FORCE Technology
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Methods and technologies to support Periodic Technical Inspection of emission-controlled systems on heavy duty vehicles

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Abbreviations

BC	Black Carbon
CD	Charge Diffusion
CITA	International Motor Vehicle Inspection Committee
CLD	Chemiluminescence
CPC	Condensation Particle Counter)
DETEC	The Federal Department of the Environment, Transport and Communication, Switzerland
DOAS	Differential Optical Absorption Spectroscopy
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EIB	Environmental Inspection of Buses, Miljøsyn, Denmark
ES	Electrochemical Sensors
FEDRO	Swiss Federal Office for the Roads, Switzerland
FTIR	Fourier Transformed Infrared Spectroscopy
IR	Infrared
METAS	Swiss Federal Institute of Metrology, Switzerland
NDUV	Non-Dispersive Ultra-Violet
NMI	Nederlands Meetinstituut, Netherlands
OBD	On-Bord Diagnostic
PEMS	Portable Emissions Measurement System
PM	Particular matter, $PM_{2.5}$ and PM_{10} are particle below 2.5 μm and 10 μm respectively
PN	Particle Number
PTB	Physikalisch-Technische Bundesanstalt, Germany
PTI	Periodic Technical Inspection
SCR	Selective Catalytic Reduction
CARP	California Air Resources Board
HDVIP	Heavy-Duty Vehicle Inspection Program
PSIP	Periodic Smoke Inspection Program

1 Dansk resumé

Denne rapport er baseret på et litteraturstudie af alternative målemetoder til kontrol og inspektion af det emissionsreducerende system på tunge køretøjer til brug ved periodesyn jf. direktiver 2014/45/EU. Desuden er rapporten baseret på kontakt til de relevante myndigheder og institutioner i en række europæiske lande med henblik på at indhente oplysninger om de respektive landes tiltag og overvejelser i forhold til at indføre alternative metoder til kontrol og inspektion af de emissionsreducerende systemer ved periodesyn. Rapporten har primært fokus på udstyr til måling af NO_X, men udstyr til måling af partikelantal adresseres også.

Der findes et bredt udvalg af målemetoder til måling af NO_X fra dieselkøretøjer. De mest gængse måleprincipper er Non-Dispersiv Ultraviolet spektroskopi (NDUV), Kemiluminescens (CLD), Fourier Transformeret Infrarød spektroskopi (FTIR) og elektrokemiske sensorer (ES). Det vurderes, at instrumenter med måleprincipper CLD og ES er de meste egnede til brug ved testkørsel. Alle typer af måleinstrumenter er dog anvendelige ved stationære test på rullefelt. Måleprincipper der ikke vurderes anvendelig til måling af NO_X i udstødningsgasser er ikke beskrevet. Denne rapport beskriver et bredt udvalg af kommercielt tilgængelige instrumenter. Prototyper og ikke-kommercielt tilgængelige instrumenter er ikke omfattet denne rapport.

Erfaringer med kontrol af SCR-systemer viser, at katalysatoren skal være tilstrækkelig varm inden målingerne af NO_X udføres, og at motoren skal være belastet under testen. Dette kan opnås enten ved at udføre testen på et rullefelt eller ved en testkørsel.

Kontrol af dieselpartikelfiltre bør ske ved måling af partikelantal. Målingen kan foretages som stationær test uden at belaste motoren (fx ved fri acceleration mm) eller ved en testkørsel. Antallet af partikler kan bestemmes ved hjælp af måleudstyr, der baserer sig på charge diffusion (CD) eller som anvender måleprincippet CPC (Condensation Particle Counter). Der findes en række måleinstrumenter, som er kommercielt tilgængelige til måling af partikelantal i udstødningen fra køretøjer. Flere af instrumenterne er ligeledes certificeret af forskellige nationale testinstitutioner.

Rapporten beskriver resultaterne af et 'nabo-tjek' med fokus på de respektive landes tiltag og overvejelser i forhold til at indføre alternative metoder til kontrol og inspektion af de emissionsreducerende systemer ved periodesyn. Relevante myndigheder og institutioner er blevet kontaktet i følgende ni lande: Sverige, Norge, Finland, Tyskland, Storbritannien, Holland, Østrig, Schweiz og Frankrig.

Resultatet af nabo-tjekket viser, at ingen af de kontaktede lande udfører konkrete test eller har indført alternative målemetoder til kontrol af emissioner fra de NO_X reducerende systemer på tunge køretøjer.

Holland og Schweiz har indført eller har planer om at indføre kontrol af partikelfiltre. Denne kontrol skal udføres ved måling af partikelantal på dieseldrevne køretøjer. Holland indfører kontrol af partikelantal fra juli 2022. Schweiz har indført måling af partikelantal som et frivilligt alternativ til opacitetsmålinger på entreprenørmaskiner. Det forventes, at ordningen i fremtiden vil blive anvendt til dieseldrevne køretøjer i den vejgående trafik.

2 Introduction

This report is the result of a desktop study performed by FORCE Technology for the Danish Road Traffic Authority. The information and views set out in this report are those of the authors and do not necessarily reflect the official opinion of the Danish Road Traffic Authority. The Danish Road Traffic Authority does not guarantee the accuracy of the data included in this study. Neither the Danish Road Traffic Authority nor any person acting on the Danish Road Traffic Authority´s behalf may be held responsible for the use that may be made of the information contained therein.

In 2018 the Danish Environmental Authorities and the Danish Road Traffic Authority initiated a task to strengthen inspection and control in order to avoid tampering of NO_X reducing systems on heavy duty vehicles. As part of this activity, it was decided to investigate control methods that can be implemented and used to enforce the relevant regulations of emissions from heavy duty vehicles. The first part of the work task focused on tampering of NO_X reducing systems and field inspection of trucks. The second phase of the work task focus on alternative ways to inspect emission reducing systems on heavy duty diesel vehicles through Periodic Technical Inspection (PTI).

This report has been elaborated as a result of a study focusing on methods and technologies that can support PTI of emission-controlled systems on heavy duty vehicles. The report is based on a literature study and through correspondence with authorities and key stakeholders in a number of European countries.

3 Objective

The objective of this report is to investigate alternative ways to inspect emission reducing systems on heavy duty diesel vehicles during PTI. The report describes the results of the following project activities:

- A literature study on methods and technologies there can be used for PTI of emission-controlled system on buses and truck (Euro V and Euro VI), with a special focus on control methods for inspection of NO_X emissions from heavy duty diesel vehicles equipped with Selective Catalytic Reduction (SCR) technology. Inspection of Diesel Particulate Filters (DPF) by particle number (PN) concentration measurements has also been addressed.

- A survey on how other neighbouring countries is targeting the issue with respect to alternative ways of PTI on emission reducing systems on (ex. SCR or DPF) on buses and trucks. Selected countries in the survey were Norway, Sweden, Finland, Germany, The Netherlands, France, Austria, Switzerland and England.

A short overview of current ways of performing PTI on diesel vehicles with regards to emissions is given in Chapter 4. Chapter 5 describes the emissions from heavy duty vehicles that will be addressed in this study. Chapter 6 and chapter 7 encompass information on alternative methods for inspection of SCR and DPF during PTI. Chapter 8 presents how the countries selected, consider using other methods than On-Bord Diagnostic (OBD) and measurements of opacity for inspection of emission-controlled systems on heavy duty diesel vehicles during PTI. Chapter 9 summarizes the conclusion of the study. Appendix A shows a list of instrument specifications for measurements of NO_X and PN.

