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TNO report

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Real-world emissions of non-road mobile machinery

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Samenvatting

Mobiele werktuigen en stationaire bronnen worden hoofdzakelijk door dieselmotoren aangedreven en dragen daardoor bij aan opwarming van de aarde, luchtvervuiling en stikstofdepositie. Over het algemeen is maar heel weinig bekend over de praktijkuitstoot van mobiele werktuigen en stationaire bronnen op bijvoorbeeld bouwplaatsen. Daarnaast is er ook maar weinig bekend over de inzet van deze machines. In opdracht van het Ministerie van Infrastructuur en Waterstaat heeft TNO daarom een emissiemeetprogramma uitgevoerd aan een selectie mobiele werktuigen en stationaire bronnen, zoals graafmachines, laadschoppen, pompen, generatoren en een koelaggregaat voor wegtransport.

De gegevens die worden verzameld in meetprogramma's vormen de basis voor de vaststelling van de officiële getallen voor praktijkemissies – de zogenaamde emissiefactoren – die TNO jaarlijks oplevert. Emissiefactoren worden gebruikt op landelijk, regionaal en gemeentelijk niveau als input voor rekenmodellen voor luchtkwaliteit, emissieverspreiding en stikstofdepositie (EMMA en AERIUS), en voor de beoordeling van huidig en voorgenomen beleid. Deze getallen vormen tevens de basis voor de nationale en internationale rapportages over de emissies (ER rapportages en GCN/GDN).

Er zijn langdurige praktijkmetingen verricht om inzicht te krijgen in de emissies en het gebruik van de machines tijdens hun dagelijkse inzet. De metingen zijn gedaan aan een aantal zware bouwmachines, maar ook aan lichtere machines zoals een minigraver en een koelaggregaat zoals gebruikt in de transportkoeling. Daarnaast zijn ook verkennende metingen verricht aan stationaire bronnen zoals pompen en aggregaten. De werktuigen en machines voor het meetprogramma zijn geselecteerd uit werktuigparken van Nederlandse ondernemingen en zijn doorgemeten in de praktijkinzet zoals op bouwplaatsen.

Zware mobiele werktuigen
Resultaat van het onderzoek is dat de doorgemeten grote Stage IV en V mobiele werktuigen (motorvermogen 56 - 560 kW) qua emissieniveaus een positief beeld laten zien; de metingen laten zien dat door inzet van Stage IV en V motoren voor zwaardere werktuigen de NO_x-uitstoot in de praktijk fors kan afnemen van 2,8 tot 4,9 g/kWh voor Stage IIIB tot zo'n 0,8 en 0,5 g/kWh voor Stage IV en V.
Met aanpassing van het gedrag van de machinist (motor afzetten) kan de NO_x-uitstoot in de praktijk nog zo'n 30% extra afnemen. Met waardes van 0,5 tot 0,8 g/kWh ligt de NO_x-uitstoot van de doorgemeten Stage IV en V werktuigen in de praktijk nog wel boven de limiet voor de Stage IV en V norm (0,4 g/kWh) die geldt voor een officiële motortest.

De ammoniakslip, die op kan treden bij Stage IV en V machines met een SCR (Selective Catalytic Reduction) systeem, is laag met gemiddelde ammoniakconcentraties in de uitlaat van 1 tot 8 ppm. Over een officiële motortest mag voor Stage V de gemiddelde ammoniakconcentratie niet hoger zijn dan 10 ppm.

Lichte mobiele werktuigen
De lichte mobiele werktuigen zijn qua emissies erg vuil, ook de nieuwste.
Voor kleine motoren (vermogen 8 - 56 kW) gelden per saldo zeer soepele emissie-eisen voor NO_x, inclusief Stage V, waardoor de NO_x-uitstoot hoog is. Zo stoot een Stage V mini-graver (18,5 kW) ongeveer net zo veel NO_x uit als een zware Stage IV of V bouwmachine. Ook de fijnstofuitstoot van de mini-graver is hoog omdat ook de emissie-eisen voor fijnstof voor lichte motoren (vermogen < 19 kW) zeer soepel zijn.

Stationaire machines
De doorgemeten stationaire machines (pompen en aggregaten), die aan oude en erg milde emissienormen moesten voldoen, zijn allemaal erg vuil. Pompen en aggregaten maken veelal veel draaiuren en vele vuile bronnen die veel uren draaien stoten samen heel veel uit. Ook hangt het niveau af van de grootte van een machine (maximum vermogen) en het actuele vermogen van een machine.
Een enkel groot aggregaat (770 KW) had tijdens bedrijf een NO_x-uitstoot van 4,1 kg/u en stoot in dit geval net zoveel NO_x uit als ongeveer 100 zware Stage IV/V bouwmachines of 100 Euro VI vrachtwagens.
Twee stationaire machines, één met een stage V motor (>= 56 kW) met af-fabriek SCR en één met een oudere motor met een retrofit SCR waren zeer schoon qua NO_x-uitstoot. Dit suggereert dat de Stage V-limieten voor zwaardere motoren (>= 56 kW) en de gebruikte emissiereductie (SCR) ook effectief kunnen zijn voor stationaire machines.

Koelaggregaat voor een vrachtwagen
De dieselmotor van een koelmachine op een koeltrailer stoot ongeveer 1,5 maal zoveel NO_x en tenminste 10 maal zoveel fijnstof uit als de Euro-VI trekker van de koeltrailer. Hier bovenop komt het effect dat een vrachtauto veelal wordt uitgezet als deze niet rijdt, terwijl een koelaggregaat vaak blijft doordraaien, ook als er niet wordt gereden. Dit maakt de bijdrage van koelaggregaten aan luchtvervuiling nog groter.

In dit onderzoek zijn metingen gedaan aan een beperkt aantal mobiele werktuigen en stationaire bronnen op een bouwplaats. Daarmee is een eerste indicatie gekregen van het niveau van de NO_x- en fijnstofuitstoot in de praktijk.
Meer metingen zijn nodig om een compleet en betrouwbaar beeld te krijgen van de uitstoot van deze erg brede categorie machines.

Summary

Mobile machinery and stationary sources are mainly powered by diesel engines and therefore contribute to global warming, air pollution and nitrogen deposition.
In general, very little is known about the real-world emissions of non-road mobile machinery and stationary sources on, for example, construction sites. In addition, little is known about the use of the aforementioned machines. On behalf of the Ministry of Infrastructure and Water Management, TNO has therefore conducted an emissions measurement program on a selection of non-road mobile machinery, such as excavators, wheel loaders, pumps, generators and a cooling unit for road transport.

The data collected in measurement programs form the basis for determining the official numbers for real-world emissions - the so-called emission factors - that TNO produces annually. Emission factors are used at national, regional and municipal level as input for calculation models for air quality, emission dispersion and nitrogen deposition (EMMA and AERIUS), and for the assessment of current and proposed policy. These numbers also form the basis for the national and international reports on emissions (ER reports and GCN / GDN).

Long-term field measurements were carried out to gain insight into the emissions and the use of the machines during their daily operation. The measurements were carried out on a number of heavy construction machines, but also on lighter machines such as a mini excavator and a cooling unit as used in transport refrigeration. In addition, exploratory measurements were also carried out on stationary sources such as pumps and generators. The machinery for the measurement program have been selected from machinery parks of Dutch companies and have been measured in real-world use, such as on construction sites.

Heavy mobile machinery
The result of the study is that the measured large Stage IV and V mobile machines (power 56 - 560 kW) show a good picture in terms of emission levels:
The measurements show that the use of Stage IV and V for heavier implements can significantly reduce NO_x emissions in the real-world from 2.8 to 4.9 g/kWh for Stage IIIB to around 0.8 and 0.5 g/kWh for Stage IV and V. By adjusting the driver's behaviour (switching off the engine), the NO_x emissions can decrease by about 30% more. With values of 0.5 to 0.8 g/kWh, the NO_x emission of the measured Stage IV and V machinery is in real-world still above the limit for the Stage IV and V standard (0.4 g/kWh) that applies for an official engine test.

