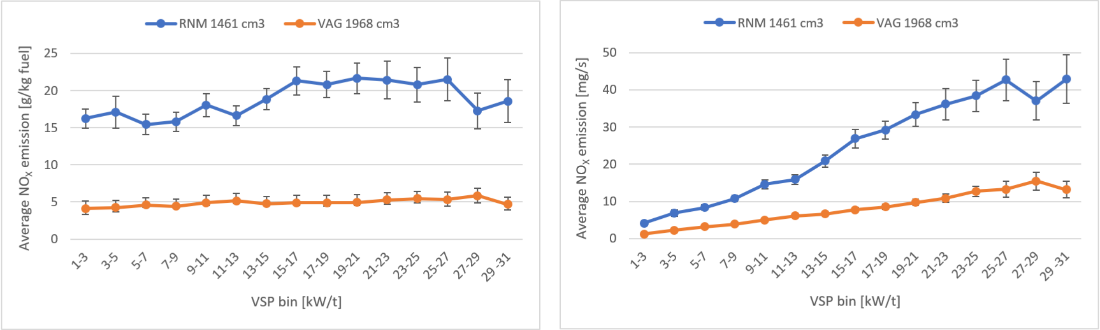

Figure 24 **NOx emissions - expressed as g/kg fuel (left) and as mg/s (right) - vs VSP for the worst and best performing (in terms of NOx emissions) Euro 6ab diesel LDV engines (the RNM alliance 1461 cm^3 capacity engine and the VAG alliance 1968 cm^3 capacity engine, respectively) according to the remote sensing measurements carried out in this study, based on data retrieved from the CONOX database by March 2021.**

As can be seen by the left plot in Figure 24, the NO_x emissions of the RNM 1461 cm^3 engine - when expressed as g/kg fuel - increase moderately with VSP, e.g. the emission level is 30-40% higher for VSP values exceeding 20 kW/t compared to the emission level for VSP values below 10 kW/t. Moreover, the emissions are about a factor of 4 higher for the RNM alliance engine compared to the VAG alliance engine over the full VSP range. There is some slight VSP dependence of the NO_x g/kg fuel emissions also for the VAG alliance engine, i.e. the emissions at the high end of the VSP range are some 25% higher compared to those for the lowest VSP values.

In the right plot in Figure 24, the NO_x emissions expressed as g/kg fuel have been converted to mass emissions in g/s, building on the methodology developed by Borken *et al.* (2018) and further refined and applied by Davison *et al.* (2020) and Hausberger (2020). Since the conversion involves multiplication with a fuel consumption or fuel flow factor, which has a strong dependence of VSP, the VSP dependence of the NO_x emissions expressed in mass units is very pronounced for both engines, increasing by one order of magnitude from the low end to the high end of the VSP range, over which the NO_x emissions of the RNM alliance engine consistently are a factor of 3-4 higher compared to the VAG alliance engine.

3.6.2 Euro 6c and 6d-temp NO_X emissions

As mentioned earlier, only a small fraction of the vehicles measured by remote sensing in Haninge in 2018 were certified against the Euro 6c and Euro 6d-temp standards (and no vehicles against the Euro 6d standard). 497 valid NO_x measurements were made on 266 unique Euro 6c vehicles, whereas 141 measurements were made on 91 unique Euro 6d-temp vehicles. The shares of different vehicle brands among these vehicles are presented in Table 4. It can be seen that for both standards there are only a few makes represented of which one is predominating, i.e. Mercedes for Euro 6c and Volvo for Euro 6d-temp.

Table 4 **Shares of vehicle makes for the Euro 6c and Euro 6d-temp light-duty diesel vehicles measured by remote sensing in Haninge 2018.**

Vehicle make	Euro 6c	Euro 6d-temp
Audi	1.2%	0.7%
BMW	18.5%	2.1%
Ford	14.3%	-
Mercedes	47.3%	0.7%
Opel	0.4%	-
Skoda	4.6%	-
Volkswagen	13.7%	0.7%
Volvo	-	95.7%

Percentile distributions of the measured NO_x emissions for the Euro 6c and Euro 6d-temp vehicles are presented in Figure 25. The distributions are very similar for the two Euro 6 categories except for the highest percentiles, for which the emissions of the Euro 6c category is clearly higher than for the Euro 6d-temp category. The reason behind this can be seen by Figure 26. There were five different makes represented in significant numbers within the Euro 6c category. Of these, Ford stood out as the make with the highest average emissions and was also clearly overrepresented among the vehicles for the highest emission percentiles, i.e. the 98th percentile. Furthermore, it was found that all the Ford vehicles were represented by only one model – the LCV Ford Transit equipped with the 3198 cm^3 engine. In contrast, the Euro 6d-temp category was completely dominated by Volvo, the emissions of which were close to those of the best performing Euro 6c makes Mercedes, Volkswagen, and BMW.

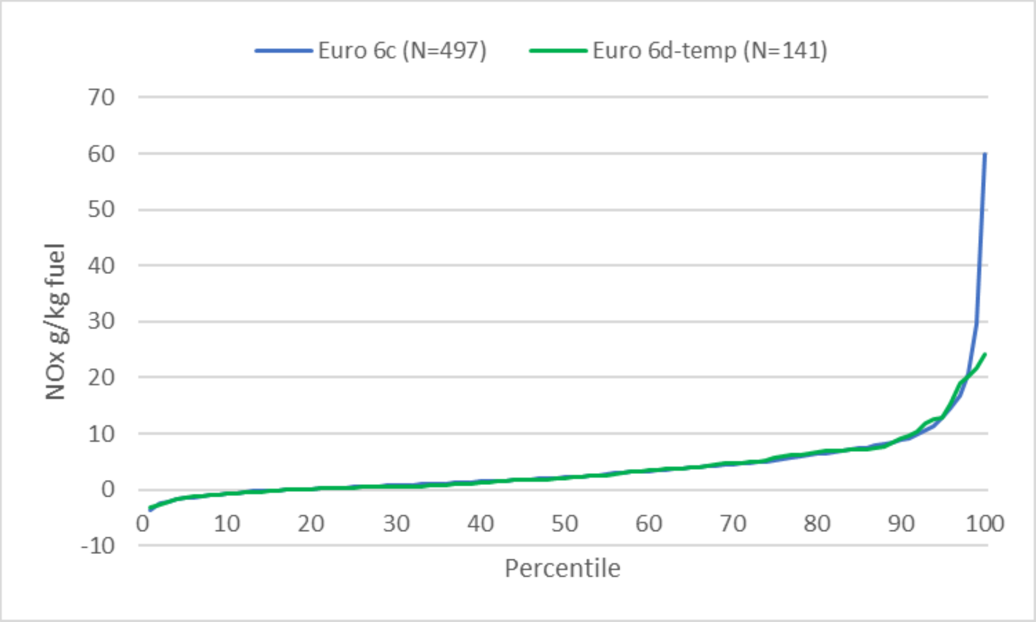

Figure 25 Percentile distributions of NOx emissions (in g/kg fuel) for Euro 6c and Euro 6d-temp light-duty diesel vehicles as measured by remote sensing in Haninge in 2018.

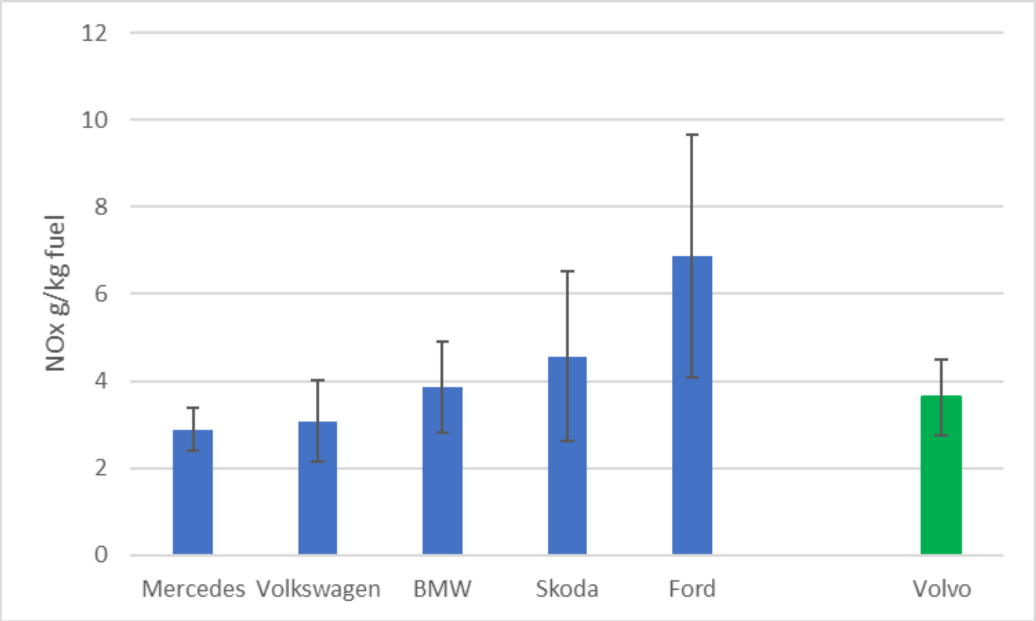

Figure 26 Average NOx emissions (in g/kg fuel) by make for Euro 6c (blue bars) and Euro 6d-temp vehicles (the green bar) according to the remote sensing measurements in Haninge in 2018. Error bars represent the standard error (95% CI).

The influence of VSP on NOx emissions was also investigated for Euro 6c and Euro 6d-temp vehicles. The results are presented in Figure 27 for the two predominant makes in the Euro 6c category (Mercedes) and the Euro 6d-temp category (Volvo), respectively. Since this analysis was hampered by the low number of data for both Euro 6 categories, it is not possible to draw any firm conclusions regarding the relationship between NOx emissions and VSP. However, there is some tendency that NOx emissions for the Euro 6c Mercedes vehicles exhibit a minimum at VSP values around 15 kW/t, whereas emissions for the Euro 6d-temp Volvo vehicles increase with increasing VSP in the range 0-30 kW/t.