4 Periodic inspection of heavy duty vehicles

Current EU legislation on emission testing during PTI is addressed in Directive 2014/45/EU (1). The regulation in the directive was implemented in 2018 and covers both light duty and heavy duty vehicles. For diesel vehicles emission, control and inspection is limited to a visual check of the emission-controlled system and a tailpipe measurement of opacity for vehicle emission classes up to Euro 5 and Euro V. For vehicle with an emission class of Euro 6 and Euro VI, tailpipe measurement of opacity or OBD for inspection may be used, depending on the individual state authorities.

The opacity is measured during unloaded accelerations from low idle to fast idle (maximum speed without engine load). Limit values are given in the EU Directive (1). A more detailed description of the measure principles of opacimeters can be found in ISO 11614 (2).

In Directive 2014/45/EU, inspection of the NO_X reducing emission systems are limited to a visual inspection and, if specified by the authorities, supplemented with and OBD reading. Measurements of NO_X are not covered by Directive 2014/45/EU.

5 Emissions from heavy duty diesel vehicles

The main targeted parameters of tailpipe emission from heavy duty diesel vehicles are NO_X (NO + NO_2) and soot particles. Other parameters from tailpipe emission includes CO and volatile hydrocarbons (HC) as well as CO_2. As CO_2 is categorized as a climate gas, it is not at parameter that directly affect ambient air quality (3). Tailpipe emissions of NH_3 which originates from the SCR system are not considered in this study.

5.1 NO_X Emissions

NO_X emission is generally controlled by Exhaust Gas Recirculation (EGR) or SCR technologies. NO_X is formed during the combustion process and mainly attributed to the oxidation of N_2 from the intake air during the combustion process as described by the Zeldovich mechanism. High combustion temperatures will increase the formation of NO_X.

EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. This will reduce the O_2 in the incoming air for combustion and provides gases inert to combustion. This will act as absorbents of combustion heat to reduce peak in-cylinder temperatures and thereby reduce the formation of NO_X (4).

SCR reduces the NO_X by a reaction with NH_3 over the catalysis. In most SCR systems, the NH_3 originates from an aqueous urea solution (ex. AdBlue) which is injected into the exhaust gas stream and thermally decomposed into NH_3 + CO_2 through a intermedial side reaction step involving HNCO (5) (6) (see Figure 1). In the presence of O_2 and a suitable catalyst, NH_3 will react with NO_X to form N_2. A pre-oxidation catalyst is sometimes used which helps to oxidize a fraction of the NO to NO_2 before the gas enters the SCR. Gases like CO will also be oxidized over the per-oxidation catalyst. The present of NO_2 in the exhaust gas will increase the reaction speed in the SCR as the catalytic reaction involving NO_2 is faster than the reaction between NO and NH_3.

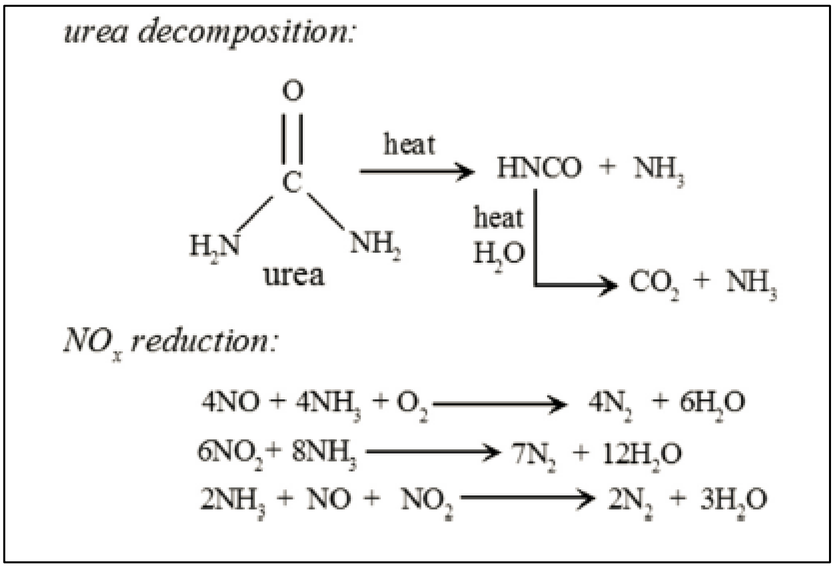

Figure 1. Overview of general chemical reactions over the SCR catalyst (5).

The catalytic reaction of NO_X to N_2 in an SCR requires heat. An SCR catalyst will therefore typically require an exhaust gas temperature of 200 – 250ºC or more in order to have significant effect on the NO_X reduction. More detailed information of SCR technology can be found in e.g. (7) and (8).

5.2 Particle emissions

Particle emissions from diesel exhaust is a less dominant source of $PM_{2.5}$ and PM_{10} found in ambient air. This is because particles emitted from internal engine combustion are typical well below 200 nm in size, and their particle mass are less significant compared to the mass of $PM_{2.5}$ and PM_{10} in ambient air. Particle number (PN) and black carbon (BC) are important health related parameters when documenting particle emissions from exhaust of diesel vehicles. Emission of PN is regulated from type approval of newer light duty and heavy duty vehicles (Euro 5b, Euro 6 and Euro VI). Before the introduction of Euro 5, particle emissions were mainly controlled by optimizing the engine setting and the use of ex. EGR. However, with the regulation of PN concentration, DPF became a standard after treatment system installed in most heavy duty vehicles. Particles are collected efficiently in the DPF. The DPF is regenerated according to the approach of the individual manufactures, ex. passive or active regeneration. It is not the scope of this report to go into detail with the different approaches for DPF regeneration etc.

One way to control the efficiency of the DPF is to measure the differential pressure across the filter. If a large hole/crack appears in the filter, the differential pressure will fall outside a given threshold limit. However, this method will not be able to detect smaller cracks in the filter (9). A suitable way to inspect the DPF is to measure the PN concentration in the tailpipe of the vehicle. This method is a much more sensible approach to detect faulty filters. Tampering of DPF will also be more difficult if actual measurement of PN is applied.

6 Methodology for alternative inspection of NO_X reducing systems during PTI

6.1 Emission test at loaded and unloaded engine conditions

CITA-studies (10) from 2011 have addressed new approaches on how to test NO_X reducing systems on diesel vehicles. The report concludes that it is not possible to use the NO_2/NO_X ration as identification on faulty components for heavy duty and light duty vehicles. It was also shown that heavy duty vehicles with a faulty SCR was not detected during PTI, primarily because the SCR system does not work efficiently under low load conditions. The report concludes that measurements of NO_X under the current PTI emission cycle cannot sufficiently detect faulty SCR.

Newer studies (11) have also tried to address the problem of functional behaviour of the NO_X controlled system by comparing measurements of emissions from light duty vehicles. Results showed that there seems to be a direct relation between NO_X emission levels and particulate emission levels, and that NO_X concentration obtained through measurements performed during a free acceleration test with high RPM may be used to inspect the EGR valve for faults. However, to our knowledge no results on vehicles equipped with a SCR system were presented. Therefore, an unloaded engine test cycle does not seem to be a suitable approach to test SCR for faults.

There are two different ways of applying load to the engine during an emission test.

- Emission test on a chassis-dynometer
- Emission testing during a short test ride

If the PTI should be performed on a chassis-dynometer it will require a substantial investment (>130.000 Euro (12)) to cover the wide range of different type of heavy duty vehicles. Investment in emission monitoring instruments will have to be included besides the chassis-dynometer itself. Special tyres might also be needed in order to obtain the right degree of friction between the rollers and tyres during test.

Testing the efficiency of after treatment systems through road drive emission testing seems to be more economical favourable compared to emission tests on a chassis-dynometer. The main challenges for performing a loaded test through a short test ride is (1) the installation of test equipment on the actual vehicle, and (2) ensuring that the engine and the system for after treatment of exhaust gas are sufficiently warm during test. Low ambient temperatures can prolong or prevent the temperature of the engine and emission control system to reach the required temperature. This may limit the period during which the tests can be carried out. Including a short test drive during a PTI will also increase the time needed for testing compared to the existing PTI.