The ammonia slip, which can occur on Stage IV and V machines with an SCR (Selective Catalytic Reduction) system, is low with average exhaust ammonia concentrations of 1 to 8 ppm. On an official engine test for Stage V, the average ammonia concentration should not exceed 10 ppm.

Light mobile machinery
The light mobile machinery are very dirty, including the newest ones. For small engines (power 8 - 56 kW), very mild emission requirements for NO_x apply, also for Stage V, which means that NO_x emissions are high. For example, a Stage V mini excavator (18.5 kW) emits about as much NO_x as a heavy Stage IV or V construction machine. The particulate matter (PM) emissions of the mini-excavator are also high, because the emission requirements for PM for light engines (power <19 kW) are very mild.

Stationary machines
The measured stationary machines (pumps and aggregates), which had to meet old and very mild emission standards, are all very dirty. Pumps and generator sets often run for many hours a day. Many dirty sources that run for many hours together emit a lot. The level also depends on the size of a machine (maximum power) and the current power of a machine. A single large generator set (770 kW) had a NO_x emission of 4.1 kg / h during operation and in this case emits about as much NO_x as 100 heavy Stage IV / V construction machines or 100 Euro VI trucks.
Two stationary machines, one with a stage V engine (>= 56 kW) with factory SCR and one with an older engine with a retrofit SCR, were very clean in terms of NO_x emissions. This suggests that the Stage V limits for heavier engines (>= 56 kW) and the emission reduction used (SCR) may also be effective for stationary machines.

Transport cooling unit for a truck
The diesel engine of a refrigeration machine on a truck trailer is 1.5 times as dirty in terms of NO_x emissions and at least 10 times as dirty for particulate matter as the Euro-VI truck driving in front of it. On top of this is the effect that a truck is often switched off when it is not moving, while a refrigerated trailer often continues to run, even when it is not being driven. This makes the contribution of refrigerated trailers to air pollution even greater.

In this study, measurements were carried out on a limited number of mobile and stationary machinery on construction sites. This provides a first indication of the level of NO_x and particulate matter emissions in real-world use. More measurements are needed to get a complete and reliable picture of the emissions of this very broad category of machines.

Contents

1 Introduction

1.1 Background

Non-road mobile machinery (NRMM) such as excavators, wheel loaders, tractors and stationary machines such as pumps, generating sets and transport cooling machines today are mainly equipped with diesel engines and make a significant contribution to the emissions of air pollutants (NO_x and particulate matter). Locally, the emissions can lead to European standards for air quality being exceeded and a negative impact on the living environment (health and nitrogen deposition). Running on regular diesel the machines also contribute to global warming.

Non-Road Mobile Machinery (NRMM) is the term used to refer to all machines with a combustion engine that do not fall under the categories of road vehicles, sea-going vessels or aircraft. In addition to construction machines, this group also includes diesel trains, inland vessels and generator sets.

In order to reduce environmental impact, there are European emission standards[1] for NO_x and particulate matter emissions from this group of mobile machines. These requirements apply to the conditions of the type approval test. In terms of emission limits the emissions legislation applicable to NRMM lags behind that regulating emissions of road vehicles. In some categories, the limits are still very mild or have been very mild for a long time until entry into force of Stage V as of 2021. This means that in the coming years the fleet still contains a lot of machinery with diesel engines without emission abatement.

For NRMM there are concerns that the legislation does not adequately cover emissions during normal use and emissions only have been optimized over formal test procedures while in normal use the emissions can increase beyond the level of the applicable limit. During in-service operation, for example on a construction site, the NO_x emission levels may deviate from the standard (Sandström Dahl & Willner, 2015) and (Sandström Dahl & Willner, 2015), (Ligterink, Louman, Buskermolen, & Verbeek, 2018), (Wisell, Jerksjö, Hult, & Lindgren, 2018), (Desouza, Marsh, Beevers, Molden, & Green, 2020). On the one hand, the emission control system can't reach operating temperature when running under conditions with low engine load, on the other hand, such operational conditions often fall outside the limits of the applicable official test.

Also very little is known about the use of this machinery. Some categories such as generating sets and pumps may run continuously. Another complicating factor is tampering or even removal of the emission control systems or parts thereof in order to save on operating costs (van den Meiracker & Vermeulen, 2020). For the machinery there is no periodic inspection. This means that new machines that are put on the market and run for thousands of operating hours over the lifetime are never inspected for proper emissions levels.

[1] DIRECTIVE 97/68/EC, REGULATION (EU) 2016/1628

For the Clean Air Agreement (Schone Lucht Akkoord, SLA), especially for improving local air quality on construction sites and in urban areas.

The Ministry of Infrastructure and Water Management is investigating policy options for further reducing of nitrogen oxides from combustion engines of mobile machines.

Some examples of policy options for reducing nitrogen emissions from combustion engines are:

- Improve EU source policy: tightening of EU standards, in-service or real world emissions testing and monitoring, increasing the durability period, and increase tamper resistance of emission control systems.
- Emission monitoring and periodic inspection: checking the presence and correct operation of the particulate filter and the SCR system. Prevent manipulation of emission control systems (e.g. Adblue killers) by the users, ensure proper maintenance and repair.
- Stimulating the use of clean(er) techniques, for instance in tenders.
- Stimulating proper use of the equipment to reduce the emissions.
- Accelerated replacement of old machines.

Emissions data is needed to substantiate achievable effects of the policy options. However, only few data is available of the usage patterns and the real-world tail pipe emissions of the various categories of non-road mobile machinery. Especially, little is known about emission levels of newer equipment (Stage IV and V) and also little data is available from ‘forgotten sources’, such as generator sets and pumps. Data is also needed for emissions modelling and reporting (ER report, GCN/GDN, AERIUS, EMMA). In order to gain insight into the effectiveness of the various policy options and to obtain data for the various national emission models and pollution dispersion models, it is important that there is a clear picture of the emissions of different types and different generations of mobile machines in actual use.

1.2 Goal and objectives

The goal is to extend the existing small knowledge base of real-world emissions of non-road machinery in the Netherlands and get a first insight in the real-world emissions levels. This is done by measuring the tail pipe NO_x and particulate matter emissions and the usage patterns of a selection of mobile machinery in actual use in the Netherlands, with a focus on newer equipment (Stage IV and V) and the generally underexposed group of stationary machines such as generating sets, pumps and transport cooling units.

1.3 Approach

To obtain the required insight in the real-world emissions of non-road mobile machinery, a measuring program has been defined with two objectives:

1. Mobile machinery long term monitoring: On a number of machines emissions were measured continuously in daily usage, up to several months in time.

For this programme, a Smart Emissions Measurement System (SEMS) was installed in various machines. The selection of machines contains two wheel loaders, (mini-) excavators and a cooling unit on a truck semi-trailer.

2. Stationary machinery spot measurements: On a construction site, spot measurements were done on the stationary machines that were present on the construction site such as generating sets, pumps, a light pole and a drilling rig.

The engines of the machines are certified according various EU emissions standards, from Stage II to V.

The SEMS measures autonomously the emissions of NO_x, O_2, NH_3 and CO_2 and fuel consumption during normal operation of the machines for a period of several weeks up to a few months without interfering the user.

The emissions of generator sets and pumps were measured with a handheld instrument and gravimetric PM measurement were performed by taking samples from the tail pipes of the engines.

1.4 Structure of this report

The methodology of the measuring programme is discussed in chapter 2. The results of the programme are discussed in chapter 3, followed by the conclusions in chapter 4.