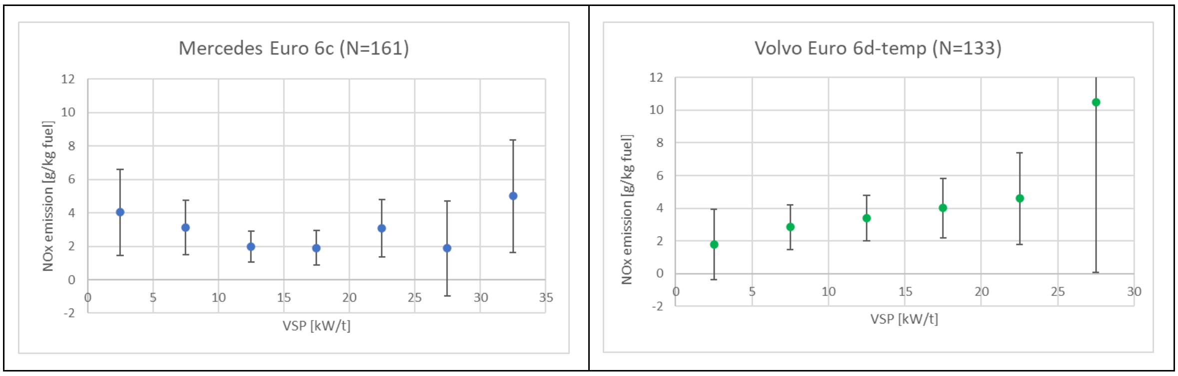

Figure 27 **Average NOx emissions in g/kg fuel by VSP bin (bin interval = 5 kW/t) for Mercedes Euro 6c (left) and Volvo Euro 6d-temp vehicles (right).**

3.6.3 Ability of remote sensing to identify individual Euro 6 NO_X high-emitters

The main Euro 6 light-duty diesel vehicle category, i.e. Euro 6ab, analyzed in this report is not subject to the new RDE regulation, however, the results from the comparison of remote sensing measurements with PEMS RDE measurements on the same individual early Euro 6 vehicles, as presented in chapter 3.4, can be used to study the ability of remote sensing measurements to identify Euro 6 light-duty diesel vehicles with emissions above the RDE limits. For this purpose, the graph presented in Figure 28 was prepared, based on the same dataset as that behind Figure 9 (chapter 3.4).

It can be seen in Figure 28 that for 12 (of the 15 vehicles measured, i.e., 80%) exceeding an arbitrary chosen cut-point in the remote sensing measurements of 5 g NOx/kg, emissions were above the Euro 6 RDE limit (regardless of which conformity factor that was applied). Only one vehicle slightly exceeding 5 g NOx/kg in the remote sensing measurements was found to be (well) below the Euro 6 limit of 0.08 g NOx/km. This translates to a *false failure rate* or an *error of commission of ≈7%* of the remote sensing measurements when used as a means to identify Euro 6ab vehicles with emissions exceeding the Euro 6 RDE limit. Two vehicles were below the remote sensing cut-point of 5 g NOx/kg (one vehicle was well below this cut-point, whereas one was almost at it), but had high emissions in the RDE test, about a factor 2 and 5 higher, respectively, than the Euro 6 limit, when applied with a conformity factor of 2.1. This translates to a *false pass rate* or an *error of omission* or in the remote sensing measurement *of ≈13%*.

Thus, with the assumption that the Euro 6ab category works as a proxy for Euro 6 categories subject to the new RDE regulation (6d-temp and 6d), these results provide some proof for that remote sensing could be considered as capable of identifying Euro 6 vehicles having emissions in excess of a factor of about 3 higher than the Euro 6 limit, with reasonably low errors of omission and commission when applying a remote sensing cut-point of 5 g NOx per kg fuel.

Moreover, based on the data behind Figure 19 (i.e., the decile distribution of the average NOx emissions of the 427 unique Euro 6ab light-duty diesel vehicles measured four times or more by the remote sensor), the probability of a vehicle within the 10% highest emitting fraction of this fleet (the 10th decile) having a single remote sensing reading exceeding 5 g NOx per kg fuel was calculated to as high as 91%. Or, in other words, of the overall 238 remote sensing measurements conducted on these 43 vehicles, the value of 5 g NOx per kg fuel was exceeded in as many as 217 measurements. The average emission of the lowest emitting vehicle within the 10th decile was 11 g NOx/kg fuel.

Thus, even for a single remote sensing measurement, the cut-point of 5 g NOx per kg fuel would be rather successful to single out vehicles by far exceeding the Euro 6 limit.

In this context it may also be worth mentioning that for the 10% lowest emitting fraction of the fleet visualized in Figure 18, the probability of a vehicle having a single remote sensing reading exceeding 5 g NOx per kg fuel was calculated to only 4.3%, i.e., this value was exceeded in only nine of the overall 210 emission measurement events.

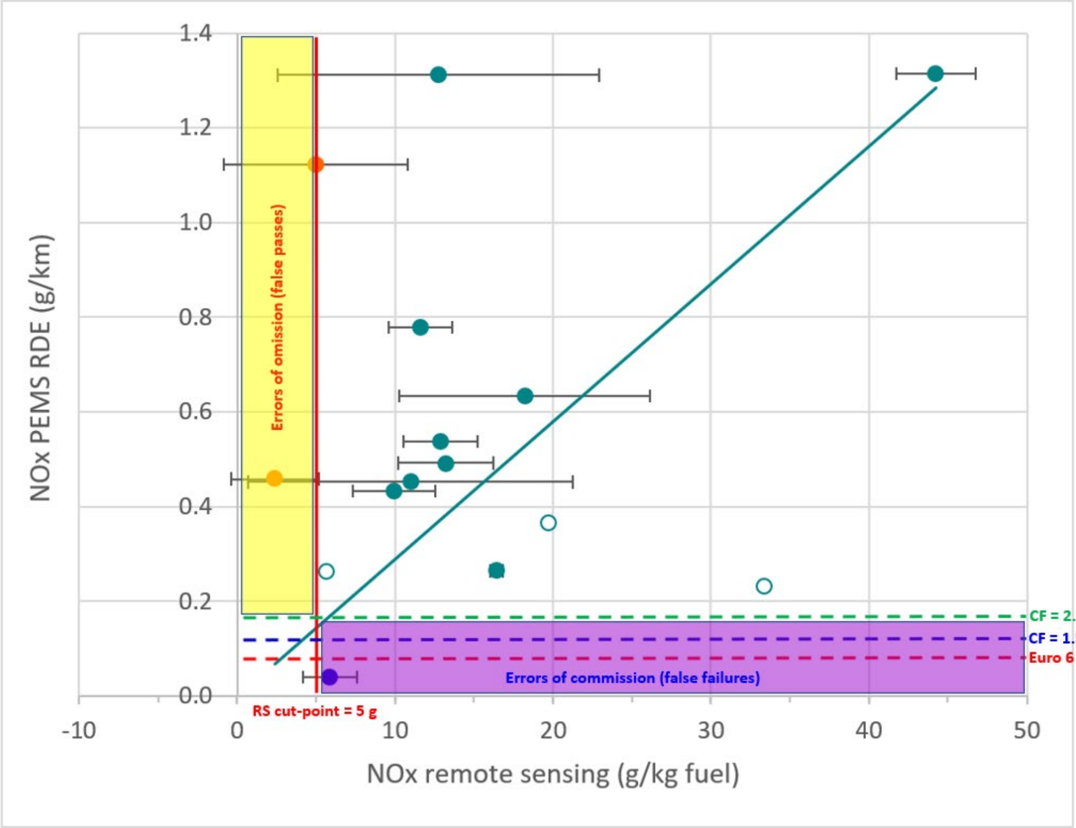

Figure 28 PEMS RDE NOx (in g/km) emissions vs NOx emissions as measured by the remote sensor (in g kg/fuel) at the Haninge site for 15 Euro 6b light-duty diesel vehicles. Green circles represent vehicles exceeding the Euro 6 RDE limit (filled circles are vehicles measured by the remote sensor more than 2 times, unfilled circles are vehicles with single passes), orange circles represent vehicles that were below an arbitrary remote sensing cut-point of 5 g NOx per kg fuel burned, but exceeding the Euro 6 RDE limit (errors of omission or false passes), and the blue circle is the vehicle that was above the remote sensing cut-point but was below the Euro RDE limit (error of commission or false failure). The yellow area represents the area of errors of omission and the purple area represents the area of errors of commission.

3.6.4 PM emissions

The remote sensing instrument deployed in the Haninge 2018 measurements provides a proxy of PM (particulate mass) emissions in g/kg fuel units derived from measurements of opacity, i.e., smoke density through light extinction in the UV (Ultra Violet) region (ESP, 2004; Stedman, 2010). The measured PM emissions on light-duty diesel vehicles as averages by Euro class 3 through 6 (data on earlier Euro standards were too sparse to make a meaningful comparison) are presented along with the Euro standard limits in Figure 29.

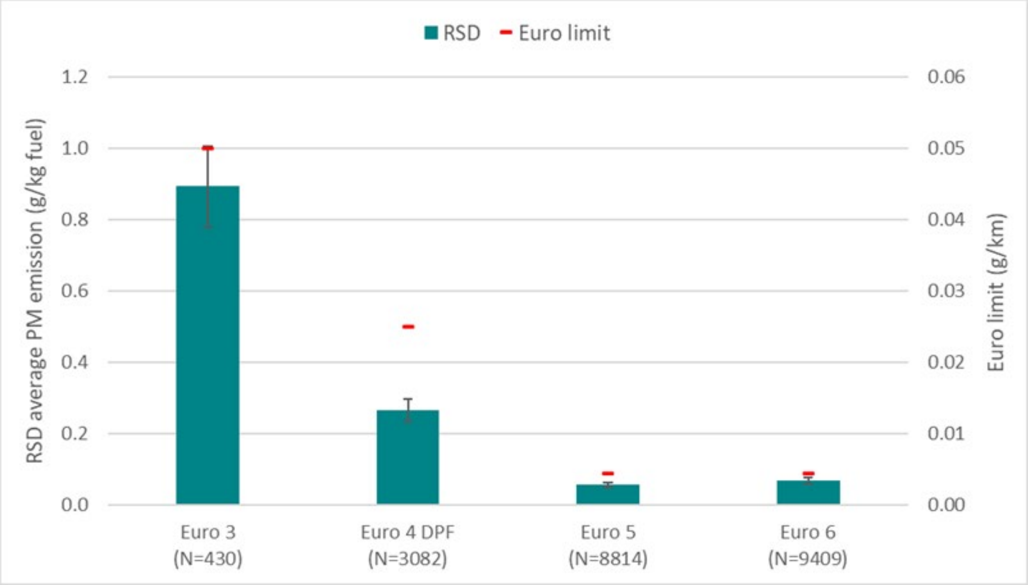

Figure 29 **Average PM emissions by Euro class for diesel LDVs as measured by remote sensing in g/kg fuel values compared to the Euro limits in g/km.**

The success of the introduction of effective DPFs (diesel particulate filters), being a direct consequence of the implementation of the very strict PM emission standard from Euro 5, is clearly reflected in the remote sensing data. Compared to Euro 3, the average PM emissions are lowered by more than 90% for Euro 5 and Euro 6, i.e., very similar to the reduction implied by the change in the emission standard (0.05 g/km to 0.005 g/km).