A field study from 2019 (13) have analysed six different kinds of test cycles as candidates for testing of faulty SCR system. Three test cycles were performed under unloaded conditions and three test cycles were performed under loaded conditions. The study was made on light duty vehicles only.

The study evaluated the test cycles based on the following parameters:

- Ability to detect failures of different emission systems
- Overall accuracy of method
- Applicable for all tested vehicles (light duty)
- Time and investment needed

Results shows that it was not possible to obtain a suitable test cycle without applying load on the engine. Also, the results showed that it is necessary to have an acceptable SCR temperature over the catalyst.

One of the most promising test cycles identified during the study were the ASM2050 test cycle (see Figure 2). The ASM2050 test cycle focuses on the driving cycle which is directed towards urban driving up to 50 km/h. The ASM2050 test cycle was tested in two variations depending on whether a change to second gear at 20 km/h which were kept throughout the test or a change from second gear to third gear at 50 km/h was performed.

All tests were conducted mainly with the focus on periodic inspection of light duty vehicles (Euro 5 + Euro 6), however FORCE Technology assess that the general principles may be considered also to cover testing of heavy duty vehicles, although test cycles may need to be adjusted to meet the practical applications with testing heavy duty vehicles. The ASM2050 test cycle on vehicles was however performed on a chassis-dynometer which apply less constraints on the flexibility and portability of the emissions monitors. A road test drive under a similar test conditions on a selection of heavy duty vehicles should be considered in order to evaluate the ASM2050 test cycles use for PTI.

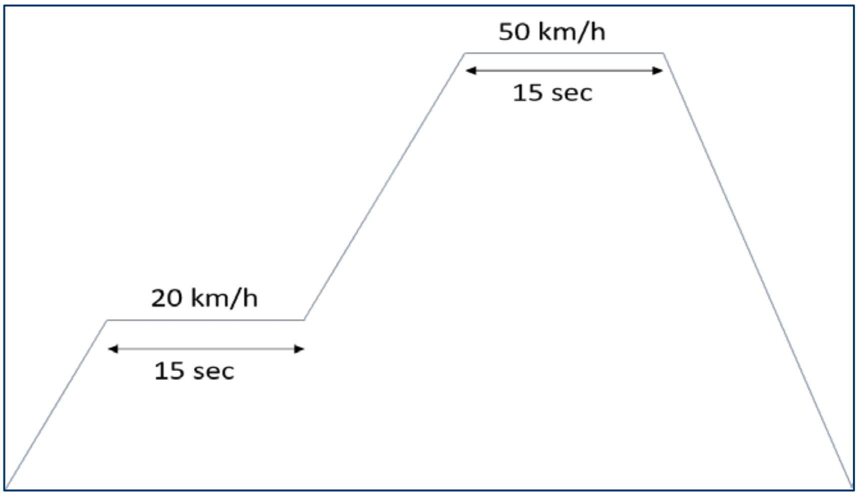

Figure 2. ASM2050 test cycle.

In 2019, the California Air Resources Board (CARB) initiated a Heavy-Duty Inspection and Maintenance Program (HD I/M program) in consultation with the Department of Motor Vehicles and the Bureau of Automotive Repair. CARB's existing programs, the Heavy-Duty Vehicle Inspection Program (HDVIP) and the Periodic Smoke Inspection Program (PSIP), are intended to ensure that vehicle emission control systems are properly operating throughout the life of the vehicle. However, these programs do not adequately ensure the inspection of the NO_X reducing systems. The HD I/M program will focus on a more comprehensive test method for PTI inspection with special attention on NO_X emissions. Results describing the HD I/M program's findings and recommendations have not yet been published.

An alternative method of inspecting the emission reducing systems is currently being performed in Denmark ("Environmental Inspection of Buses" (EIB), "Miljøsyn af Busser" in Danish) (14). EIB is not established under Danish law but is a supplement that public transportation companies can request from the bus operator if such an agreement is part of their mutual contract. EIB involves a direct measurement of NO_X, CO_2, PN and PM during a short driving cycle which involves three acceleration tests from idle to maximum speed as shown on Figure 3. These tests are often done on a road found in a suitable driving distance from the garage, to ensure that the engine and emission-controlled system are warm prior to the actual emission test. The test drive must be done on a road with a minimum of elevation to make each test reproducible and comparable with other tests. CO_2 are measured in addition to NO_X, PM and PN. CO_2 is used to present the results at reference conditions (10 vol% CO_2). Emission peak values are recorded of each of the three acceleration tests and an average is reported at reference conditions. Each test on the bus takes ca. 45 min[1] (ca. 15 min of driving to ensure a warm engine and emission-controlled system, ca. 15 min to perform tests and ca. 15 min to drive back to the garage). Emission parameters are measured continuously with a time resolution of 1 sec. The measurement principle of PM and PN is charge diffusion. NO_X are measured continuously with a chemiluminescence (CLD) or Non-Dispersive Ultraviolet monitor (NDUV) and CO_2 is measured with a Non-Dispersive Infrared monitor (NDIR). Both gas analysers shall meet the requirements in 582/2011/EU (15) or section 9.3.1, appendix 4B in UN/ECE Regulation nr. 49 (16) (see Table 1).

Table 1. Specifications of instrument for gas emission measurements during EIB in Denmark.

Parameter	NO_X	CO_2
Unit	ppm (dry conditions) Reference conditions (10% CO_2)	vol% (dry conditions) Reference conditions (10% CO_2)
Range	0 – 1500 ppm	0 – 18 vol%
Resolution	1 ppm	0.1 vol%

The magnitude of NO_X concentrations in tailpipe emissions depend on many parameters. One of the most important parameters is the temperature of the SCR system. Experimental measurements from EIS on in-service city buses, show that NO_X emissions from a Euro V bus can increase up to 1500 ppm NO_X or higher during an acceleration cycle (sampling rate of 1 Hz). The NO_X concentration is typically well below 500 ppm during more static driving conditions. When the SCR system is sufficiently warm and serviced, maximum concentration of NO_X during a full acceleration test (from zero to maximum velocity) is below 1000 ppm, which is also used as threshold limit (14) for the EIS test. Based on measurements from EIS, instruments used for tailpipe measurements of NO_X should therefore be able to apply a range of e.g. 0 – 2500 ppm for Euro V vehicles. It may not be suitable to use a much higher range if the uncertainty of the measured concentration for the given NO_X monitor is specified as a percentage of the maximum measurement range by the manufacturer. On-road emission measurements on heavy duty trucks (China V emission class) reports that NO_X concentrations are generally below 600 ppm during real driving at medium/high speed and with a SCR temperature above 250 °C (17). NO_X concentrations were in this study measured using a PEMS with a NDUV measurement technique for NO_X monitoring. In terms of NO_X emission type approval, China V is similar to Euro V for steady-state testing. A direct comparison to on-road driving with a Euro V truck is therefore not straightforward.

Measurements of NO_X emissions from Euro VI buses are generally much lower compared to Euro V buses. Measurement results from EIS show that NO_X emissions from a Euro VI bus are typically well below 250 ppm during a full acceleration test (warm and well-functioning SCR). Similar measurements on heavy duty trucks are expected to be in a similar concentration range. It is recommended that for Euro VI vehicles, instruments used for tailpipe measurements of NO_X should be able to monitor concentrations with a good accuracy in the range 0 – 500 ppm. However, the concentration range will depend on the type of PTI test run implemented. Reported transient measurements from an in-service Euro VI bus in UK has shown NO_X peak concentrations op to 1200 ppm during an acceleration and 100 – 300 ppm during deceleration (18). However, reported exhaust temperatures of 210 – 215 °C could indicate that the SCR-system might not have been sufficiently warm during this test. It must also be emphasized that latter emission measurements were performed with a CLD instrument with an ultra-fast response time and a sampling rate higher than 1 Hz.