2 Methodology

2.1 Programme overview

For this testing programme six machines were selected for long term measurement of NO_x emissions. The machines comprise excavators, a mini excavator, wheel loaders and a cooling unit as used in a semi-trailer for cooling transport over the road. For the equipment, machines were selected with engines certified according EU emission Stages IV and V. The cooling unit uses a Stage II certified engine.

Because little is known about in-use emissions of stationary machinery, such as generator sets and pumps, the second part of the testing programme was executed at a construction site where spot measurements were done on the machines running that day at the site.

An overview of the selected machines is shown in Table 1 below.

Table 1: Overview of the measurement campaigns and machinery. All machinery used diesel engines running EN 590 diesel oil.

Testing programmes	Machinery
1) Long term NO_x, NH_3 and usage measurement and PN measurement on DPF equipped machines	Wheeled excavator, Stage IV
	Excavator, Stage V
	Wheel loader, Stage IV
	Wheel loader, Stage V
	Mini excavator, Stage V
	Trailer cooling unit, Stage II
2) Construction site spot measurements: NO_x, particulate matter	4 Generator sets (19-770kW), Stage II to IIIA
	1 Sewage pump, Stage IIIA
	1 High pressure pump, Stage IIIA
	1 Drilling rig, Stage V
	1 Light pole, Stage II

2.2 SEMS, Smart Emissions Measurement System

SEMS is a sensor-based system developed by TNO [Heijne et al., TNO 2016a] and is used in the programme to measure and analyse the tail-pipe NO_x emissions during daily operation and a range of vehicle/engine parameters to be able to characterize the typical operation of the vehicles. In this way, for the group of vehicles, weeks up to months of data was collected per vehicle. The SEMS uses an automotive NO_x sensor, an ammonia sensor, GPS and a data-acquisition system to record the sensor data and data from the vehicle and engine at a sample rate of 1Hz. The system can operate autonomously and wakes up at ignition/key-on of the vehicle. The system can be stowed away so that normal operation is not hindered by the measurement.
The recorded data is sent hourly to a central data server.

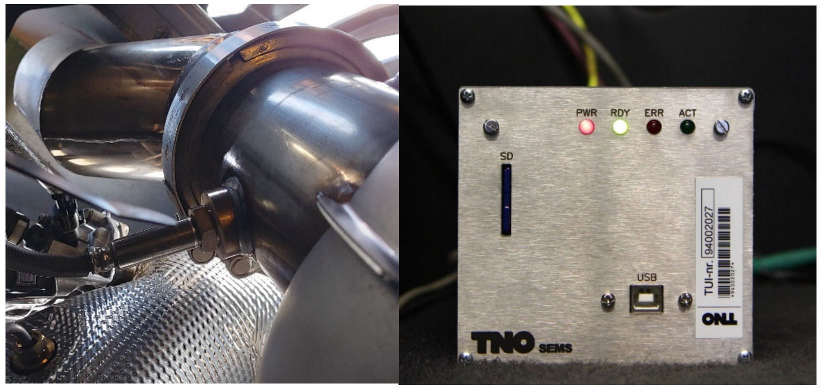

Figure 1: SEMS. Left, calibrated NO_x-O_2 sensor mounted in the tail pipe. Right, autonomously running data recording unit with hourly data transmission to a central server via GPRS.

The raw data on the central server is post-processed automatically to filter and check the data. Sensor output is corrected using sensor specific calibration values. Mass-emissions and instantaneous engine power are calculated combining sensor data (NO_x and O_2 concentration) and engine and vehicle data such as manifold-air pressure, mass air flow, engine speed, fuel rate, engine torque.

Accuracy
The concentration measurements can be converted to absolute mass emissions, using different engine signals available on the CAN bus. When concentration is multiplied with the exhaust gas mass flow, the total mass can be determined. The inlet mass air flow has been the most accurate signal for the purpose. The exhaust air flow requires a minor correction of a few percent for the combustion products. This can be done using the measured oxygen concentration.

In the absence of mass air flow, which was the case for the engines of the machines tested in this programme, there are a number of alternatives to determine the mass air flow. Special care must be taken of the alignment of the concentration signal and the flow signal. Due to a mismatch of the peaks in the concentration with the corresponding flow, uncertainties can arise. Further down the exhaust line the measured concentrations are more smoothened than directly after the engine, which limits this problem somewhat.

Two alternatives methods stand out. Given the inlet air temperature and the pressure, the amount of inlet air can also be determined, using the cylinder volume and engine speed. This turns out to be a stable method to determine the exhaust mass flow. This method was used for the machines tested. For smaller, faster engines, and in the case of high-pressure EGR, this method is less suitable. A second method is a reconstruction of the exhaust mass flow from the CO_2 concentration and the fuel consumption from the CAN bus. The second method shows a large variation, which lead to systematic deviations. The source of the variation is, in part, the erratic fuel consumption itself.

However, the time misalignment of the fuel consumption and the oxygen concentration measurement, is probably also a large source of uncertainty. The third element that may affect the uncertainty and bias of the fuel consumption-based approach is the inherent mathematical uncertainty. A small part of the exhaust gas flow, i.e., a few percent combustion products, is used to reconstruct the remaining 95 % of the flow. Minor measurement errors are therefore magnified.

In the correlation of the two approaches, one sees a large spread in the fuel consumption-based method around the, more stable, speed-density method. The variation is larger than the average, but bounded from below. Consequently, the variation, which is more upwards than downwards, created a bias on the average of about 20 -30 % above the true average. Comparing the sums of the CO_2 emissions from the speed-density method and the recorded fuel consumption, shows, on the other hand, typically 5 % lower fuel consumption from the CAN bus than the independent determination of the fuel consumption, through the speed-density approach. The brake specific CO_2 emissions can be calculated by using the CAN data engine torque and engine speed to calculate the engines work. While broadcasted engine torque and speed are in principle parameters with unknown accuracy these values in combination with fuel consumption indicate a diesel engines efficiency.
The brake specific CO_2 emission of a diesel engine is a rather stable value at medium speed high torque which can vary some 20 % in relation to known engine parameters such as displacement and the presence of turbo.

Large spread in data, and weak correlations, can therefore lead to apparent inconsistent conclusions. When correlating the time-dependent results, the skewed distribution will lead to an overestimation. At the same time independent sum results can lead to the opposite conclusion. Independent validation of the results is therefore essential for the appropriate confidence.

Correlation tests with a reference system with known accuracy is necessary to further investigate possibilities to improve the calculation methods to derive mass emissions using sensor- and CAN based data.

2.3 Testo 350 gas analyser

Instrument	Testo 350
Gases configuration	CO, NO, NO_2, C_xH_y, O_2, CO_2 from O_2
Device nr., Certificate nr.	230400 3506, 2002543

Figure 2: Testo 350 gas analyser used for the measurement of gas concentrations NO, NO_2, O_2, CO, C_xH_y and CO_2 (from O_2) in the exhaust of stationary machines at a construction site.

2.4 Particulate matter

2.4.1 Particle number concentration: NPET, Nanoparticle Emission Tester

Stationary measurements of the tail pipe particle number concentrations are performed on machinery with a diesel particle filter (DPF). The results are used to obtain an indication of the diesel particle filters (DPF) filtration performance. The measurements are conducted during installation of SEMS on the machinery. For the measurements, the particle number (PN) concentration in the tail pipe is measured at idle or stand-by mode with the engine running (600-800 rpm) and at a high constant engine speed (1500-2000 rpm). Additionally, the ambient PN concentration is measured before and after the exhaust measurements. The instrument used is an NPET model 3795 of the manufacturer TSI. The instrument is meant to measure the solid particle number concentration downstream the DPF in diesel exhaust and uses a volatile particle remover to reduce semi-volatile and nucleation mode particles.

Table 2: Specifications of the Nanoparticle Emission Tester, NPET.