The diesel LDV PM emissions by Euro class according to the remote sensing measurements are also compared to the petrol d:o in Figure 30. As expected the PM emissions from petrol cars are much lower compared to diesel cars for Euro class 0-4, but for Euro 5 and 6 there is no statistically significant difference between the two, i.e. in both cases the Euro 5 and Euro 6 PM emissions can be considered as being below or at the level of detection of the remote sensing instrument[2]. Dedicated studies on heavy-duty diesel vehicles indicate a precision/detection limit of the RSD PM channel in the order of 0.1 g/kg fuel for a single measurement (Stedman, 2010). It is also interesting to note that for petrol cars the remote sensing data shows a clear downward trend in PM emissions over the pre-Euro through Euro 4 range.

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[2] A PM emission standard for petrol cars was introduced for the first time with Euro 5 and is applicable only to cars with DI engines.

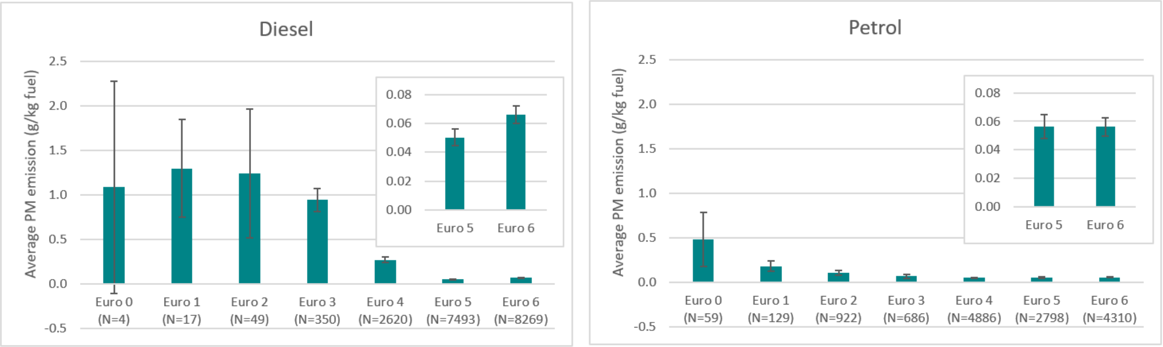

Figure 30 Average PM emissions by Euro class for diesel and petrol LDVs as measured by remote sensing in g/kg fuel.

Percentile distributions of the measured PM emissions for the Euro 3 through Euro 6 classes are presented in Figure 31. It is clear that for Euro 5 and Euro 6 vehicles the emissions are consistently below or close to the detection limit of the remote sensing instrument, as seen by the high share of negative readings (in the range of 35-40%), and that the highest values, i.e. above 1 g/kg fuel, are of the same order of magnitude as the lowest negative values, i.e. below -1 g/kg fuel. This is also clear from the frequency distribution of the remote sensing data for Euro 6 (Figure 32), approximating a normal distribution with the maximum number of observations gathered around zero.

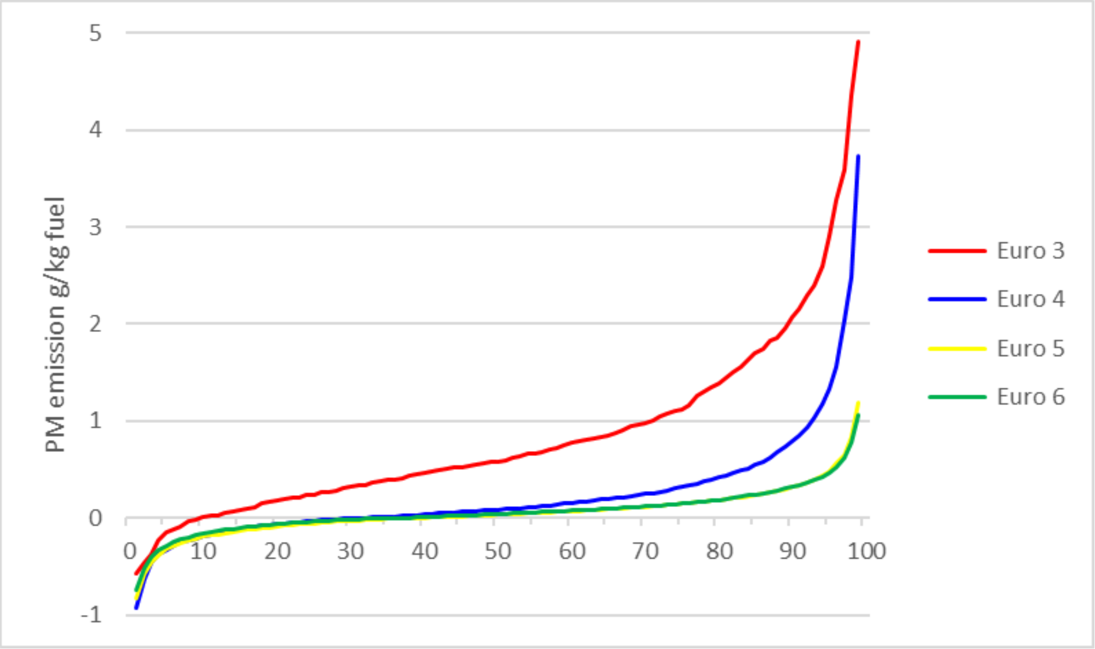

Figure 31 Percentile distributions of the PM emissions (in g/kg fuel) for light-duty diesel vehicles by Euro standard as measured by remote sensing in Haninge in 2018.

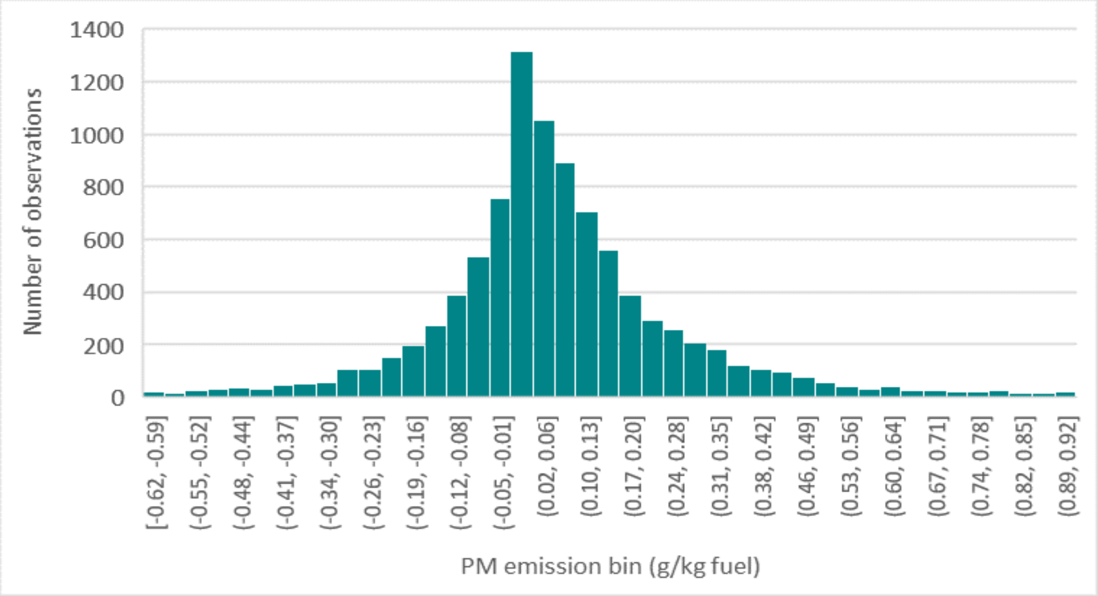

Figure 32 **Frequency distribution of PM emissions for Euro 6 light-duty diesel vehicles as measured by remote sensing in Haninge in 2018.**

A similar analysis as the one carried out for NOx emissions from Euro 6 vehicles in chapter 3.6.1.1, and presented in Figure 20, was also made for PM emissions, i.e., comparing the results of the ten highest emitting vehicles with those of the ten lowest emitting vehicles among the Euro 6 vehicles that were measured four times or more by the remote sensor. The main observation from this analysis was above all the large scatter in PM emissions as the same vehicle individual was passing the remote sensor multiple times, associated with a large overlap in single emission readings between the two groups compared, i.e., high- vs low-emitters. Of the overall 50 emission measurements on the ten highest emitting vehicles as many as 30 measurements (60%) overlapped with the highest value recorded for the lowest emitting vehicles. Similarly, of the overall 48 emission measurements on the ten lowest emitting vehicles, as many as 37 measurements (77%) overlapped with the lowest value recorded for the highest emitting vehicles. Thus, for PM emissions and Euro 6 vehicles it seems really hard to single out high-emitters from what can be considered as normal (or low) emitting vehicles, even when a large number of repeat measurements are carried out on the same vehicle individual. From the resemblance in PM emission performance between Euro 6 and Euro 5 vehicles, as seen from e.g. the percentile distributions in Figure 31, it was assumed that the same conclusion could be drawn for Euro 5.

A similar analysis was made for the measured Euro 4 vehicles for which it could be confirmed from the Swedish vehicle register that they were equipped with a diesel particulate filter (DPF), and similarly also for Euro 4 vehicles proven to lack DPF and Euro 3 vehicles.

The results of the PM emission analysis for diesel LDVs of different Euro standards/emission control concepts (with and without DPF, respectively) are compiled and compared in Table 5. It can be seen that there is a significant difference in the average PM emissions between the highest and lowest emitters for all the three vehicle category groups investigated here, i.e., Euro 3 plus Euro 4 vehicles lacking DPF, Euro 4 with DPF and Euro 6 for which DPFs are mandatory. However, when looking at single remote sensing measurements, the overlap between the two groups high-emitters and low-emitters, increases from 22% for the category lacking DPF (Euro 3 and 4) up to 77% for Euro 6. The higher the overlap, the higher the risk to classify a high-emitter as a low-emitter and vice versa, when the identification is based on a single remote sensor reading.

Table 5 Average PM emissions (in g/kg fuel) for the ten lowest and highest emitters, respectively, among light-duty diesel vehicles of various Euro standards and PM emission control concepts being measured by remote sensing four times or more. The N value refers to the number of unique vehicles measured for each of the three vehicle category groups.