[1] Installation of test equipment is not included in the estimated time needed to test each bus.

Averaging of data to 1 Hz average values will reduce peak hight concentrations. Comparing the measured data must always be done on basis of equivalent averaging values.

If, however a future test cycle for NO_X monitoring during PTI should involve a test drive without the use of a full acceleration test (e.g. ASM2050 test cycle), the NO_X concentrations measured may be lower compared to a more simple acceleration from zero to maximum velocity. This applies both for Euro V and Euro VI vehicles. Once a test cycle is specified, the establishment of a future threshold limit for NO_X emissions for heavy-duty vehicles should be done on the basis of results from further tests.

In short, the requirements for the measurement range will not only differ between Euro V and Euro VI vehicles, it may also depend on the choice of test cycle. However, most instruments for NO_X monitoring allows the user to choose between different ranges and thereby adapt to the range of concentration needed. It is concluded that the instrumentation discussed in section 6.2 can be used for testing of both Euro V and Euro VI vehicles.

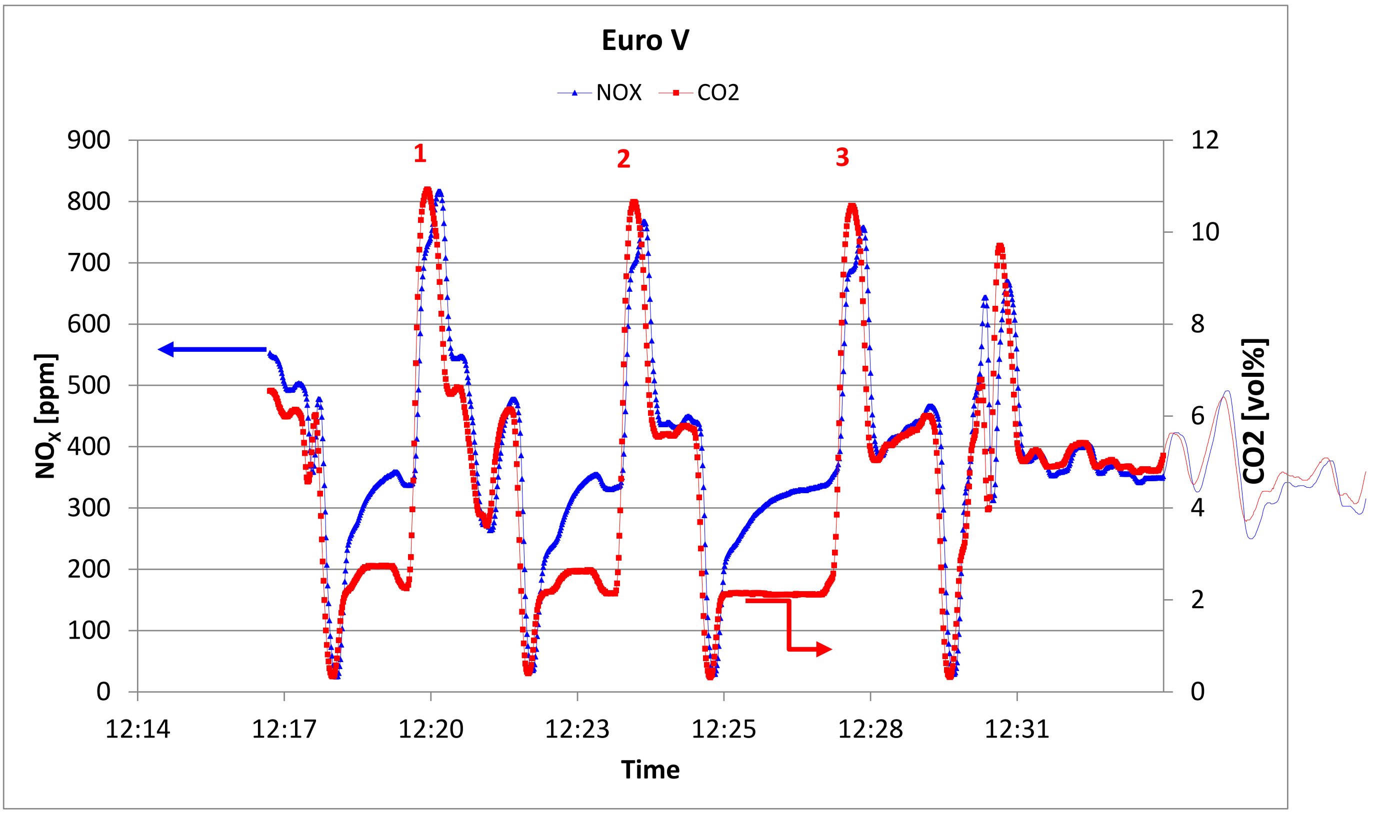

Figure 3. An example of a test drive which involves three acceleration tests from idle to maximum speed on a Euro V bus. The blue graph shows the recorded NO_X concentrations and the red graph shows the recorded CO_2 concentrations.

In summary, inspection of NO_X emissions from heavy duty vehicles seem to require a loaded engine test with a sufficiently warm SCR system. Although it is a much more time-consuming test compared to the existing inspection of emission systems during PTI, the test drives performed in Denmark on city buses seems as a plausible approach for testing SCR systems. A significant drawback for expanding the test method to heavy duty trucks is the required space for mounting of instruments and the need of electrical power. The test setup could be modified to cover only emission testing of NO, using electrochemical sensors and with the use of an unheated sample line. This will reduce the space and need for power supply. However, it will also require a certain effort to make sure that the instrument is always properly calibrated prior the test drive.

Instruments suitable for NO_X concentration measurements of Euro V and Euro VI heavy duty vehicles should be able to switch between different measure ranges depending on the type of Euro class vehicle. Any test of particle emission from DPF may be done at unloaded conditions as discussed in chapter 7 and therefore does not need to be a parameter measured during test drive.

6.2 Emission monitoring equipment for NO_X measurements

Several measurement techniques for NO_X monitoring are used for inspection purposes. Type approval of vehicles uses either Non-Dispersive Ultraviolet monitors (NDUV) or chemiluminescence (CLD) for measuring of NO_X (15) (16). CLD is also the main reference method for NO_X measurements in ambient air quality measurements (19), emission measurements from stationary sources (ex. incinerators, power plants etc.) (20) and for marine engines[2] (21).

Electrochemical sensors are also used in e.g. 5-gas monitors for garage inspection of vehicles. Ceramic electrochemical NO_X sensors are also widely used to control the injection of urea/AdBlue in SCR-systems.

Section 6.2.1 – 6.2.3 discusses the different type of measurement techniques for NO_X sensing. Table 2 – Table 5 show some examples of suitable instruments for measurement of NO_X from engine exhaust. It should be noted that some of the instruments may acquire an additional gas conditioning system to remove water vapour from the exhaust gas stream before it enters the instrument. Heated instruments or instrument with a build-in water trap may not acquire an additional gas conditioning system other than a filter to protect the sample cell from contamination with soot particles. Technical specifications of commercially available instruments for direct NO_X monitoring in engine exhaust (certified or tested against reference instruments) can be found in Table 9 of Annex A. The instrumentation can be used for testing of both Euro V and Euro VI vehicles. All instruments are found scalable for PTI in terms of portability (size and weight) and ease of operation. However, the SEMTECH-NOx from Sensors Inc. are less portable and more applicable for stationary use of NO_X measurements.