Instrument	**NPET**
Model	3795
Range	1,000-5,000,000 1/cm^3
Mode	Semi volatiles and nucleation mode particles are evaporated and oxidized and therefore not counted
Detection efficiency	23nm: <50% 41nm: >50% 80nm: 70-130% 200nm: <200% 30nm C40 droplets: <5%
Response time **10-90%-10%** **0-90%**	 <5 s <10 s

2.4.2 *Particulate matter mass: gravimetric on filter*

Particulate matter mass emissions were measured from the exhaust of the stationary machines on a construction site. Raw exhaust gas or diluted exhaust gas is sampled from the exhaust. A continuous flow controlled by means of mass flow controllers is drawn by a downstream pump through two parallel 40 mm filters, quartz and PTFE. A sample time of about two minutes is used. The loaded filters are conditioned for several days until stable in mass. Mass of the filters is determined before the measurement, during and after conditioning. The difference is the mass of solid particulate matter collected on the given filter medium.

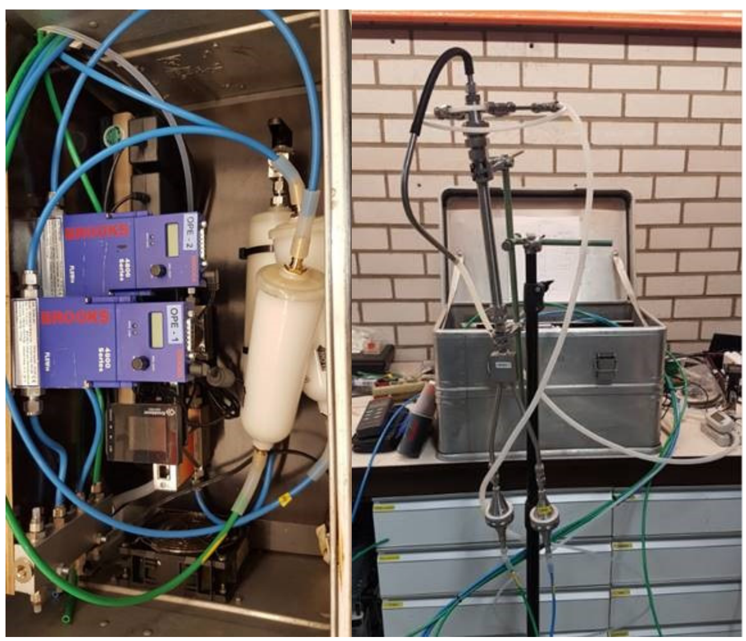

Figure 3: Measurement set up for measurement of particulate matter gravimetrically. Left: mass flow controllers for a stable sample flow and dilution. Right: filter holders.

3 Measurement results

In this chapter the results of the measurements are presented.

3.1 Cooling unit for delivery truck

The cooling unit is a common type seen on refrigerated semi-trailers. The unit offers multi temperature zones. The units internal power source is a Stage II D, 2.1 litre Yanmar diesel engine without emission abatement system.
Stage II D (19 ≤ P < 37 kW) means a NO_x limit of 8 g/kWh and a PM limit of 0.8 g/kWh. These limits haven’t been changed until Stage V which enters into force end of 2021. This means that the in-use fleet of cooling units today still mainly uses Stage II certified engines.

The NO_x emission is 52 g/h, which is about 1.5 times the average NO_x emission of a Euro VI tractor with a 300 kW engine. Based on the assumption that the unit would emit around the Stage II limit value (0.8 g/kWh) and using emission factors for tractors it can be estimated that the PM emission of this cooling unit would at least be 10 times higher than of a 300 kW Euro VI truck engine.

When active, the cooling unit ran on average for about 11 hours a day.
For this engine the actual engine power could not be calculated from CAN bus signals because this bus was not present. The power was modelled from the CO_2 emissions which were fitted to the max. output as provided in the engine specifications and to the minimum output without any load. Still a certain amount of uncertainty remains as the zero load point could not be determined exactly.

During the tests the engine runs most in a low speed, low power setting of about 20 to 30% of the maximum engine load.

TNO test code	**TK_SL**
Brand, type	Thermoking, SLXi spectrum, Engine: Yanmar, TK486V
Configuration	Cooling unit on semi-trailer
Engine power [kW], displacement [l]	25.3, 2.09 l
Emission Stage	II (D)
Emission abatement system	-
TA number	e13*97/68DA*2012/46KA*557*17

Total test period [days], days active [days]	206, 164
Total activity [hours], [hours/day]	1787, 10.9
Average power [%]	22
Stand-by [minutes/hour]	6
NO_x [g/h], [g/kWh]	52, 9.5
Total NO_x [kg]	92
CO_2 [kg/h]	5.9
Total CO_2 [t]	10.6
Fuel consumption [l/h]	2.2

3.2 Stage V mini-excavator

A mini-excavator was hired for a day and typical manoeuvres and work were performed simulating normal operation. Hydraulics propel the machine, lift and tilt the arm and bucket and rotate the cab. The hydraulics in turn are propelled by a 1.5 litre Stage V NRE 2 (8 <= P < 19) 4 cylinder atmospheric diesel engine without emission abatement system. The engines net power lies just below the 19 kW boundary and therefore just falls in Stage V category NRE v/c 2 which has less stringent HC+NO_x limits (7.5 g/kWh) than the Stage II NRE v/c 3 for net power of 19 to 37 kW (4.7 g/kWh). With an easy NO_x limit of 7.5 g/kWh no emissions abatement system is necessary. This explains the relatively high measured brake specific NO_x emissions of this Stage V engine. The Stage V NRE v/c 2 category with easy limits for PM (0.4 g/kWh) and the lack of a PN limit also make that this Stage V engine does not require a diesel particulate filter whereas for the category NRE v/c 3 (19 <= P < 37 kW) a filter would be required to reduce the engines particulate emissions.

TNO test code	**KU_KX**
Brand, type	Kubota, KX-027-4
Configuration	Mini-excavator
Weight [t]	2.6
Engine power [kW], displacement [l]	18.5, 1.498 l
Emission Stage	V (NRE v/c 2)
Emission abatement system	-
Fuel	EN590 diesel
Running hours	1716

Total test period [days], days active [days]	2, 2
Total activity [hours], [hours/day]	8.3, 4.2
Average power [%]	19
Stand-by [minutes/hour]	20
NO_x [g/h], [g/kWh]	36, 10.2
Total NO_x [kg]	0.3
CO_2 [kg/h]	5.8
Total CO_2 [t]	0.05
Fuel consumption [l/h]	2.2

3.3 Stage IV wheeled excavator

The Liebherr A914/916 is a very common excavator. The engine is a Stage IV (R) using 'SCR only' to reduce the NO_x emissions of the diesel engine and uses no diesel particle filter. The Stage IV NO_x limit of 0.4 g/kWh requires the use of SCR. The PM limit of 0.025 g/kWh usually does not require a DPF. The PM level can be kept below that level, when high pressure diesel injection strategy is used and no EGR. For Stage IV, some manufacturers prefer to apply DPF's though.

For this machine no NO_x emissions data is available. The NO_x sensor frequently broadcasted NO_x ready = 0 but this was probably caused by the rapid change of the NO_x or O_2 value which the sensor could not follow (too slow response time). The sensor broadcasted NO_x values in a normal range, however the sensor showed intermittently high and fixed oxygen concentration values of 20.8% when the engine was running under load.

After the measurement system was uninstalled the sensor was checked with calibration gases. The sensor responded to changes in calibration gas concentrations but showed off sets in different directions, i.e. when the concentration of calibration gas was increased, mostly the sensor value also increased but at some occasions also decreased in response to an increased concentration of the calibrations gas. This means that the sensor is broken and that the logged sensor data can't be used for calculating the NO_x emissions.

The activity data that was recorded shows a low average engine power of 10.9%. Although the average power is low, the post SCR temperature measured for this machine indicates that for of the most operation the SCR was at working temperature, roughly above 200 ºC.