Vehicle category defined by Euro standard/ PM emission control concepts	Average PM emission (g/kg fuel)		Overlap between high- and low-emitters[2]
	Ten lowest emitters	Ten highest emitters	
Euro 3 and Euro 4 without DPF (N=65)[1]	0.06±0.07	2.2±0.5	22%
Euro 4 with DPF (N=81)	-0.07±0.06	0.93±0.34	49%
Euro 6 (N=693)	-0.02±0.09	0.75±0.32	77%

[1] The Euro 3 vehicles were on average 3 years older than the Euro 4 vehicles without DPF. Together with the fact that Euro 3 vehicles are subject to a higher emission limit than Euro 4, this can explain the observation that only one among the ten lowest emitters was a Euro 3 and the majority of the highest emitters were Euro 3 (6 out of 10).

[2] The overlap presented here represents the share of the measurements on the ten highest emitters overlapping with the single highest measured PM emission value among the ten lowest emitters.

The average PM emission by make for the most abundant makes in the data presented in Table 5 was investigated and the results are presented in Figure 33. It seems clear that the remote sensing measurements are able to distinguish differences in the average emission performance between makes, at least when comparing the makes exhibiting the highest average emissions with the best performing ones within the same vehicle category group. Neither model year (age) nor driving conditions (VSP) could be shown to have a significant impact on the PM emissions as measured by remote sensing, be it on vehicle group level or on individual vehicle level (i.e., as concluded from the results for the vehicles measured multiple times by the remote sensor).

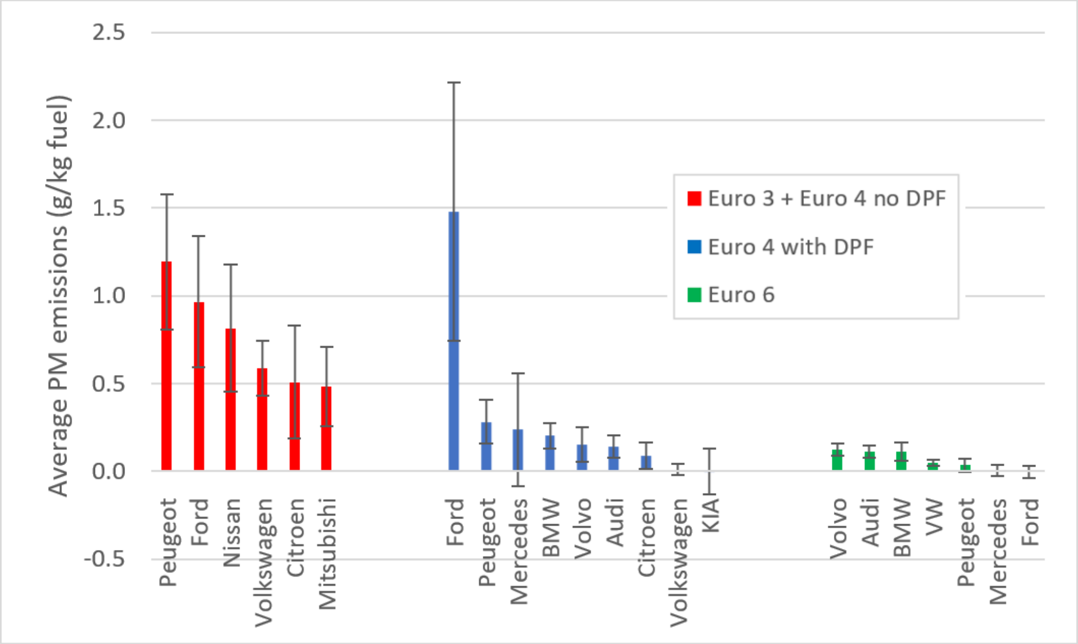

Figure 33 Average PM emissions (in g/kg fuel) by make for the most abundant makes in the data presented in Table 5.

3.7 Real driving NO_X and PM emission measurements at a PTI-station

This section presents the results from the measurements conducted at a PTI station in Göteborg in May 2019. The measurements were carried out with an Opus RSD5000, a TSI EEPS and a simplified PEMS (Mini-PEMS) as described in section 2.1.4.

The Mini-PEMS system used for NO_X measurements has previously been evaluated and showed a good agreement with the legislative RDE method for NO_X measurements (Öhlund and Eriksson, 2019). In that study a method for roughly estimating a vehicle's emission performance compared to the legislative limits, by using the measured NOx/CO_2 ratio (by the authors referred to as the "Emission Index") in combination with an estimated fuel consumption was also presented. With the method it is possible to estimate the emission performance without connecting to the OBD. Hence the vehicle will not be able – through some kind of defeat device – to recognize an emission test being conducted, which excludes the risk that such a device would bias the emissions during the test. Since the method does not involve a connection to the OBD it does not allow calculations of the absolute emissions (e.g. in g/km) or fuel consumption. Thus, the method does not provide results directly comparable with the legislative test, but it works well as a diagnosing tool to find out whether the vehicle's emissions deviate largely from the legislative limit. If information on the absolute emission levels is required, these can be derived from reading the OBD signal (if available).

The concept of measuring NOx with Mini-PEMS and using the emission index to estimate the real-world emission performance of vehicles was further elaborated by Köhler (2019). The aim of this study was to establish the minimum length of a PEMS route, for which the results would still be usable to provide a robust estimate of the vehicle's real-world emission performance. One of the conclusions was that in most cases a driving distance of 2.5 kilometers in urban conditions is sufficient to find out whether the exhaust after-treatment system is working properly or not. The PEMS route used at the PTI station in Göteborg was about 5 km, hence it fulfills the estimated minimum driving distance suggested by Köhler (2019).

3.7.1 Evaluating NO_X emissions with Emission index from Mini-PEMS measurements

The Emission Index concept was used to evaluate the NOx emission performance of 29 vehicles tested at the PTI-station in Göteborg. The NO_X and PN emissions were also measured for all 29 vehicles from the roadside using the remote sensor and the TSI EEPS. Further, all vehicles also went through the standard emission test procedure used within the Swedish PTI. It is notable that all the vehicles passed the PTI test. The measured emission indexes (y-axis) and declared g CO_2/km (x-axis) for urban driving are presented as markers in Figure 34. The emission index that corresponds to the legislative limits for each Euro standard is presented as a function of the CO_2 emission in g/km. Vehicles with markers well above the line representing the emission standard of the vehicle can be suspected to have elevated emissions, e.g. due to a malfunctioning exhaust after-treatment system. Since limits for RDE tests are only applicable from Euro 6d-temp, the emissions measured in the RDE tests for vehicles complying with earlier emission standards will deviate a lot from the legislative limits when tested on-road. To take this into account, the RDE limits for standards earlier than Euro 6d-temp in the figure have been estimated based on the legislative limit by applying a conformity factor of 2.1.

It can be seen in Figure 34 that all the tested Euro 6 vehicles are close to or lower than the corresponding emission limit. Further, most Euro 5 and Euro 4 vehicles are close to or above the fictive RDE limits for their respective Euro standards. However, there were three vehicles that significantly exceeded the fictive RDE limit, one Euro 3 (petrol), one Euro 4 (petrol) and one Euro 5 (diesel). These vehicles are marked with their vehicle id. - S, AD and Y, respectively - in the figure (see Appendix 4 for detailed vehicle information). Vehicle AA is not deviating as clearly from the other vehicles of the same Euro standards as vehicles S, AD and Y, but has been marked with its vehicle id. in Figure 34 for easier comparison with data presented in Figure 35.

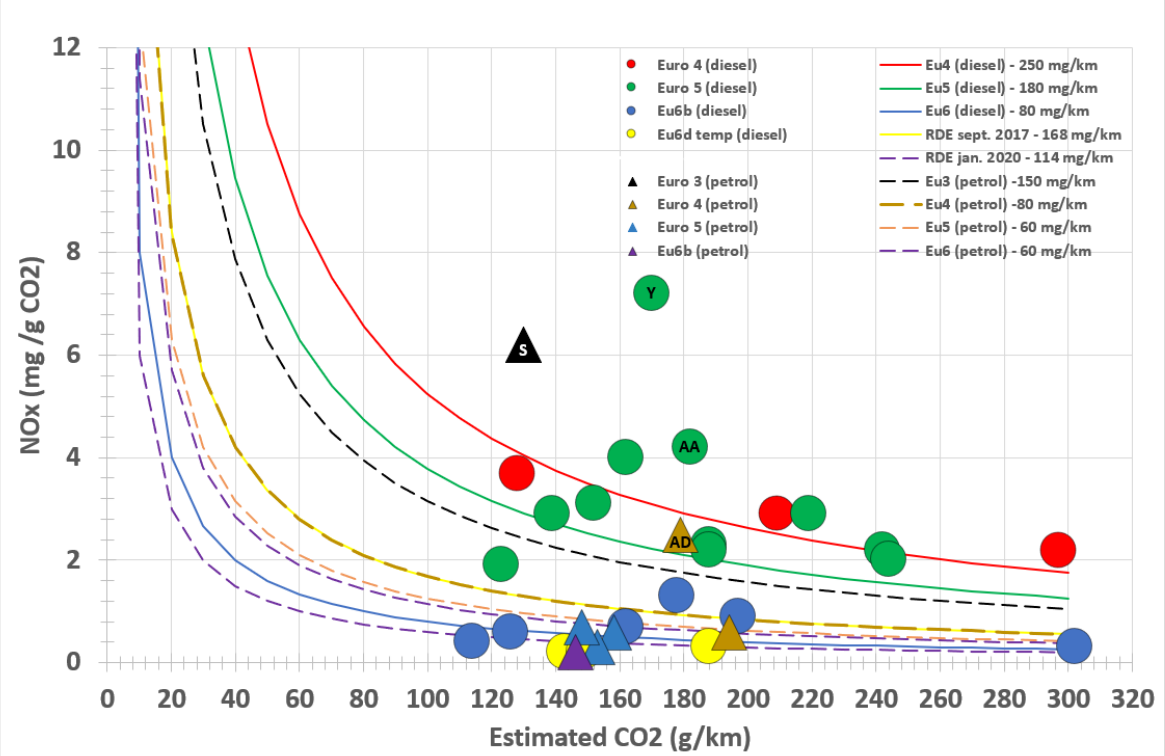

Figure 34 Emission Index and estimated CO_2 emissions for the vehicles tested at the PTI station (markers) compared to emission standards (lines). Lines for Euro 6b and earlier emission standards represent fictive RDE limits derived from the legislative emission limit together with a conformity factor of 2.1. Vehicles deviating substantially from the emission limit are marked with vehicle id (see Appendix 4 for detailed vehicle information).