Other techniques can also be used to detect NO_X –gasses, however they are not relevant for exhaust measurements from combustion engines due to size, costs or concentration levels etc. (ex. UV or IR Differential Optical Absorption Spectroscopy (DOAS), mass spectroscopy (MS) or wet chemistry absorption). Instruments and measure techniques which are in a prototype phase or will not be covered in this report.

6.2.1 Non-Dispersive Ultra-Violet analysis (NDUV)

Non-Dispersive Ultra-Violet analysis is an absorption spectroscopy technique used for gas analysis of e.g. NO and NO_2. The sample gas is continuously passed through a measurement cell where the gas molecules are exposed to UV-light. Different molecules absorb different wavelengths. In the measurement cell, and the corresponding signal after passing the cell is collected with a detector. The absorption of light in the cell is proportional to the given gas concentration. The NDUV technique has less cross sensitivity to water vapor and CO_2 compared to absorption in IR-region. Table 2 shows an example of a suitable instrument for measurement of NO_X from engine exhaust from Euro V and Euro VI heavy duty vehicles. For measurement range, weight, size etc. please refer to Table 9. However, the SEMTECH-instrument is not portable which makes it less suitable for PTI test drives with a loaded engine performance and with a sufficiently warm SCR system.

[2] Other measure methods may be applied if certified accordingly (ex. TESTO 350 MARITIM).

The specific instrument is more suitable for stationary sampling of NO_X unless the PEMS version is taken into consideration. PEMS equipment designed for real driving emission test is considered in this report.

Table 2. Examples of commercially available equipment for emission monitoring of NO_X from after treatment of exhaust gas from internal combustion engines.

Parameter	Instrument	Manufacturer	Measurement principle	Comments
NO_X (NO and NO_2 are measured from two separate wavelengths)	SEMTECH-NO_X	Sensors Inc.	Non-Dispersive Ultraviolet monitor (NDUV)	Generally, not portable. Model available for real driving emission test (PEMS). Available measurement ranges are suitable for testing of Euro V and Euro VI heavy duty vehicles. The instrument is less suitable for PTI test drives.

6.2.2 Chemiluminescence (CLD)

Chemiluminescence (CLD) is based on the production of light from a chemical reaction. Two chemicals react to form an excited (high-energy) intermediate, which breaks down releasing some of its energy as photons. CLD for NO_X analyses involves the reaction between NO and ozone (O_3) to form NO_2 plus O_2 and a photon (light):

$$\mathrm{NO} + \mathrm{O_3} \rightarrow \mathrm{NO_2} + \mathrm{O_2} + \mathrm{photon}$$

The intensity of the light emitted is proportional to the mass flow rate of NO into the reaction chamber and can be measured with high sensitivity using a photomultiplier tube. This therefore represents the basis for a sensitive, quantitative analysis of gaseous NO. An ozone generator provides the necessary O_3 through a stream of externally provided oxygen (22). A linear output allows for more precise measurement of low concentrations.

The NO_X-concentration is measured with CLD monitor by sampling a partial flow of flue gas, free of particles into the reaction chamber. Selected monitors can monitor both NO_X, NO_2 and NO by having two measurement channels, however most often only one measurement channel is used. Sample gas is passed through a built-in converter (convert NO_2 to NO) into the measurement cell as only NO will react with O_3. As all NO_2 is converted to NO before entering the measurement cell, measured values are given as NO_X (NO + NO_2). In some instruments it is possible to toggle the sample gas between measurement of NO or NO_X (bypass of converter) which makes it possible to determine the NO_2 concentration as the difference between the NO_X and NO measured values.

Table 3 shows an example of a suitable commercially available instruments for measurement of NO_X from engine exhaust. For measurement range, weight, size etc. please refer to Table 9. The CLD50 is expected to be commercially available in 2021. The CLD500 instrument have been tested on city buses during test drive (18). An extended version of the instrument that also includes NO_2 monitoring is under development. The PG 300 from Horiba is currently used for environmental inspection of buses in Denmark (section 6.1) and has proven its stability during test drives (14). The CLD is recommended as suitable method for NO_X emission of from diesel exhaust.

Table 3. Examples of commercially available equipment for emission monitoring of NO_X from after treatment of exhaust gas from internal combustion engines.

Parameter	Instrument	Manufacturer	Measurement principle	Comments
NO_X	PG 300	Horiba Ltd.	Chemilumines-cence (CLD)	Portable multicomponent gas monitor.
NO_X (CLD500) NO (CLD50)	CLD500 and CLD50	Cambustion Ltd.	Chemilumines-cence (CLD)	The CLD500 is a semi-portable NO_X monitor. A new portable in-strument (CLD50), will later in 2021 be commercially available. An extended version of CLD50 that also includes NO_2 is under development. Available measurement ranges are suitable for testing of Euro V and Euro VI heavy duty vehicles.

6.2.3 Electrochemical sensors (ES)

Electrochemical gas sensors (ES) are gas detectors that measure the concentration of a specific gas by oxidizing or reducing the gas at a working electrode. Based on Nernst law for electrochemical reactions, the resulting current is measured between the counter electrode and the working electrode which are separated by an electrolyte. Often the sensors also include a reference electrode to correct the signal. The magnitude of the current is controlled by how much of the target gas is oxidized at the working electrode and the concentration is linearly proportional to the gas concentration. A linear output allows for more precise measurement of low concentrations and much simpler calibration.

The electrochemical reactions will degrade the electrolyte over time which will reduce the signal depending on applied concentrations and use. This will require a more frequent calibration or control of the sensor if a quantitative result is needed. Furthermore, electrochemical sensors are generally more sensitive to cross interference from other type of gasses compared to NDUV or CLD. The signal from some electrochemical sensors will also vary with fluctuations in temperature.

Electrochemical sensors are now becoming more frequently used in portable instruments due to their light weight and low cost. Table 4 lists examples of instruments with an electrochemical sensor for NO_X measurements. For measurement range, weight, size etc. please refer to Table 9. In order to measure NO_X concentrations, two electrochemical sensors are needed (NO and NO_2). Some of the instruments in Table 4 only measure NO as only one electrochemical sensor is applied.

High temperature electrochemical ceramic NO_X sensors are often used to control the NO_X emission over a SCR catalyst. These ceramic NO_X sensors are widely used in the car industry. The ceramic electrolyte requires high temperature in order to have a sufficient transport of ions across the electrolyte. The sensors are relative robust and designed to work under harsh conditions in a hot and wet exhaust gas. The high temperature results in a relative high power consumption compared to low temperature electrochemical sensors. Electrochemical ceramic NO_X sensors of the type used for SCR systems is therefore not used much in commercially available NO_X analysers for portable applications.

Most of the instruments based on the EC measurement principle are designed for us in workshops. Many of them are portable. EC measurements are not much used in scientific publications. There is a general lack of literature where portable 4/5-gas testers have been used to monitor of tailpipe emissions during test drives. An exception is the environmental inspection of buses in Denmark (section 6.1) where it previously have been allowed to use the portable 4/5-gas tester for tailpipe emission during test drive (23). In terms of nitrogen oxides, only NO where measured.

Table 4. Examples of commercially available equipment for emission monitoring of NO_X from after treatment of exhaust gas from internal combustion engines. Available measurement ranges are suitable for testing of Euro V and Euro VI heavy duty vehicles.