TNO test code	**LI_A9**
Brand, type	Liebherr, A914
Configuration	Wheeled excavator
Weight [t]	14,9-16,2t
Engine power [kW], speed [min^{-1}]	105 @1500
Emission Stage	IV (R)
Emission abatement system	SCR
Fuel	EN590 diesel
Running hours	731

Total test period [days], days active [days]	151, 51
Total activity [hours], [hours/day]	272, 5.3
Average power [%]	10.9
Stand-by [minutes/hour]	16
NO_x [g/h], [g/kWh]	Not available due to sensor failure.
Total NO_x [kg]	Not available due to sensor failure.
CO_2 [kg/h]	22
Total CO_2 [t]	5.9
Fuel consumption [l/h]	8.2
Average ammonia slip [ppm]	1

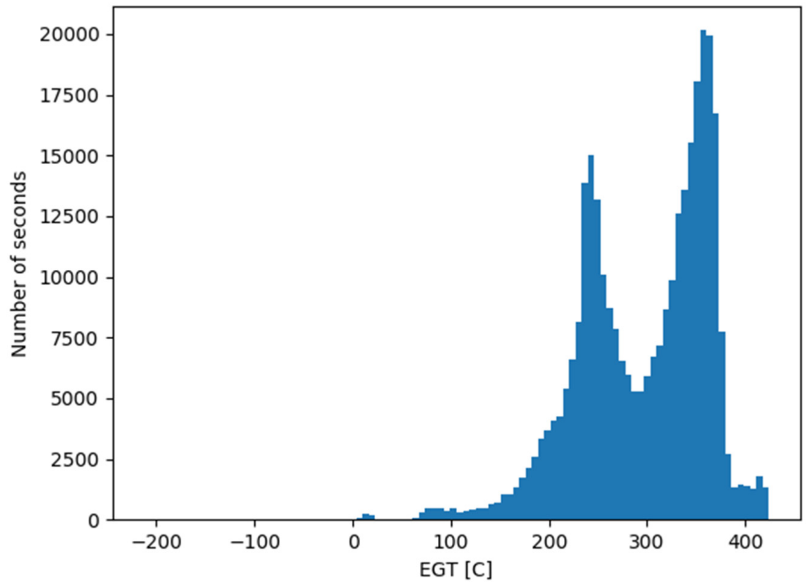

Figure 4: Exhaust gas temperature post SCR. This temperature indicates the working temperature of the SCR which should roughly be above 200 ºC to be able to efficiently reduce NO_x emissions of a diesel engine.

3.4 Stage IV wheel loader

The engine is a Stage IV (R) using EGR and SCR to reduce the NO_x emissions of the diesel engine and as opposed to the Liebherr uses a diesel particle filter to reduce the particulate emissions. 211 hours of data were collected over 28 active days of the machine. About a quarter of the time the machine is in stand-by mode with the engine running, performing no or hardly any work. The post SCR temperatures are mostly above 200 ºC, but still there is a share of the time with lower temperatures, caused by the idling or stand-by mode of the engine running at very low load. This probably explains a large part of the higher NO_x emissions which on average in real-world operation for this machine are about twice the Stage V limit value.

TNO test code	**VO_L7**
Brand, type	Volvo, L70H
Configuration	Wheel loader
Weight [t]	15.5
Engine power [kW]	127
Emission Stage	IV (R)
Emission abatement system	EGR, SCR, DPF
Fuel	EN590 diesel
Running hours	3635

Total test period [days], days active [days]	41, 28
Total activity [hours], [hours/day]	211, 7.5
Average power [%]	35
Stand-by [minutes/hour]	16
NO_x [g/h], [g/kWh]	38, 0.8
Total NO_x [kg]	7.9
CO_2 [kg/h]	44
Total CO_2 [t]	9.3
Fuel consumption [l/h]	16.6
Average ammonia slip [ppm]	6

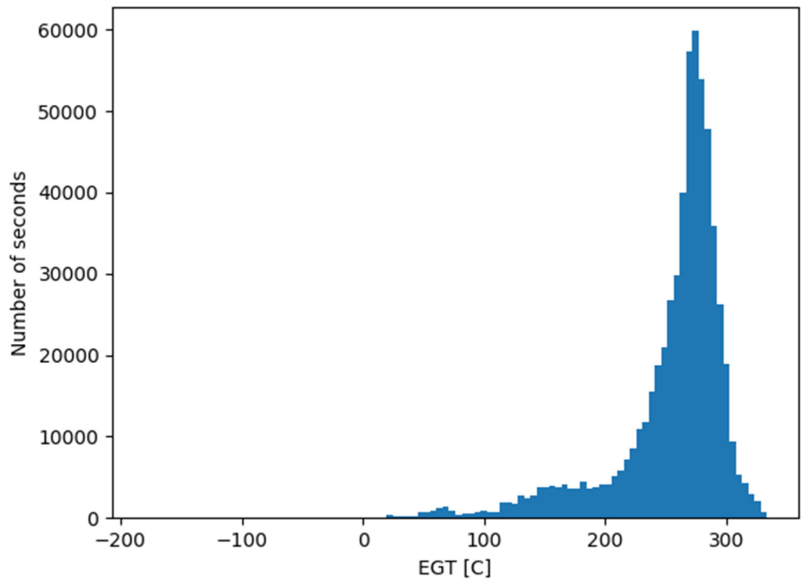

Figure 5: Exhaust gas temperature post SCR. This temperature indicates the working temperature of the SCR which should roughly be above 200 ºC to be able to efficiently reduce NO_x emissions of a diesel engine.

3.5 Stage V wheel loader

The engine is a Stage V (NRE v/c 6) using SCR to reduce the NO_x emissions of the diesel engine and uses a diesel particle filter to reduce the particulate emissions. 468 hours of data were collected over 62 active days of the machine. On average the daily activity was 7.5 hours with 4 days were the machine ran almost continuously for 24 hours. About a quarter of the time the machine is in stand-by mode with the engine running, performing no or hardly any work. The post SCR temperatures are mostly above 200 ºC, but still there is a share of the time with lower temperatures, caused by the idling or stand-by mode of the engine running at very low load. This probably explains a large part of the higher NO_x emissions which on average in real-world operation for this machine are about 1.5 times the Stage V limit value.

TNO test code	**CA_95**
Brand, type	Caterpillar, 950M
Configuration	Wheel loader
Weight [t]	19.2
Engine power [kW], speed [min^{-1}]	171
Emission Stage	V (NRE v/c 6)
Emission abatement system	SCR, DPF
Fuel	EN590
Running hours	405 (1766km)

Total test period [days], days active [days]	144, 62
Total activity [hours], [hours/day]	468, 7.5
Average power [%]	35
Stand-by [minutes/hour]	17
NO_x [g/h], [g/kWh]	35, 0.6
Total NO_x [kg]	16.2
CO_2 [kg/h]	56
Total CO_2 [t]	26.4
Fuel consumption [l/h]	21.3
Average ammonia slip [ppm]	4

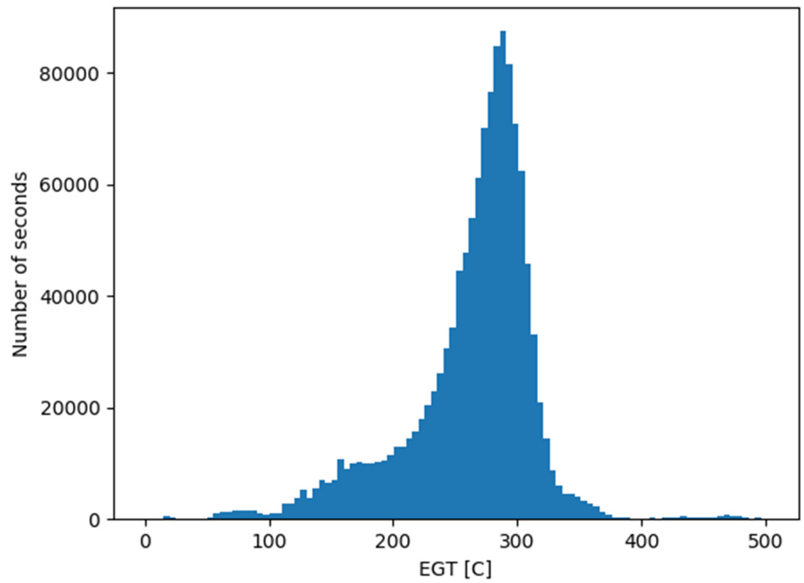

Figure 6: Exhaust gas temperature post SCR. This temperature indicates the working temperature of the SCR which should roughly be above 200 ºC to be able to efficiently reduce NO_x emissions of a diesel engine.