3.7.2 Evaluating NO_X emissions with distance specific emissions from Mini-PEMS and remote sensing measurements

For 11 of the 29 tested vehicles the OBD signal was read, making it possible to calculate absolute NO_x-emissions (in g/km) over the test route. Three of these, vehicles P, Y and AA, had NOx emissions in the range 1.2-1.7 g/km. This is substantially higher than the other tested vehicles and seven times or more higher than the emisson limits and they can therefore be suspected to have a not optimally working exhaust after-treatment system. These three vehicles had the highest emissions also in the remote sensing measurements, even though the difference to the other vehicles was not as significant as when measured with PEMS, see Figure 35. Note that vehicles Y and AA also had a relatively high emission index (Figure 34), whereas vehicle P did not appear as a high-emitting vehicle according to the emission index method but exhibited one of the highest measured distance specific emission factors. The reason for this is not fully understood, but the measured fuel consumption of this vehicle over the PEMS route was very high, much higher than the declared fuel consumption, which may be a possible explanation.

Note that vehicles S and AD, which were identified as high-emitters according to the emission index method, were both petrol vehicles for which information from the OBD to derive absolute emissions was not available and hence they are not included in Figure 35.

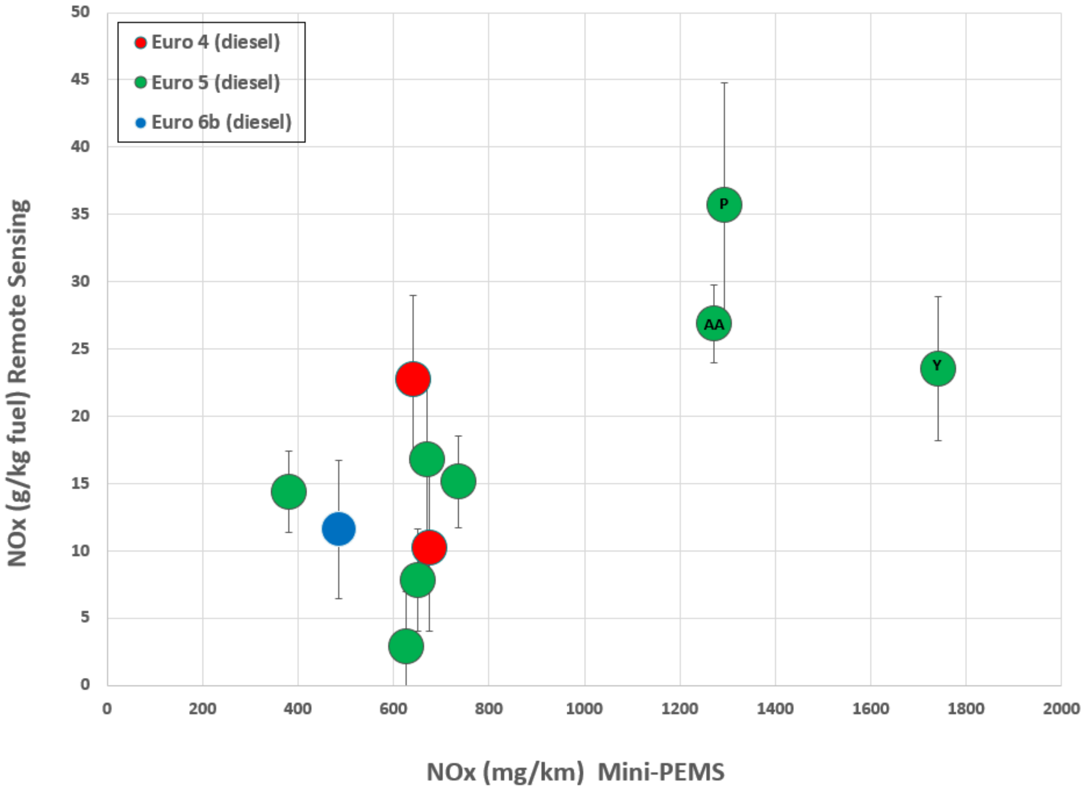

Figure 35 NOx emissions (g/kg fuel) as measured by the remote sensor and NOx (mg/km) measured with mini-PEMS. Suspected high emitters are marked with vehicle id (see Appendix 4).

3.7.3 Remote sensing test conditions

Most of the remote sensing measurements were carried out at a vehicle specific power within the range 10-30 kW/t, but for some measurements the VSP was outside of this range. To study if the difference in VSP of the tested vehicles affected the assessment of suspected high-emitting vehicles, the NOx emissions versus VSP for each singe measurement is presented in Figure 36. The figure shows that in most cases the measured NOx emissions were below 30 g NOx/kg fuel for vehicles tested within the VSP range 2-65 kW/t. The main exceptions are vehicle S and P for which most measurements were above or well above 30 g NOx/kg fuel with VSP in most cases being within the range 10-30 kW/t.

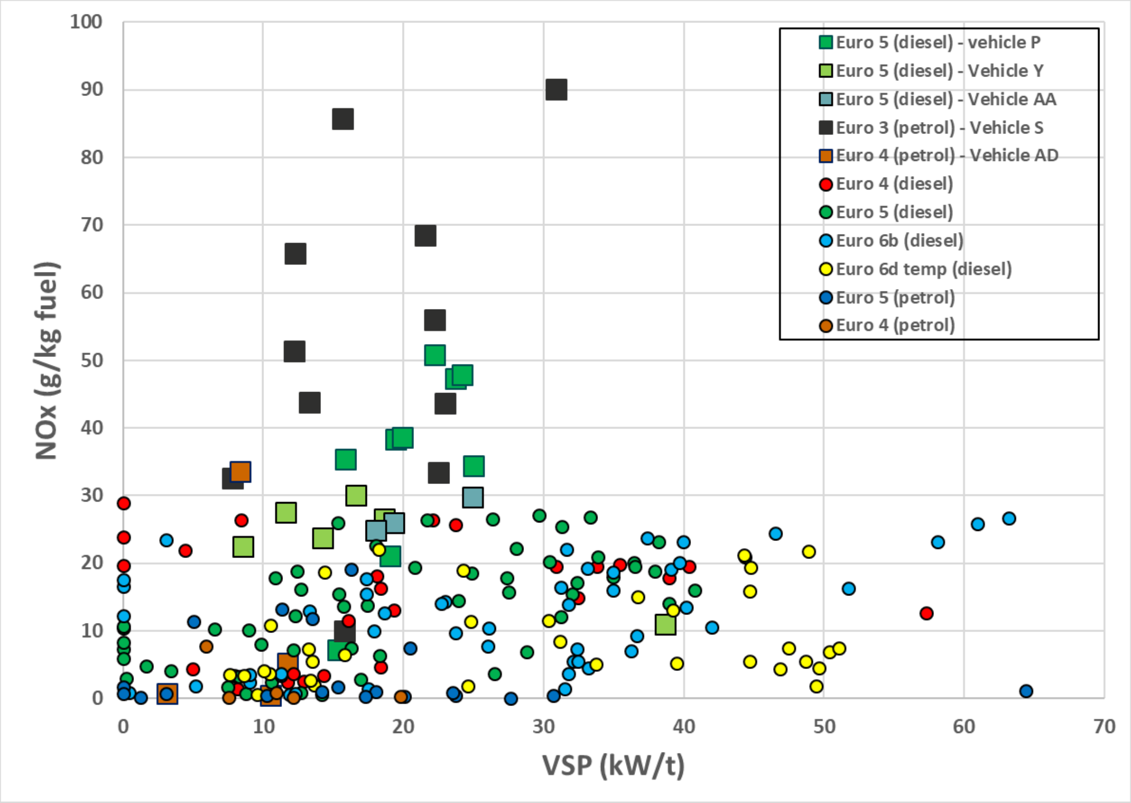

Figure 36 NOx emissions (in g/kg fuel) as measured by remote sensing versus VSP (kW/t). Each marker represents one single measurement. Square markers are used for vehicles with high emissions according to the Mini-PEMS measurements (see Figures 34 and 35). Circle markers are for all other measured vehicles.

3.7.4 Conclusions from the NO_X measurements at the PTI station

From this study it is not possible to draw any conclusion on where to set a general "cut-off" level in the remote sensing measurements for identifying vehicles having excess emissions due to a malfunctioning exhaust after-treatment system. Further investigations are needed before such a limit can be accurately set. However, results from this study show that two vehicles with repeat remote sensing measurements above or well above 30 g NOx/kg fuel (Vehicle S and P) also showed high emissions (6 mg NOx/g CO_2 and 36 mg NOx/km, respectively) during the used PEMS route. This indicates that vehicles with repeated measurements over 30 g NOx/kg under the test conditions used in this study should be interesting to test further with other methods. For three vehicles with repeated remote sensing measurements between 20 and 30 g/kg two of the vehicles (vehicle AA and Y) also had high emissions when measured during the PEMS route. Further, one vehicle (vehicle H) had relatively high emissions when measured with remote sensing but moderate emissions when measured with PEMS. Table 6 summarizes conclusions from the different tests on the six vehicles that showed high emissions when tested with at least one of the methods.

Table 6 Summary of verdicts from the three test methods. Only vehicles suspected to be a high emitting vehicle outgoing from at least one of the methods are included. Verdicts are colour coded for easier overview, green = Low emissions/not a suspected high-emitter, orange = Medium to high emissions/possible high-emitter and red = High emissions/highly suspected high-emitter.

Vehicle id.	Euro standard and fuel	Verdict - PEMS EI	Verdict – PEMS + OBD	Verdict – Remote Sensing
H	Euro 4 diesel	Low emission index	Low emissions	Medium to high emissions Most measurements between 20 and 30 g NOx/kg
P	Euro 5 diesel	Low emission index	High emissions – 1.3 g/km	High emissions Most measurements between 30 and 50 g NOx/kg
S	Euro 3 petrol	High emission index	Not measured	High emissions Most measurements between 30 and 90 g NOx/kg
Y	Euro 5 diesel	High emission index	High emissions – 1.7 g/km	Medium to high emissions Most measurements between 20 and 30 g NOx/kg
AA	Euro 5 diesel	High emission index	High emissions – 1.3 g/km	Medium to high emissions Most measurements between 20 and 30 g NOx/kg
AD	Euro 4 petrol	High emission index	Not measured	Medium to high emissions One of five measurements over 30 g NOx/kg, remaining measurements below 6 g NOx/kg

3.7.5 PN measurements

The measured number of emitted particles per kg fuel burnt for 26 light-duty vehicles, for which at least three valid measurements were conducted, are presented as box plots in Figure 32. As reference also PN emission factors (as number/kg fuel) from the Handbook Emission Factors for Road Transport (HBEFA, 2020) are presented as dotted lines. The HBEFA emission factors represent average emission factor for passenger cars driving in traffic situations with an average speed between 25 to 35 km/h. Four of the vehicles (vehicle id. L, P, Q and AC) are diesel powered Euro 5 and Euro 6 light commercial vehicles class III. The corresponding HBEFA emission factors for these vehicles are not included in the figure but are in both cases according to HBEFA lower than for diesel passenger cars of the same Euro class.