Parameter	Instrument	Manufacturer	Measurement principle	Comments
NO_X (two separate sensors, NO and NO_2)	TESTO 350	TESTO Inc.	Electrochemical sensors (ES)	Portable multicomponent gas monitor. Relative high response time, which does not make it suitable for transient testing during PTI.
NO_X (two separate sensors, NO and NO_2)	Infralyt N	Saxon-Junkalor GmbH	Electrochemical sensors (ES)	Semi-portable multicomponent gas monitor.
NO	Infralyt Smart	Saxon-Junkalor GmbH	Electrochemical sensor (ES)	Portable multicomponent gas monitor.
NO_X (two separate sensors, NO and NO_2)	MET 6.1	MAHA GmbH	Electrochemical sensors (ES)	Portable 4/5-gas tester. Multicomponent gas monitor.
NO	BAE 060	Bosch GmbH	Electrochemical sensors (ES)	Portable 4/5-gas tester. Multicomponent gas monitor.
NO_X (two separate sensors, NO and NO_2)	parSYNC PTI	3DATX	Electrochemical sensors (ES)	Portable multicomponent gas monitor.

The parSYNC PTI has been demonstrated during test drives on vehicles (light duty and heavy duty) (24) (25) and is currently being tested in Sweden by Opus Bilprovning AB (25). Results of these test are not yet available.

Instruments with electrochemical sensors for measurements of NO_X can be used for tailpipe emission measurements of NO_X during test drives with heavy duty vehicles. For measurement of NO_X, instruments that only measure NO is not recommended for PTI testing. The response time (T90 <40 sec) of the Testo 350 (see Table 9, Annex A) is somewhat higher than the other ES based instruments. If the Testo 350 should be used for transient testing during PTI, it should be demonstrated that the actual response time is suitable for the test requirements and setup.

Careful considerations should be taken regarding specifications of the frequency of intervals where a test gas is applied to verify and inspect drift and gain of the instrument. Heated sample lines are also recommended in order to avoid condensation of water vapor and potential losses of NO_2 as latter is highly soluble in water.

6.2.4 Fourier Transformed Infrared Spectroscopy (FTIR)

Fourier Transformed Infrared Spectroscopy (FTIR) is a measurement technique where a portion of sample gas is analysed for many gas components simultaneously.

A partial flow of the exhaust gas is led through a sample cell. There it is radiated with polychromatic light covering a specific part of the infrared (IR) region (typically 900 – 4000 cm^{-1}). The source radiation is modulated by a Michelson interferometer and all optical frequencies are recorded simultaneously in the measured interferogram. This allows the measurement of a number of different gas species simultaneously.

Molecules in a gas phase vibrate and rotate at frequencies characteristic to each molecule. Each frequency is associated with an energy state of a molecule. Infrared radiation moves the molecules to higher energy states and characteristic frequencies are absorbed by the molecule in the process. This results in an IR absorption spectrum which is unique to each molecule except for diatomic elements such as O_2, N_2 or noble gasses which do not absorb in the IR region. The absorbance is directly proportional to concentration according to Beer's law. The cost for FTIR gas analysers is however relative high compared to other kind of NO_X-analysers described in section 6.2.1 - 6.2.3. However, the instrument is only semi-portable which makes it less suitable for PTI test drives with a loaded engine performance and with a sufficiently warm SCR system. To our knowledge FTIR analyzers are not used for monitoring of emission during a test drive.

Table 5. Example of commercially available equipment for emission monitoring of NO_X from after treatment of exhaust gas from internal combustion engines.

Parameter	Instrument	Manufacturer	Measurement principle	Comments
NO_X (NO and NO_2 are measured at two separate wavelengths)	DX4000	Gasmet Technologies Oy	Fourie Trans-formed Infrared Spectroscopy (FTIR)	Semi-portable multicomponent gas monitor. Available measurement ranges are suitable for testing of Euro V and Euro VI heavy duty vehicles. The instrument is less suitable for PTI test drives due to weight, size potential warm-up time.

7 Methodology for alternative inspection of DPF during PTI

7.1 Emission test at loaded and unloaded engine conditions

In Switzerland, PN emission testing of DPF are conducted at high idle (approx. 2000 rpm) on non-road diesel vehicles. The test is a supplement to the traditional opacity measurements. Free acceleration to high idle is performed three times in periods of 10 seconds each. The particle concentration is measured as the average PN concentration within each of the 10 seconds. Limit values for PN concentration are $2.5 \cdot 10^5$ $1/cm^3$. Some vehicles may be tested at low idle due to technical limitations and the concentration limits are then adjusted accordingly. Until now, only two instruments have been approved for such measurements - namely NPET from TSI and HEPaC, an instrument developed by Institut für Sensorik und Elektronik, Switzerland. Further technical specifications on the instruments can be found in Annex A.

The Netherlands have recently incorporated PN emission testing for inspection of DPF on diesel vehicles. The test method will become effective from July 2022 (26) (27). The test is performed as an unloaded test at low idle. The test starts with a period of 15 seconds in order to wait for the measurements to stabilize. Then measurements are then performed over a period of 15 seconds. Limit values for particle number concentration are $2.5 \cdot 10^5$ 1/cm^3 for diesel vehicle registered after 2015 and 10^6 1/cm^3 for diesel vehicle registered before 2015.

A similar approach has been debated in Germany concerning implementing PN concentration measurements for PTI of diesel vehicles. In Germany, all instruments for PN measurements to be used for PTI must be certified by the Physikalisch-Technische Bundesanstalt (PTB). A study from PTB is expected to be finished in 2021. Any official procedural changes in the inspection of DPF in Germany will presumably not be ready before 2023 (28).

An alternative emission test of faulty diesel particle filters has been done on city buses in Denmark since 2019. The test (EIB) is done together with test of NO_X-emissions for SCR inspection (see chapter 6). The test is done under loaded engine conditions. Particle emission measurements (PN and PM) is performed with measurement instruments based on charge diffusion and results are reported at reference conditions (10% CO_2). Table 6 show an overview of the specification for particle measurements. For further information regarding test cycles can be found in chapter 6.

In summary, inspection for PN emission from heavy duty vehicles can be done on an unloaded engine test at low or high idle. It is recommended that the approach of PN measurements used in the Netherlands and Switzerland is followed closely in preparation for a possible introduction of the inspection method in other countries. Equipment, instrumentation and test cycles for inspection of DPF are, however highly defined by national authorities and a future task could be to regulate and standardise the different approach to PTI inspection across the European Union.

Table 6. Specifications of the instrument for particle emission measurements during EIB in Denmark.

Parameter	PM	PN
Unit	mg/m^3 (wet) Reference conditions (10% CO_2)	1/cm^3 (wet) Reference conditions (10% CO_2)
Particle size	≥23 nm	
Range	0 - 50 mg/m^3	10^4 - 10^9 1/cm^3
Resolution	0.001 mg/m^3	10^3 1/cm^3
Comments	The instrument must be heated as well as the sample line.	

7.2 Emission monitoring equipment for PN measurements

In general, principles for particle number concentration measurement can be described in two categories: Condensation particle Counters (CPC) and Charge Diffusion (or diffusion charging). The two types of measurement principles are briefly discussed in section 7.2.1 and section 7.2.2.

Earlier studies (29) have tested several prototypes and commercially available instruments for PN monitoring. Technical specifications of commercially available instruments for direct PN monitoring in engine exhaust (certified or tested against reference instruments) can be found in Table 10, Annex A. All instruments are found scalable for PTI in terms of both portability (size and weight) and ease of operation. However, Mi3 from Pegasor is less portable in terms of weight. This might limit the instrument to measurements at stationary conditions. However, since particle number measurements can be done at stationary condition, the size and weight of instruments for PN concentration measurements is less important.

7.2.1 Condensation Particle Counter (CPC)

A condensation particle counter or CPC is a particle counter that detects and counts aerosol particles. This is done by introducing a partial flow of the exhaust gas through a super saturated zone with e.g. butanol. The butanol will then condensate onto the particles using the particles as nucleation centers. This will enlarge the particles and make it possible to count them optically by passing them through measurement cell with a laser beam and a light detector. Table 7 shows an example of a possible CPC instruments that can be used for PN measurements in engine exhausts. The NPET from TSI are currently certified for PN concentration measurements in Switzerland.