3.6 Stage V Excavator

In the measurement period of 38 days this machine was only used for 3 hours. This means that few data are available and the data thus only represents this limited use of the machine. The data contains a relatively high share of cold engine operation and idling of the engine which both explains the very high brake specific NO_x emissions (the engine produces hardly any work while running).

TNO test code	**VO_EC**
Brand, type	Volvo EC250
Configuration	Excavator
Weight [t]	27
Engine power [kW], speed [min^{-1}]	159 kW, 1800
Emission Stage	V (NRE v/c 6)
Emission abatement system	SCR, DPF
Fuel	EN590 diesel
Running hours	1244

Total test period [days], days active [days]	38, 3 **(few data)**
Total activity [hours], [hours/day]	2.9, 1
Average power [%]	3
Stand-by [minutes/hour]	48
NO_x [g/h], [g/kWh]	115, 24
Total NO_x [kg]	0.3
CO_2 [kg/h]	14
Total CO_2 [t]	0.04
Fuel consumption [l/h]	5.1
Average ammonia slip [ppm]	3

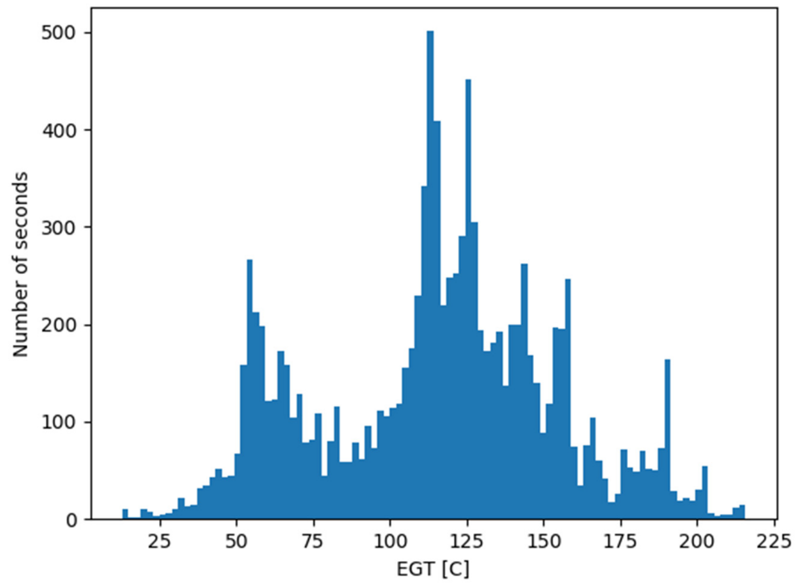

Figure 7: Exhaust gas temperature post SCR. This temperature indicates the working temperature of the SCR which should roughly be above 200 ºC to be able to efficiently reduce NO_x emissions of a diesel engine. The short test period and the large share of cold engine operation in this period resulted in exhaust temperatures below 200 ºC and high brake-specific NO_x emissions.

3.7 Particle number emissions

A particle number test was conducted on the machines equipped with a DPF. With a warm engine and when idling a well-functioning DPF of a passenger car has a PN emission below 5.000 #/cm^3 (Kadijk, 2020). With a cold engine PN concentrations can be higher, up to 250.000 #/cm^3. For the future periodic inspection test of passenger cars with a DPF the PN concentration of 250.000 #/cm^3 is proposed as a limit value (Kadijk, 2020). The results with PN concentrations at idling around 5000 to 10000 #/cm^3 indicate that the tested machines have properly functioning diesel particle filters. The PN measurement equipment is meant for engines with DPF. For three machines no measurements were done because the PN concentrations are very high and foul the measurement instrument in a few minutes. These three machines have no diesel particle filter (DPF). For one machine the measurement was aborted because of an error of the instrument.

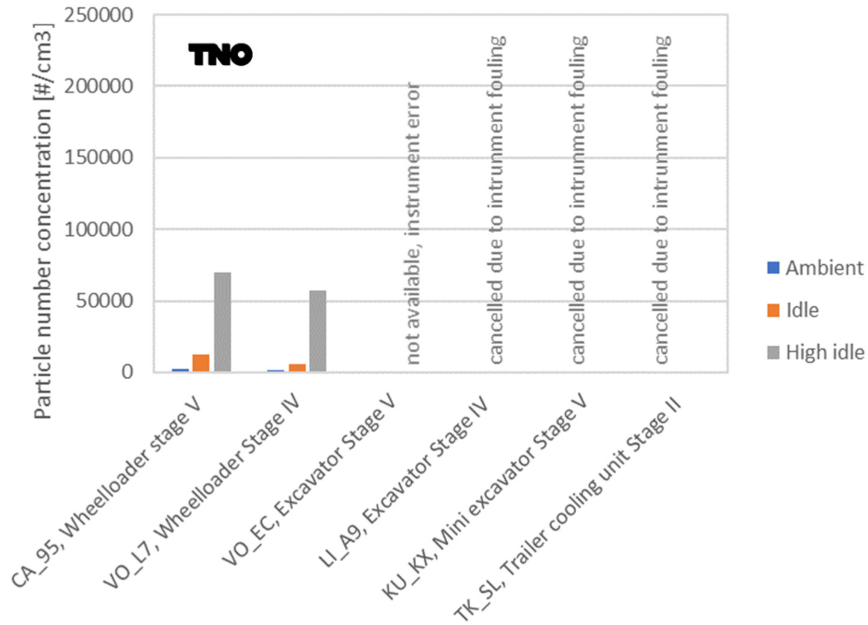

Figure 8: Particle number concentrations: ambient concentrations and concentrations measured at the tail pipe. For three machines no measurements were done because the PN concentrations are very high and foul the measurement instrument in a few minutes. These three machines have no diesel particle filter (DPF). For one machine the measurement was aborted because of an error of the instrument.

3.8 Overview long term measurements mobile machinery

Results of long term in-use NO_x emissions measurements as discussed in this report can be presented together with the same kind of measurements conducted on a number of construction equipment conducted in the framework of Connekt (Ligterink, Louman, Buskermolen, & Verbeek, 2018).
The NO_x emissions (Figure 9 and Table 3) show that Stage IV (3) and V (1) machines with an engine power >= 56 kW are clearly cleaner than the Stage IIIB machines (2). Expressed in g/kWh, the Stage V mini-excavator and the trailer cooling unit emit the most, around 9-10 g/kWh. For the Stage V mini-excavator this is caused by the fact that for Stage V only a very loose limit is applicable for NO_x (7.5 g/kWh). For the Stage II cooling unit the Stage II limit applies which is 8 g/kWh. The high brake specific NO_x emissions of the mini excavator and the cooling unit lead to absolute emissions that are about as high in g/h as the NO_x emissions of the large stage IV and V machines.