The measured emissions for most vehicles were in the same order of magnitude as the HBEFA emission factors but six vehicles (vehicle id. A, I, L, U and G) had emissions significantly higher than the HBEFA factors. For three of the vehicles with a high number of emitted particles a study of the particle number size distributions (PNSD) was made. Two of the cars used for this analysis were the highest emitting Euro 4 and Euro 6 diesel cars, and the third vehicle was a Euro 5 petrol car to enable also a comparison of size distributions between diesel and petrol cars. The distributions are presented in Figure 37. For all cars the PNSD were generally bimodal with a dominating nucleation mode, peaking at ~10 nm. The Euro 6 diesel emitted a very high number of nucleation mode particles. All three cars had an accumulation/soot mode at ~ 50-80 nm.

During the tests, efforts were made to have the driving conditions being as uniform as possible but even so there was to some extent a variation of the speed and acceleration between the tested vehicles and also between different tests of the same vehicle. This may explain some of the variations in PN as the driving conditions have a very significant effect on these emissions

(Karjalainen *et al.*, 2014). PN is also a very dynamic parameter that is dependent on e.g., dilution and temperature (Zhou *et al.*, 2020). On average, the speed and acceleration were approximately 30 km/h and 8 km/h/s, respectively, during the tests. The effect of driving conditions on the PN emissions was outside the scope this study.

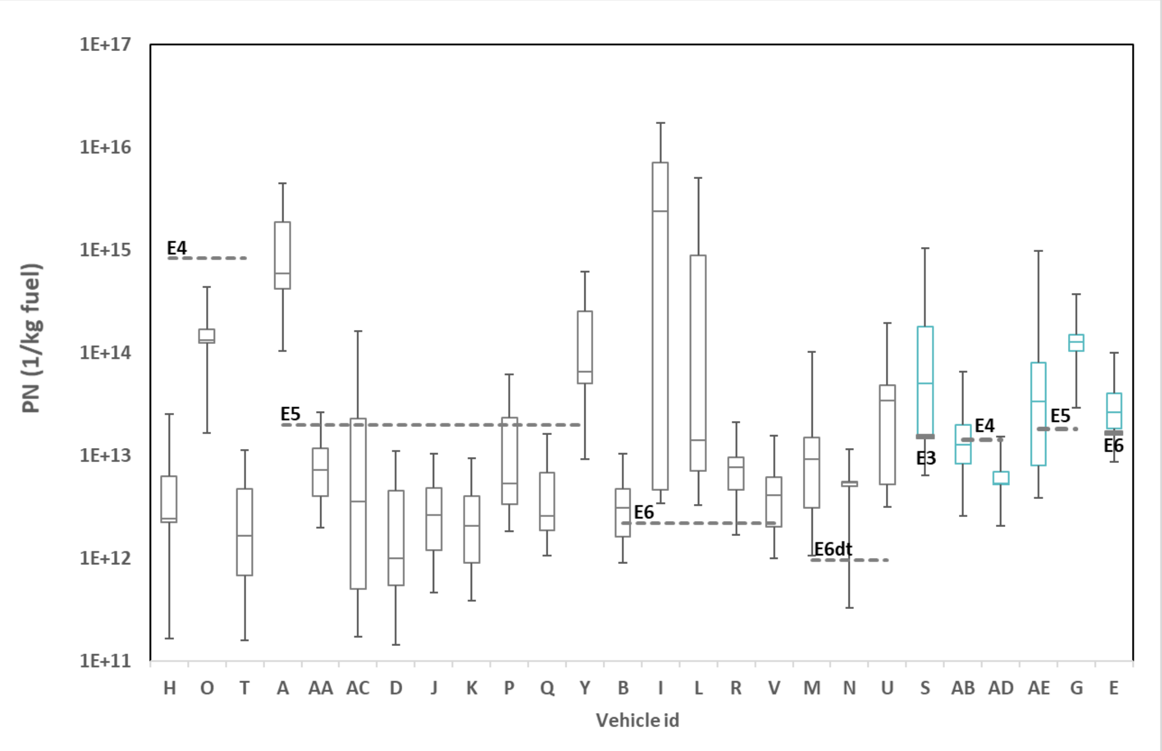

Figure 37 Measured PN emissions for 22 passenger cars and 4 light commercial vehicles Class III (vehicle id L, P, Q and AC). Grey boxes represent diesel vehicles and turquoise petrol vehicles. Text above dashed lines is the Euro standard. Lower and upper box lines represent 25th and 75th percentiles, middle box line represents median and whiskers represents 10th and 90th percentiles. Dotted lines are PN emission factors from the HBEFA model (HBEFA, 2020).

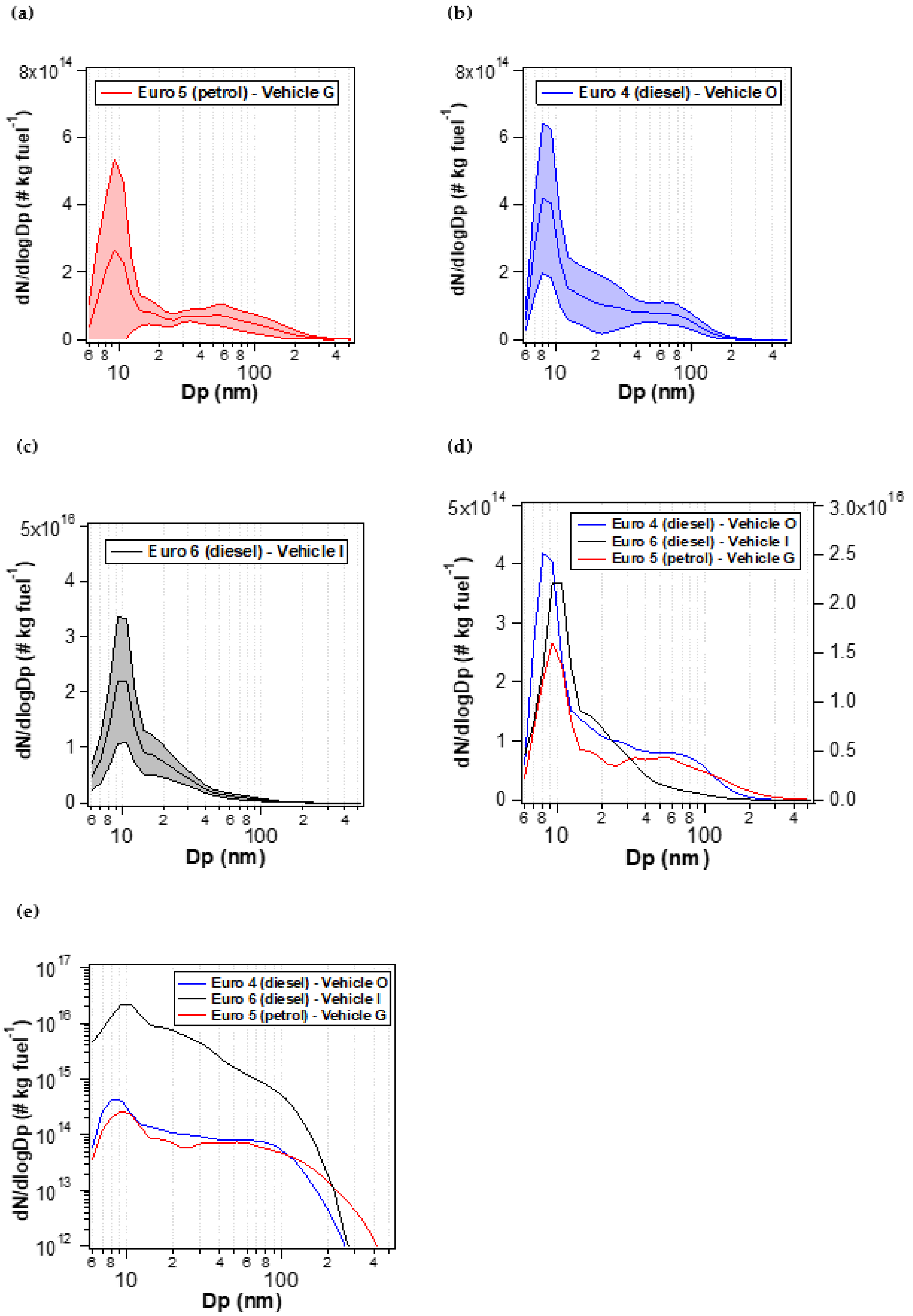

Figure 38 Mean size-resolved number of particles of one Euro 5 petrol car (a), one Euro 4 diesel car (b) and one Euro 6 diesel car (c). All distributions are also presented in the same figure with a secondary y-axis for vehicle I (d) and with a logarithmic y-axis (e). Shaded areas represent the statistical 95 % confidence interval.

4 Discussion and conclusions

4.1 Real-world emissions of diesel LDVs as measured by remote sensing and PEMS

4.1.1 NOx emissions

Data from the measurements carried out in this study and also from the analysed extended datasets containing data from several European countries – be it from remote sensing or PEMS measurements – show a substantial decrease in NOx emissions from Euro 5 to the early Euro 6 (ab) light-duty diesel vehicles. Also, a further decrease can be seen by both methods from Euro 6ab to the later Euro 6 steps (6c and 6d-temp). According to the remote sensing measurements conducted in this study NOx emissions decreased on average by 53% from Euro 5 to Euro 6ab. According to the much larger CONOX dataset the corresponding reduction was 51%. Further, comparing Euro 5 with Euro 6c emissions, the remote sensing data from Haninge 2018 showed a reduction of 78%, whereas the corresponding figure according to the most recent CONOX data was 80%. These reductions figures are very similar to the 48% and the 84%, respectively, that could be derived from the PEMS RDE measurements carried out in this study, although it should be noted here that only one Euro 6c vehicle was included in the PEMS measurements.