Table 7. Examples of commercially available equipment for emission monitoring of particles from after treatment of exhaust gas from internal combustion engines.

Parameter	Instrument	Manufacturer	Measurement principle	Comments
PN	NPET	TSI Inc.	Condensation Particle Counter (CPC)	Portable
PN	APB	Sensors Inc.	Condensation Particle Counter (CPC)	Portable

Both instruments shown in Table 7 may be suitable for particle number concentration measurements of tailpipe emission.

7.2.2 Charge Diffusion (CD)

Charge diffusion or diffusion charging is a technique where a partial gas stream is lead through a corona charger which electrically charges particles/aerosols. An electrometer then counts the number of particles through measurement of the charge or induced charge of the particles. The signal is converted to a particle number concentration by the instrument software. The technique does not require a liquid to make the particles grow which is why many portable instruments are based on the measurement principle of charge diffusion.

Table 8 shows an example of possible instruments that are based on charge diffusion and can be used for PN measurements from exhaust gasses of vehicles. Some instruments (ex. Mi3) are heated and uses a heated sample line in order to avoid condensation of water and to remove semi-volatiles compounds. Other instruments (ex. HEPaC) uses an unheated sample line but heat up part of the instrument instead. Further technical specification on instruments in Table 8 can be found in Annex A. Some of the instruments calculate the particle mass (PM) concentration simultaneously through an algorithm using an assumed soot density.

Table 8. Examples of commercially available equipment for emission monitoring of particles from after treatment of exhaust gas from internal combustion engines.

Parameter	Instrument	Manufacturer	Measurement principle	Comments
PN	HEPaC	Institut für Sensorik und Elektronik	Charge diffusion	Portable (handheld instrument)
PN	Mi3*	Pegasor Oy	Charge diffusion	Semi-portable
PN	CAP3070	Capelec	Charge diffusion	Portable
PN	TEN AEM	Test Equipment Nederland B.V.	Charge diffusion	Portable
PN	parSYNC PTI**	3DATX	Ionization/opacity/ scattering	Portable

*particulate matter (PM) in mass (mg/m^3) is also calculated from instrument software.

** particulate matter (PM) in mass (mg/m^3) is also measured in some instrument configurations.

The instrument from 3DATX work somewhere different from the measure principles of charge diffusion. Particle measurements are done by a combination of three sensor techniques: Ionization of particles, opacity measurements and optical scattering. The signal from all three sensors are combined in a software algorithm and converted to a particle number concentration. For fine particle concentration counting ionization is the main sensor application. Good comparable results have been shown with e.g. PEMS measurements (30) (31). In 2021 Opus Bilprovning AB will perform a field test in Sweden with the instrument from 3DATX (25).

All instruments in Table 8 are found scalable for PTI in terms of both portability (size and weight) and ease of operation. Only, Mi3 from Pegasor is less portable in terms of weight. However, since particle number measurements can be done at stationary conditions, the size and weight of instruments for PN concentration measurements is less important.

8 Status on PTI in selected European countries

Competent authorities or private companies with relevant knowledge within PTI were in this study contacted in selected European countries to establish the latest information on PTI of emission-controlled systems. A special focus was given to matters related to control and inspection of after treatment systems of emissions (SCR, DPF) on heavy duty vehicles. Section 8.1 - 8.9 summarizes the information from each country regarding alternative methods for inspection of the emission reducing systems in diesel vehicles.

8.1 Norway

Statens Vegvesen in Norway informs that diesel vehicles are tested with OBD during PTI together with a visual inspection of the emission reducing systems. If the OBD indicates a faulty emission-controlled systems, opacity measurements may be applied. No additional test is performed to inspect or measure direct NO_X-emissions from SCR other that visual inspection.

8.2 Sweden

The Swedish road authorities, Transportstyrelsen informs that Sweden follows the PTI Directive 2014/45/EU regarding emission control of heavy duty diesel vehicles. No additional test is performed to inspect or measure direct NO_X-emissions from SCR other than visual inspection. No alternative control methods for inspection of DPF is about to be incorporated into PTI of heavy duty vehicles. However, a new field test of equipment for measurements for NO_X and PN during PTI is about to be initiated I 2021 by Opus Bilprovning AB (25).

8.3 Finland

The Finnish Transport and Communications Agency (Traficom) informs that Finland follows the PTI Directive 2014/45/EU regarding emission control of heavy duty diesel vehicles. No additional test is performed to inspect or measure direct NO_X-emissions from SCR other that visual inspection. Previously Finland made an internal study regarding NO_X tampering on trucks to gather information about the subject, however the information is not public.

8.4 Germany

Germany is currently following the PTI Directive 2014/45/EU regarding emission control of heavy duty diesel vehicles. TÜV Nord Mobility informs that Germany are working on incorporating measurements of PN concentration for inspection of DPF during periodic Inspection. All instruments for particle number measurements must be certified by the Physikalisch-Technische Bundesanstalt (PTB). The study from PTB is not available yet, however it is expected to finish during 2021. Any official changes in the procedure for inspection of DPF will presumably not be ready before 2023. It has not been possible during this study to clarify whether the new test method will incorporate light duty or heavy duty vehicles, or both.

8.5 The Netherlands

The Netherlands follow the PTI Directive 2014/45/EU. However, from July 2022 a new test method will be introduced for inspection of DPF during PTI. Measurements of PN concentration will be implemented. The test cycle is described in section 7.1. All instruments for PN measurements must be certified by Netherlands Meetinstituut (NMI). The Netherlands have currently no plans for incorporation of additional tests to measure direct NO_X-emissions from SCR systems. NO_X reducing systems are inspected visually.

8.6 France

Capelec, the French manufacturer of test equipment for PIT has participated in projects regarding tailpipe emissions of NO_X and particles (11) (13). Capelec informs that France follow the PTI Directive 2014/45/EU. Diesel vehicles are tested for opacity during fast idle. No additional test is performed to inspect or measure direct NO_X-emissions from SCR other that visual inspection.

8.7 Austria

AVL, the Austrian manufacturer of test equipment, has participated in projects regarding tailpipe emissions of NO_X (13). AVL informs that Austria follow the PTI Directive 2014/45/EU. Diesel vehicles are tested for opacity during fast idle. No additional test is performed to inspect or measure direct NO_X-emissions from SCR other that visual inspection.

8.8 Switzerland

The Federal Department of the Environment, Transport and Communication (DETEC) in Switzerland informs that measurements of PN have been implemented as an alternative approach to inspecting faulty DPF in non-road vehicles. Traditional opacity measurements are still allowed and still widely used for inspection in Switzerland. Equipment for measuring PN has to be certified by the Swiss Federal Institute of Metrology (METAS) according to the protocol for Swiss regulation SR 941.242 (32). Until now, two instruments have been approved for such measurements: NPET from TSI and HEPaC, a local Swiss developed instrument from Institut für Sensorik und Elektronik. It is expected that more instruments for periodic testing will be certified in 2021. Actions are being taken to use PN measurements for periodic testing of light duty and heavy duty vehicles. Inspection with PN measurements will only include vehicles, where PN concentration is included in their type approval (Euro 5b, Euro 5 and Euro 6, Euro VI). The Swiss Federal Office for the Roads (FEDRO) who is in charge for the road vehicles, consider incorporating PN measurements for periodic inspection in 2023 the earliest.