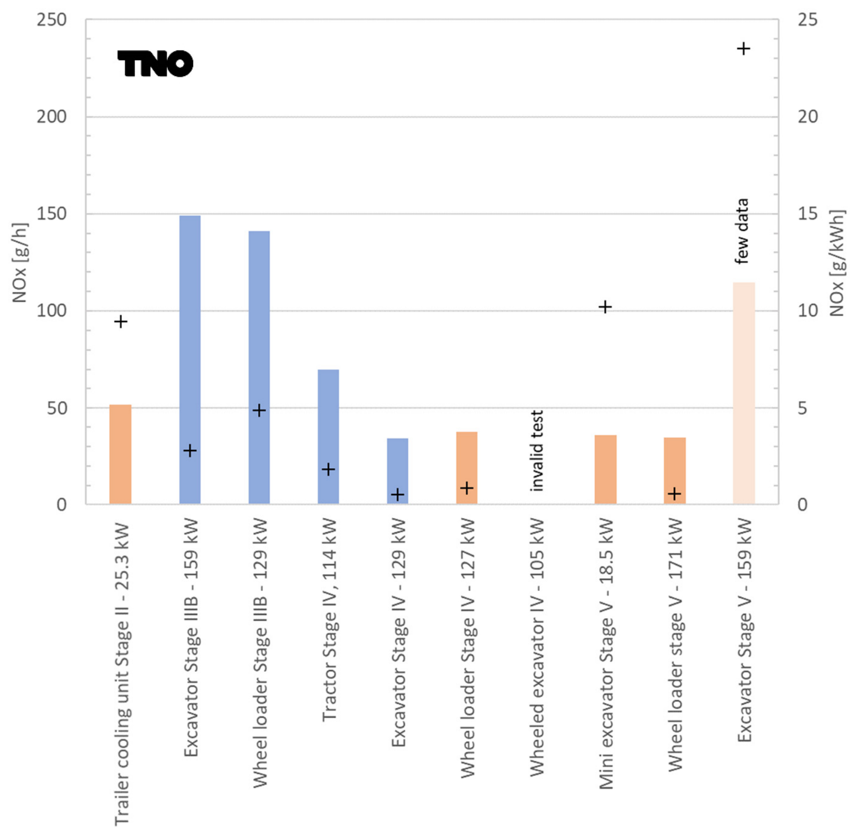

Figure 9: Overview of the long term NO_x measurements conducted in the framework of the 2020 emissions testing programme reported in this report (orange) and the measurements conducted in the framework of Connekt [Ligterink et al., 2018] (blue).

Table 3: Overview of the NO_x and CO_2 emissions, fuel consumption and activity of the mobile machinery measured in the Netherlands (this report and (Ligterink, Louman, Buskermolen, & Verbeek, 2018)).

	Max. power [kW]	NO_X [g/h]	NO_X [g/kWh]	Total NO_X [kg]	CO_2 [kg/h]	Total CO_2 [t]	Fuel consumption [l/h]	Test duration [h]	Activity[1] [h/day]	Stand-by[2] [min/h]
Trailer cooling unit Stage II	25.3	52	9.5	92.3	5.9	10.6	2.2	1787	10.9	6
Excavator Stage IIIB	159	149	2.8	43.4	53	15.4	20.0	291	7.1	11
Wheel loader Stage IIIB	129	141	4.9	48.5	18	6.2	6.8	344	7.0	34
Tractor Stage IV	114	70	1.8	3.1	30	1.3	11.3	44	5.6	15
Excavator Stage IV	129	34	0.5	4.5	42	5.5	15.9	131	6.3	21
Wheel loader Stage IV	127	38	0.8	7.9	44	9.3	16.6	211	7.5	16
Wheeled excavator IV	105	n.a.	n.a.	n.a.	22	5.9	8.2	272	5.3	16
Mini excavator Stage V	18.5	36	10.2	0.3	5.8	0.05	2.2	8.3	4	20
Wheel loader Stage V	171	35	0.6	16.2	56	26.4	21.3	468	7.5	17
Excavator Stage V (few data)	159	115	23.5	0.3	14	0.04	5.1	3	1	48

[1] Time when the engine is running.

[2] Stand-by is defined as the situation were the engine is running but the machine is not moving nor performing it's duty. During stand-by the engine may put out some power to propel electric machines, pumps and compressors.

3.9 Impact of 'stand-by mode' on NO_x emissions.

The tested machines were in stand-by mode for substantial times of around 35%. The machine that only ran for 3 hours during the entire testing programme is excluded here. NO_x is emitted when the machine is in stand-by mode and produces no effective work. In principle NO_x emissions can be prevented by shutting off the engine, but for practical reasons often it is not feasible to shut of the engine immediately.

The data was analysed to determine the share of the NO_x emissions produced during stand-by mode compared to the total NO_x emissions. This was done for different durations of stand-by times, see Figure 10. This shows that the contribution of NO_x emission during standby is extremely high. For the first three machines, this is 26% to 42% of the total NO_x if all standby is included. For the fourth machine, the Volvo Stage V mini excavator, this was even 60%, but this machine had only three running hours and is excluded from the main conclusions.

Many machines are equipped with an automatic idle shut off. This reduces fuel consumption and also NO_x emissions. The idle shut-off usually shuts off the engine after several minutes. For that reasons also the NO_x emissions are calculated for the idle periods longer than 1 minute, 2 minutes, etc. This shows how much the NO_x emissions can be reduced if the automatic idle shut is used and is adjusted to that value.

For the first three machines, 1 to 7% of the NO_x emissions is caused by stand-by, lasting more than half an hour. This is 10 to 20% for stand-by times lasting more than 10 minutes. For stand-by times lasting more than 2 minutes the NO_x emissions of this stand-by are about are about 22 to 33% of the total NO_x emissions. These values are without the Volvo Stage V excavator for which little data was collected. This showed even higher contributions of standby.

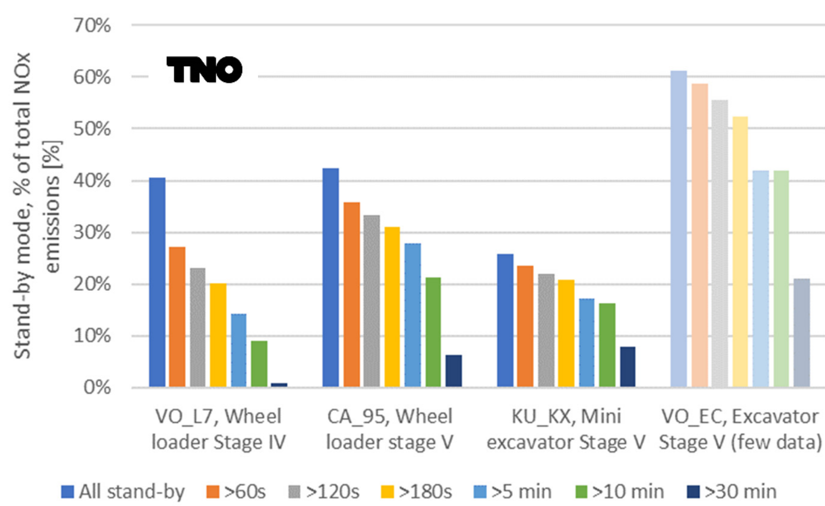

Figure 10: NO_x emissions during stand-by mode when no work is produced, for different duration of the stand-by events. For instance for the CA_95 stand-by events that last longer than 2 minutes contribute 33% to the total NO_x emissions.

Table 4: Contribution of NO_x during standby to total NOx for the first three machines of Figure 10.

	Share of total NO_x emitted during standby
All standby	26 – 42%
Only standby > 60 s	24 – 36%
Only standby > 2 minutes	22 – 33%
Only standby > 3 minutes	20 – 31%
Only standby > 5 minutes	14 – 28%
Only standby > 10 minutes	9 – 21%
Only standby > 30 minutes	1 – 7%

3.10 Generating sets and pumps

Mobile machinery mostly use diesel engines. Diesel engines are also used in stationary machines, for instance for local power generation. These engines often do not have any emission reduction system and therefore may emit high levels of NO_x and PM. In the past decades, a lot of attention was given to measuring the emissions of road traffic but little is known about the emissions level and the activity of the stationary diesel engines such as often used at construction sites. For these engines, the EU emissions standards were phased in later than for the engines of mobile machinery. Stage II was the first standard that applied to constant speed engines in 2007. Stage IIIA was phased in to constant speed engines starting in 2011.