Regarding Euro 6d-temp NOx emissions, results from the comparison were a bit inconclusive. The remote sensing data collected in this study did not show any statistically significant difference between Euro 6c and 6d-temp, whereas the PEMS-data showed that emissions were further reduced by Euro 6d-temp and were 94% lower compared to the Euro 5 level. However, PEMS data may be biased by being available for only three vehicles, all brand new or with very low mileages, whereas the remote sensing 6d-temp data may be biased by 95% of the data representing only one engine from one car manufacturer. Bernard *et al.*, (2020) presented remote sensing data (N=744) for Euro 6d-temp light-duty diesel vehicles measured in Krakow in 2019, showing a reduction in NOx emission from Euro 5 by 87%. A similar figure, 90%, was reported from remote sensing measurements (N=4,772) in Berlin in 2019 (Schmidt, *et al.*, 2020).

Finally, regarding Euro 6d, the main source of data is from remote sensing measurements carried out in Flanders, Belgium in 2019 (Hooftman et al., 2020) and Switzerland in 2020 (Alt, 2021). Taken together (N=4,077), these data show a reduction in NOx emissions by 87% compared to the average Euro 5 level according to the CONOX database.

This work also presents average NOx emissions on vehicle model level for Euro 6ab diesel cars common in the Swedish and European vehicle fleet. Moreover, the taxonomy developed recently within the ongoing H2020-project uCARe and applied to the CONOX remote sensing dataset within its H2020 “sister” project CARES (2021), allowed a comparison of emissions from different vehicle models sharing the same engine. Our analysis shows that the vehicle models with the highest average NOx emissions as measured by remote sensing (in units of g/kg fuel) had approximately four times higher emissions than the models with the lowest average emissions. With a few exceptions, models sharing the same engine according to the uCARe taxonomy had similar average NOx emissions. The reason why in some cases a rather big difference could be seen between models sharing the same engine was not studied further.

In Borken-Kleefeld *et al.* (2018b) the correlation between NO_X emissions as measured by remote sensing and as measured by PEMS was studied for Euro 5 diesel passenger cars on vehicle model level. The agreement between the two methods was found to be good. A similar analysis was done in this study for Euro 6ab light-duty diesel vehicles on both vehicle model level and engine family level by means of the uCARe engine taxonomy methodology, which in both cases also showed a good agreement between the two methods.

4.1.2 PM emissions

The remote sensing instrument deployed in this study provides a proxy of PM (particulate mass) emissions in g/kg fuel units derived from measurements of opacity, i.e., smoke density through light extinction in the UV region. The measurements in Haninge enabled an analysis of particle emissions by Euro standard and the results clearly reflects the introduction of effective DPFs (diesel particulate filters), being a direct consequence of the implementation of the very strict PM emission standard from Euro 5. Compared to Euro 3, representing pre-DPF PM emission performance, the average PM emissions according to the remote sensing measurements are lowered by more than 90% for Euro 5 and Euro 6, i.e., very similar to the reduction implied by the change in the emission standard from Euro 3 to Euro 5-6 (0.05 g/km to 0.005 g/km).

4.2 Remote sensing vs PEMS for identifying high-emitting vehicles

4.2.1 NO_X high-emitters

A NO_X high-emitter analysis was carried out on a subsample of Euro 6ab vehicles measured with remote sensing in Haninge four times or more, comprising 427 unique vehicles. One conclusion is that some engine families were more frequently represented among the highest emitting vehicles than what could be expected from their market share in Sweden. These engine families also showed to have the highest average emissions when evaluating data on a fleet level. The results indicates that the “normal” emission levels and a possible limit in gNO_X/kg fuel for determining e.g. exhaust after treatment malfunctions for Euro 6ab diesel passenger cars likely should be set outgoing from vehicle models or engine families and not from e.g. the average emission based on all Euro 6ab diesel models.

In this study also NO_X emissions as measured by remote sensing and PEMS on individual vehicles were compared. From the remote sensing measurement campaign conducted in Haninge in 2018, about 30 vehicles were recruited for further RDE tests by means of PEMS, some of which were also measured on a chassis dynamometer (for NEDC and WLTP tests). Although there were some difficulties in recruiting vehicles for these measurements, resulting in a time delay in some cases of up to 6 months between the two measurements and that some of the method comparison had to be based on only one single remote sensing measurement, the results from the remote sensing and PEMS measurements correlated fairly well. For the 15 Euro 6ab diesel light-duty vehicles exceeding an arbitrary cutpoint in the remote sensing measurements of 5 g NO_X/kg fuel, 12 vehicles exceeded the PEMS RDE limits applied for Euro 6d and 6d-temp by a factor of 1.5-16, with errors of commission and errors of omission in the range 7-13% However, it is important to point out that several remote sensing measurements is generally needed for making a robust assessment of the emission performance of a vehicle.

A further comparison between remote sensing and PEMS, in this case a mini-PEMS, was made in a measurement campaign carried out in conjunction to a PTI station. Here, the remote sensing instrument was also supplemented with a state-of-the-art instrument to measure number of exhaust particles from passing vehicles during real driving conditions. The measurement campaign comprised approximately 30 light-duty vehicles which were also subject to the PTI emission test. Two of the measured vehicles, one petrol Euro3 and one diesel Euro 5, could clearly be suspected to have higher than normal NO_x emissions with repeatedly measured emissions between 30 and 90 g NO_x/kg fuel according to the remote sensor. The same vehicles were also identified as two of those with the highest NO_x emissions when tested with mini-PEMS test. Three additional cars with high NO_x emissions as measured with the mini-PEMS also appeared with high emissions in the remote sensing measurements, although not as pronounced as the two beforementioned vehicles. In summary, the measurements at the PTI station showed that the there used procedure for remote sensing measurements has the potential to detect vehicles with deviant high NO_x emissions, which may be confirmed by further tests, e.g., by means of a mini-PEMS. The difficulty is to set a lower emission limit, above which some error in the emission control system can be suspected. Based on the relatively small group of vehicles tested at the PTI station, it appears that for Euro 5 or earlier diesel or gasoline light duty vehicles several remote sensing records above 30 g NO_x/kg could be a criteria to distinguish cars with deviant high emissions. Since the analyse on fuels specific NO_x emissions from Euro 6ab diesel light duty vehicles based on the CONOX dataset shows that the vehicle models with highest average emission emits NO_x in the rang of 20 – 25 gNO_x/kg, a criteria of several measurements over 30 gNO_x/kg fuel likely can be used also to find Euro 6 ab vehicles that has higher emissions than is normal fuel specific NO_x emissions. However, the mini-PEMS measurements also showed that vehicles with repeated remote sensing measurements between 20-30 g NO_x/kg could have higher than normal emissions during a PEMS route which indicates that more research is needed to find possible definitive cut points. If such limit is to be set a larger test sample of vehicles with varying fuels, emission standards, vehicle models, age and engine sizes is considered necessary.

4.2.2 PM/PN high-emitters

The particle number measurements performed at the PTI station showed that the method previously used by IVL to measure exhaust particle emissions from buses (Hallquist *et al.*, 2013) and heavy-duty trucks (Zhou *et al.*, 2020) from the roadside works well also for passenger cars. Since these measurements were not compared with measurements by any other method, e.g., PEMS, it is difficult to draw any conclusions about how good the method is for identifying vehicles with high PN emissions. Further, it was neither within the scope nor practically feasible within this project to compare remote emission sensing measurements with the newly proposed PN test for PTI applications (see e.g., Kadijk et al., 2017). In order to get an idea of which vehicles may have higher emissions than normal with regard to the number of particles, a comparison was made with emission factors derived from HBEFA. The comparison showed that for the majority of the 26 tested vehicles the measured emission factors were lower, while for six vehicles the measured emission factors were significantly higher than those derived from HBEFA.

4.3 Potential use of remote emission sensing in in-use compliance programs

One objective of the project, apart from comparing remote sensing and PEMS for identifying high-emitting vehicles, was to evaluate the potential of remote sensing as a possible stand-alone and cost-effective method for continuously surveying the real driving emission performance of the in-use light-duty diesel vehicle fleet.

A major advantage with remote sensing is the possibility to screen vehicle fleets by measuring several thousands of vehicles in a single day. This enables the possibility not only to detect suspicious high-emitting individual vehicles but also to analyse the emission performance of different groups of vehicles, such as by Euro standard, the type of emission control technology applied, vehicle make and model, engine family, etc. This study has demonstrated the applicability of remote sensing for such purposes, which could yield useful information for operating in-use compliance programs.

4.4 Potential use of remote sensing and mini-PEMS for PTI programs

The strongest motive for introducing remote emission sensing measurements in European PTI programs is the ability it brings to introduce - for the first time - regular NO_x emission testing on all in-use vehicles. Furthermore, it also provides an option to measure emissions of all regulated pollutants (apart from NO_x also particulate matter, hydrocarbons and carbon monoxide) when vehicles are driven under load. However, with the remote sensing instruments available on the market today, there are cost issues and/or limitations with regard to the sensitivity when measuring particularly exhaust particles. Also, there is yet not sufficient evidence for that remote sensing can be used as a stand-alone method to identify vehicles having some kind of error on their emission control systems giving rise to emissions exceeding the regulatory limit. However, the dedicated pilot measurements with remote sensing, combined with short mini-PEMS tests carried out at a PTI station in this study, as well as the much large number of repeat remote sensing measurements on individual vehicles, recruited for PEMS RDE testing, indicate that there could be a place for remote sensing for enhanced emission testing within European PTI programs in the future. For instance, the on-going H2020 project CARES (https://cares-project.eu/) has as one of its core objectives to "improve performance, reduce costs, facilitate use by unskilled personnel and achieve a broader deployment potential" for remote emission sensing. Further, the on-going H2020 project NEMO (https://nemo-cities.eu/) also aims at developing remote sensing techniques for "Identification of transgressing vehicles on the road and possible invitation to appropriate revision". Combining remote sensing with simplified PEMS tests could be particularly appealing for PTI applications. Further research on how to set adequate remote sensing cutpoints for different types of vehicles (e.g., Euro classes, petrol and diesel vehicles, etc.) and relating them to simplified PEMS tests as well as legislative RDE tests is highly recommended.

4.5 Conclusion summary

- A good agreement between remote sensing and PEMS was demonstrated in terms of real-world NOx emission reductions for light-duty diesel vehicles from Euro 5 to the various steps of Euro 6, ranging from Euro 6ab through Euro 6d. The NOx real-world emissions are reduced by about 90% going from Euro 5 to Euro 6d according to both methods.