8.9 England

The English road traffic authorities, Driver & Vehicle Standard Agency in England, informs that England follows the PTI Directive 2014/45/EU regarding emission control of heavy duty diesel vehicles. Besides from visual inspection, no additional test is performed to inspect or measure direct NO_X-emissions from SCR. No alternative control methods for inspection of DPF is about to be incorporated into PTI of heavy duty vehicles. England follows the development in other European countries regarding alternative ways to inspect the emission reducing systems on heavy duty diesel vehicles.

9 Summary and conclusions

This study shows that action is being taken to find alternative ways for PTI inspection of emission reducing systems installed on diesel vehicles.

Inspection of NO_X-reducing systems requires a loaded engine test cycle to identify faulty equipment. The test must be done on a chassis-dynometer or during a short test drive. Available commercial instruments for measurements of NO_X are based on five different methods of measurements: NDUV, CLD, ES and FTIR. All instrumentation described in this report are commercially available and found scalable for PTI. Instruments applicable for test drives need however to be portable. Here, FTIR and NDUV instruments seems more suitable for stationary tests on a chassis-dynometer due to size and weight.

The instrumentation found for NO_X measurements can be used for testing of both Euro V and Euro VI vehicles. Based on our experience with vehicle emission testing, and on literature and instrument manuals, it is our assessment that all the listed NO_X monitors are relatively easy to operate and suitable for PTI.

Inspection of DPF during PTI can be done at either loaded or unloaded engine conditions. Switzerland and in particular the Netherlands have come relatively far in their efforts to incorporate a new method for inspection of DPF: PN concentration measurements will be used to inspect DPF during an unloaded engine test at PTI from July 2022 in the Netherlands. There are several instruments available for measuring PN emissions from combustion engines. Most of the available commercial instruments for measurement of PN are based on CPC or CD techniques. It should be noted that the use of equipment, instrumentation, and test cycles for inspection of DPF is defined by national authorities. There seems to be a need for harmonization of the regulation of and approach to PTI inspection across the European Union.

With a few exceptions, where weight or portability might limit the instruments for measurements at stationary conditions, we conclude that all the listed instruments are scalable for PTI in terms for portability (size and weight) and ease of operation. This is concluded for both NO_X test with loaded engine conditions, and for PN measurement with unloaded engine conditions.

Selected European countries have been contacted to establish the latest information on PTI for inspection of emissions (NO_X and PN) from the emission reducing system on heavy duty vehicles. No countries have incorporated or established a protocol for NO_X emission measurements and control/inspection of SCR. In Denmark, emission measurements may be requested on city buses by the regional public transportation companies. The emission test is not established under Danish law but is a supplement that public transportation companies can request from the bus operator if such an agreement is part of their mutual contract. The emission measurements involve a direct measurement of e.g. NO_X and particles during a short driving cycle.

The Netherlands have recently incorporated PN emission testing for inspection of DPF on diesel vehicles. The test method will become effective from July 2022. Limit values for particle number concentration are $2.5 \cdot 10^5$ 1/cm^3 for diesel vehicles registered after 2015 and 10^6 1/cm^3 for diesel vehicle registered before 2015. A similar approach has been debated in Germany in order to implement PN concentration measurements in PTI of diesel vehicles.

In Switzerland, PN emission testing of DPF are conducted at high idle and the test is a supplement to the traditional opacity measurements. The test applies currently only for non-road diesel vehicles but is expected to be expanded to road traffic in future.

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Annex A

Technical specifications

Table 9 and Table 10 list a selection of instruments for measuring of NO_X, NO/NO_2 and PN. All instruments are easy to operate or presumable easy to operate based on literature (manuals etc.). For some application there are several types of instruments on the marked that can fullfill the requirements for testing ex. traditional 4/5-gas testers. Some of the instruments listed in Table 9 and Table 10 are mentioned in this report and others are listed as examples of equipment for emission monitoring from combustion engines during PTI.

Table 9. Technical specifications of selected instruments for measuring of NO_X or NO/NO_2.

Equipment model	Measurement principle	Measurement range[f] [ppm]	Response time[e] (T90) [sec]	Resolution [ppm]	Logging frequency [Hz]	Calibration interval	Size [cm]	Weight [kg]
SEMTECH-NO_X	NDUV	NO: 0 – 3000 NO_2: 0 – 500	<10	0.3	≥5	Depending on use and customer	44 x 31 x 14	14
PG 300	CLD	NO_X: 0 – 2500	<45[g]	1	≥1	Depending on use and customer	30 x 52 x 26	<15
CLD500	CLD	NO_X: 0 – 5000	<1	Information not available	≥1	Depending on use and customer	45 x 37 x 13	<15
TESTO 350	ES	NO: 0 –4000 NO_2: 0 - 500	<40	1 - 0.1	≥1	Annually or depending on use	33 x 13 x 44	<5
Infralyt N	ES	NO: 0 – 2500 NO_2: 0 - 500	<5	1	Information not available	Every 3 months or depending on use	21 x 42 x 27	11
Infralyt smart[b]	ES	NO: 0 – 5000	<5	1	Information not available	Every 3 months or depending on use	16 x 33 x 20	<7
MET 6.1	ES	NO_X: 0 – 5000 ($NO + NO_2$)	Information not available	1	Information not available	Every 6 – 12 months	41 x 23 x 16	5
BEA 060	ES	NO: 0 – 5000	Information not available	1	Information not available	Every 3 months or depending on use	41 x 33 x 28	<10
DiTest Gas	ES	NO_X: 0 – 5000	<10[c]	1	Information not available	Annually or depending on use	27 x 32 x 9[d]	<3[d]
parSYNC PTI	ES	NO: 0 – 3000 NO_2: 0 – 500	NO: <5 NO_2 <15	NO: 1 – 2 NO_2: 0.1	≥1	Annually or depending on use	27 x 22 x 13	4

[a] It is generally recommended that a control/test gas is applied frequently or on daily basis to account for possible sensor drift.
[b] Different models are available.
[c] Response time (T95).
[d] May need to be installed in a portable case which will increase dimensions and weight.
[e] Without sample line.
[f] Different ranges may be available for each instrument.
[g] In-house response time test of PG-300 by FORCE Technology shows T90<20 sec and T10–T90<10 sec (test gas: 1000 ppm). The response time of <45 sec is specified in Horiba's technical documentation.

Table 10. Technical specifications of selected instruments for measuring of PN.

Equipment	Measurement principle	Measurement range [1/cm^3]	Response time (T90) [sec]	Resolution [1/cm^3]	Logging frequency [Hz]	Calibration interval	Size [cm]	Weight [kg]
NPET	CPC	$10^3 – 5{\cdot}10^6$	8	10^3	1	Depending on use and customer	26 x 33 x 57	13
APB	CPC	$0 - 6{\cdot}10^5$ $0 – 5{\cdot}10^6$ (diluter)	Information not available	1	1	Information not available	16 x 10 x 21	2
HEPaC	CD	$10^3 – 5{\cdot}10^6$	5	10^3	1	Annually or depending on use	9 x 14 x 3	0.5
Mi3	CD	$6{\cdot}10^2 – 1.3{\cdot}10^9$	Information not available for the entire system. However, the response time on the sensor itself is 0.2 sec	10^3	1	Depending on use and customer	72 x 50 x 24	30
CAP3070	CD	$5{\cdot}10^3 – 10^6$	<7[a]	10^3	1	Annually or depending on use	50 x 30 x 20	7
TEN AEM	CD	$5{\cdot}10^3 – 5{\cdot}10^6$	<15	Information not available	2	Information not available	Information not available	8
parSYNC PTI	Ionization/opacity/scattering	$2{\cdot}10^4 – 1.6{\cdot}10^7$	Information not available	$2{\cdot}10^4$	1	Information not available	27 x 22 x 13	4

[a] Response time (T95)

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