- For the early Euro 6 (step a and b) light-duty vehicles:
    - With data broken down on vehicle model level for early Euro 6 diesel light-duty vehicle, and particularly on engine alliance level, a good agreement in NOx emissions was also observed between remote sensing and PEMS.
    - Even on an individual vehicle level there was a reasonable agreement between remote sensing and PEMS, indicating that remote sensing is capable of identifying vehicles exceeding the Euro 6 RDE limit with a factor of three or more, with reasonably low estimated errors of omission and commission.
    - Both remote sensing and PEMS showed large variations - a factor of 30-40 between the highest and lowest emitting vehicles - in NOx emissions between individual vehicles. High emissions were occasionally associated with certain engine families.
    - Taken together, these results demonstrate that remote sensing can be a useful tool in in-use compliance programs targeting the performance of NOx emission control systems on light-duty diesel vehicles.

- Remote sensing measurements were used to screen for high-emitting light-duty vehicles (both diesel and petrol), visiting a PTI station, the NOx emissions of which were subsequently measured with a mini-PEMS over a short route (≈5 km). The remote sensor correctly identified vehicles having very high NOx emission over the mini-PEMS route. Thus, this approach may be exploited to embarque NOx emission testing in future PTIs.

- For diesel LDV PM emissions the remote sensing data mirrors the evolution of the increasingly stricter emission standards from Euro 1 onwards, ultimately requiring all vehicles to be equipped with diesel particulate filters (DPFs) from Euro 5. Thus, the real-world emissions have been reduced by more than 90% since the introduction of DPFs.

- For diesel LDV PM emissions the sensitivity of conventional (commercial) remote sensing instruments appear to be too low correctly separate high-emitting from low-emitting individual vehicles, at least those equipped with DPF, but may work as a means to identify vehicle models or vehicle engine families, the PM emissions of which are substantially higher than a normal or the average vehicle meeting the same Euro standard.

- A more sophisticated and sensitive remote emission sensing instrument for size-resolved measurements of the number of particles from the roadside was used to measure light-duty vehicles – both diesel and petrol – for the first time and showed promising results when deployed at a PTI station. On-going further development of this state-of-the-art research grade instrument could result in low-cost sensors for PN/PM emissions that may candidate as useful screening tools to be used within both in-use compliance programs and in periodic technical inspections in the future.

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Appendix 1 – Instruments used for PEMS measurements

Technology	PEMS	Diluted/Bags
Manufacturer	AVL	AVL
Model	M.O.V.E. iS	AMA i40
Principle CO_2	NDIR	NDIR
Range CO_2	20%	1%, 20%
Principle NO_x	NDUV	CLD
Range NO_x (ppm)	5000	10, 100, 1000
EFM	Pitot 2&2.5"	-

NDIR - non-dispersive infrared detection
NDUV - non-dispersive ultraviolet detection
CLD - chemiluminescence detection

Appendix 2 – Light-duty diesel vehicles tested with PEMS

Vehicle Id	Model year	Odo-meter [km]	Euro class	Engine capacity [cm3]	Vehicle mass (kg)	EATS	Conducted tests
#1	2012	104 731	5a	1 560	1 494	DOC, DPF	NEDC, WLTC, PEMS
#2	2014	99 436	5b	1 598	1 526	DOC, DPF	NEDC, WLTC, PEMS
#3	2012	99 810	5b	1 968	1 664	DOC, DPF	PEMS
#4	2013	55 602	5b	1 461	1 469	DOC, DPF	PEMS
#5	2011	238 704	5a	1 685	1 490	DOC, DPF	PEMS
#6	2011	72 067	5a	1 582	1 419	DOC, DPF	NEDC, PEMS
#7	2014	53 734	5b	1 461	1 526	DOC, DPF	NEDC, PEMS
#8	2016	39 892	6b	1 685	1 619	DOC, DPF	NEDC, WLTC, PEMS
#9	2017	32 989	6b	1 969	1 865	DOC, DPF, LNT	NEDC, PEMS
#10	2015	33 000	6b	1 968	1 839	DOC, DPF, SCR	PEMS
#11	2014	86 251	6b	1 598	1 701	DOC, DPF, SCR	PEMS
#12	2016	49 562	6b	1 499	1 566	DOC, DPF	PEMS
#13	2015	54 704	6b	1 685	1 619	DOC, DPF	PEMS
#14	2016	31 519	6b	1 560	1 630	DOC, DPF, SCR	PEMS
#15	2017	18 375	6b	1 461	1 910	DOC, DPF	PEMS
#16	2015	58 331	6b	1 461	1 910	DOC, DPF	PEMS
#17	2016	55 241	6b	1 499	1 672	DOC, DPF	PEMS
#18	2016	66 001	6b	1 997	1 902	DOC, DPF	PEMS
#19	2014	99 601	6b	2 191	1 587	DOC, DPF	PEMS
#20	2017	35 114	6b	2 400	1 921	DOC, DPF, LNT	PEMS
#21	2016	43 679	6b	1 461	1 557	DOC, DPF	PEMS
#22	2017	88 984	6b	1 997	1 851	DOC, DPF	PEMS
#23	2015	52 954	6b	1 598	1 805	DOC, DPF	PEMS
#24	2018	14 017	6b	1 968	1 786	DOC, DPF, SCR	PEMS
#25	2017	42 758	6b	1 969	1 832	DOC, DPF, LNT	NEDC, WLTC, PEMS
#26	2019	399	6c	1 461	1 505	DOC, DPF, SCR	PEMS
#27	2018	13 488	6d-temp	1 950	1 835	DOC, DPF, SCR	PEMS
#28	2019	319	6d-temp	1 968	1 969	DOC, DPF, SCR	PEMS
#29	2019	17	6d-temp	1 968	1 976	DOC, DPF, SCR	PEMS
#30	2019	6 700	6d-temp-evap	1 995	1 803	DOC, DPF, SCR	PEMS

Appendix 3 Laboratorial and On-Road test campaign results

Vehicle	CO_2 NEDC [g/km]	CO_2 WLTC [g/km]	CO_2 PEMS [g/km]	NO_x NEDC [g/km]	NO_x WLTC [g/km]	NO_x PEMS [g/km]	NO_x mass/Fuel mass NEDC	NO_x mass/Fuel mass WLTC	NO_x mass/Fuel mass PEMS
#1	121	139	167	0.237	0.33	0.633	6.21	7.5	12.04
#2	130	142	165	0.21	0.529	0.955	5.07	11.76	18.38
#3			178			0.30544			5.45
#4			120			1.268			33.53
#5			178			0.86			15.35
#6	118		147	0.088		1.569	2.34		33.8
#7	113		125	0.18		1.321	5.01		33.35
#8	117	137	176	0.334	0.109	0.433	5.91	2.5	7.8
#9	141		164	0.071		0.262	1.58		5.05
#10			158			0.038			0.76
#11			164			1.122			21.67
#12			148			0.634			13.56
#13			171			0.452			8.39
#14			122			0.265			6.91
#15			125			0.364			9.23
#16			140			1.311			29.63
#17			158			0.779			15.66
#18			170			0.538			9.92
#19			132			0.192			4.61
#20			201			0.458			7.24
#21			137			0.396			9.17
#22			194			0.492			8.07
#23			159			1.314			26.19
#24			150			0.073			1.54
#25	126	142	147	0.039	0.085	0.205	0.98	1.89	4.41
#26			145			0.162			3.54
#27			134			0.014			0.3
#28			152			0.01			0.21
#29			179			0.09			1.6
#30			146			0.039			0.85

Appendix 4 Vehicles tested at PTI station

Vehicle Id	PC/LCV1	Vehicle model	Model year	Odo-meter (km)	Fuel	Euro class	Engine capacity (cm3)	Engine power (kW)	Vehicle mass (kg)
A	PC	Volvo V70	2011	167 000	Diesel	5a	1 984	120	1 810
B	PC	Volvo V60	2018	44 000	Diesel	6b	2 400	140	1 729
C	LCV	Hyundai H1	2016		Diesel	6b	2497	125	2 059
D	PC	VW Golf	2012		Diesel	5b	1 598	77	1 340
E	PC	VW Golf	2015		Petrol	6b	1 197	81	1 360
F	PC	Volvo V70	2011	110 000	Diesel	5a	1 560	84	1 710
G	PC	Volvo V40	2013	35 000	Petrol	5b	1 596	88	1 460
H	PC	Volvo C70	2009	51 000	Diesel	4	1 997	100	1 700
I	PC	Jaguar XE	2013	100 000	Diesel	6b	1 999	120	1 630
J	PC	Ford Focus	2009	91 000	Diesel	5a	1 560	80	1 390
K	PC	Volvo S80	2014	95 000	Diesel	5b	1 984	100	1 720
L	LCV	MB Vito	2016	188 000	Diesel	6b	2 143	140	3 200
M	PC	Volvo V60	2018	16 000	Diesel	6d-t	1 969	140	1 850
N	PC	Volvo XC90	2019	9 000	Diesel	6d-t	1 969	173	2 120
O	PC	Volvo V40	2009	185 000	Diesel	4	1 560	128	1 390
P	LCV	Ford Likbil	2014	150 000	Diesel	5b	2 198	114	2 990
Q	LCV	Peugeot Boxer	2014	144 000	Diesel	5b	2 198	110	3 500
R	PC	Audi A4	2016	134 000	Diesel	6b	1 968	140	1 700
S	PC	Toyota Yaris	2000	156 000	Petrol	3		50	1 040
T	PC	Volvo XC70	2006	139 000	Diesel	4	2 401	136	1 800
U	PC	Volvo V40	2018	16 000	Diesel	6d-t	1 996	110	1 570
V	PC	Volvo V90	2017	34 000	Diesel	6b	1 996	140	1 940
X	PC	Volvo V70	2011	169 000	Diesel	5a	1 984	120	1 810
Y	PC	Opel Mokka	2013	85 000	Diesel	5b	1 686	96	1 460
Z	PC	Renault Capture	2014	31 000	Petrol	5b	1 197	88	1 360
AA	PC	Audi Q3	2013		Diesel	5b	1 968	103	1 610
AB	PC	Toyota Yaris	2005	92 000	Petrol	4	1 298	64	1 080
AC	LCV	Hyundai i10	2015	122 000	Diesel	5b	2 497	100	3 160
AD	PC	Renault Clio	2006	149 000	Petrol	4	1 149	55	1 170
AE	PC	Mitsubishi Z30	2011	79 000	Petrol	5a	1 332	70	1 050

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