A measurement programme was conducted using a portable gas analyser (Testo 350) to measure the concentrations of the gases NO, NO_2, NO_x, CO, HC, CO_2 and O_2 at the exhaust stack of the machinery. A gravimetric method with a filter and a constant dilution system was used to collect the particulate matter from the exhaust stack.

Two ‘construction sites’ were selected. The two sites are drilling sites.
The stationary engines that are present at the sites are used for providing the power for the drills, pumps, local electricity and light. The pumps are for sewage and supply of high pressure pumping capacity for the drilling activity.

The measurements were spot measurements, which means that samples are taken of the exhaust gas as is, i.e. during the operation of the machine as available at the moment of test. In two cases more samples were taken.
For the high pressure pump, measurements were done at high and low load because the machine was intermittently switching between two load settings. This machine had a retrofit SCR NO_x reduction system attached to the stack. The SCR uses Selective Catalytic Reduction and reagent (Adblue) to reduce the NO_x emissions of the Caterpillar diesel engine. Measurements were repeated with SCR active (Adblue dosing on) and inactive (Adblue dosing off).
A light pole was tested with different settings, i.e. all of the four lights on and all lights off.

Table 5: Specifications of the machinery tested at the construction site.

Use	Engine	EU Stage	Emission reduction system	Max. engine power [kW]	Life time running hours [h]	Life time work [kWh]	Life time avg. power [kW, %]
High pressure pump	CAT C15	IIIA	Retrofit SCR	340	n.a.	n.a.	n.a.
Genset	MAN D2862LE221	II	-	770	9548	674592	70.1 , 8
Sewage Pump	Hatz 4M41	IIIA	-	33	856	n.a.	n.a.
Light pole	Kubota	II	-	2.3	3413	n.a.	n.a.
Genset	John Deere 4045HFU8112V	IIIA	-	48	6970	59181	8.5 , 18
Genset	Hatz	II	-	41	1864	n.a.	n.a.
Genset	n.a.	II	-	19	n.a.	n.a.	n.a.
Drilling rig	CAT 7.1	V	SCR, DPF	205	n.a.	n.a.	n.a.

The NO_x emission results are presented in figure 13 and also in table 6 below. The results of the NO_x measurements show variations. The high pressure pump with SCR with Adblue dosing switched on, and the Stage V drill, also equipped with SCR, show very low NO_x emissions of a few g/h. The retrofit SCR system of the high pressure pump reduces NO_x emissions of the Caterpillar diesel engine with about 98% efficiency at the given engine load points. The other light machines show NO_x emissions in the order of 50 to 140 g/h. This is in the same range as the Stage IIIB to V mobile machines summarised in table 3. It also shows that the very small machines with 12-19 kW engine power have about the same NO_x emissions in g/h as the much larger stationairy and mobile machines with 40 to 170 kW power.
The large genset with a 770 kW engine shows by far the highest NO_x emissions of 4.1 kg/h at the medium load (46%) the machine was running at. This is comparable to about 100 (!) mobile machines such as medium size excavators and side loaders with a Stage IV or V engine. This high emissions level is caused by the high power but also by the high brake specific NO_x emissions of this engine, which is 11.7 g/kWh at the measured load point. The engine for this genset is provided as a ‘low fuel’ and as a ‘low NO_x’ variant. The low fuel configuration would mean a NO_x concenration lower than 4000 mg/m^3 (< about 2000 ppm) according TA luft 2002 requirements. The low NO_x configuration would comply with the old Stage II limit which is 6 g/kWh. With a measured NO_x concentration of 1462 ppm this engine probably is a ‘fuel optimized’ variant. The generator set tested is build in 2013 but has a power rating of 770 kW and due to the high power rating falls outside the scope of the NRMM regulation. Widening of the scope to engines above 560 kW (and below 19 kW) only happens at Stage V (2021). For engines for gensets separate limits were introduced at Stage V (category NRG) of 0.67 g/kWh, 0.035 g/kWh for PM and no limit for PN. The level of the PM limit and the absence of a PN limit means that for large genset engines no DPF would be required to meet Stage V requirements.

The NO_2 emissions of the engines without emission abatement system vary from a few to 50% of the total NO_x emissions (refer to Table 6). The highest fractions of NO_2 are emitted by the engine with a retrofit SCR system, but for this machine the absolute levels of NO_x and thus also NO_2 are very low.

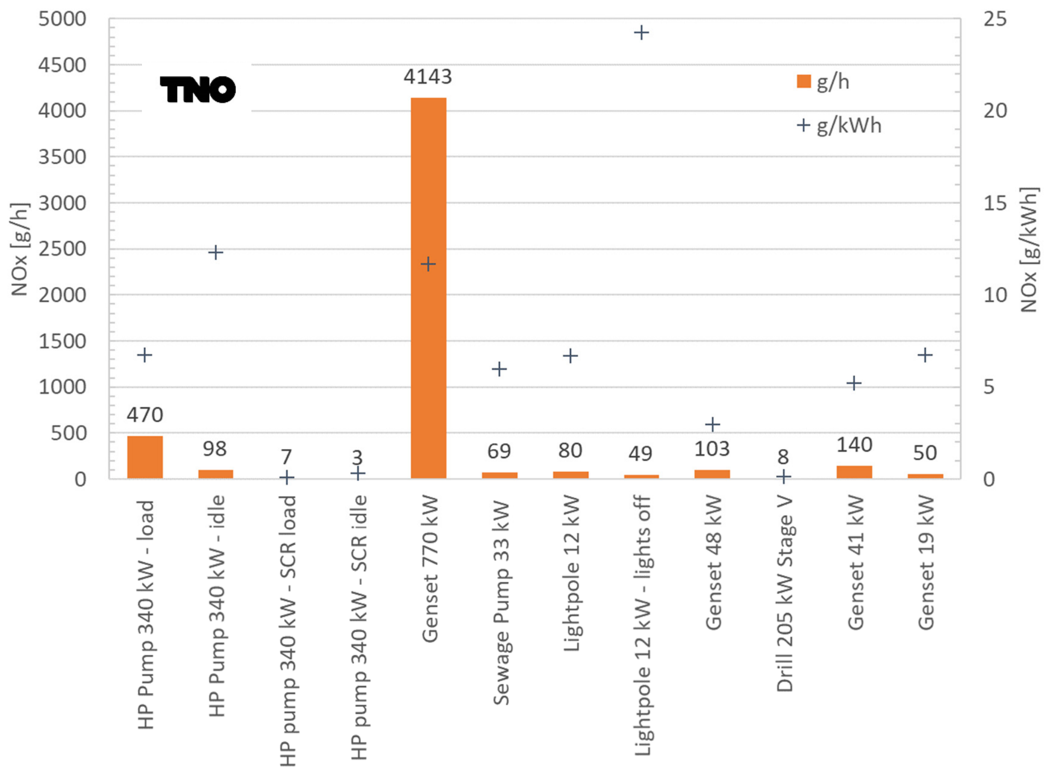

Figure 11: Spot measurements of the NO_x emissions of stationary machines at the construction site in g/h and g/kWh. The high pressure pump was measured at low and high load and with and without SCR Reagent dosing (Adblue) dosing active. The light pole was tested with all lights on and off.

The particulate matter mass emissions, PM, are presented in Figure 12 and Figure 13, and are also presented in Table 6, which also gives an overview of all emission components. The PM emissions also show variations. Also here the largest engine with the high power rating of 770 kW has the highest emissions. It's brake specific PM emission expressed in g/kWh is rather low however. The small 19 kW genset has brake specific PM emissions of about 0.5 g/kWh.

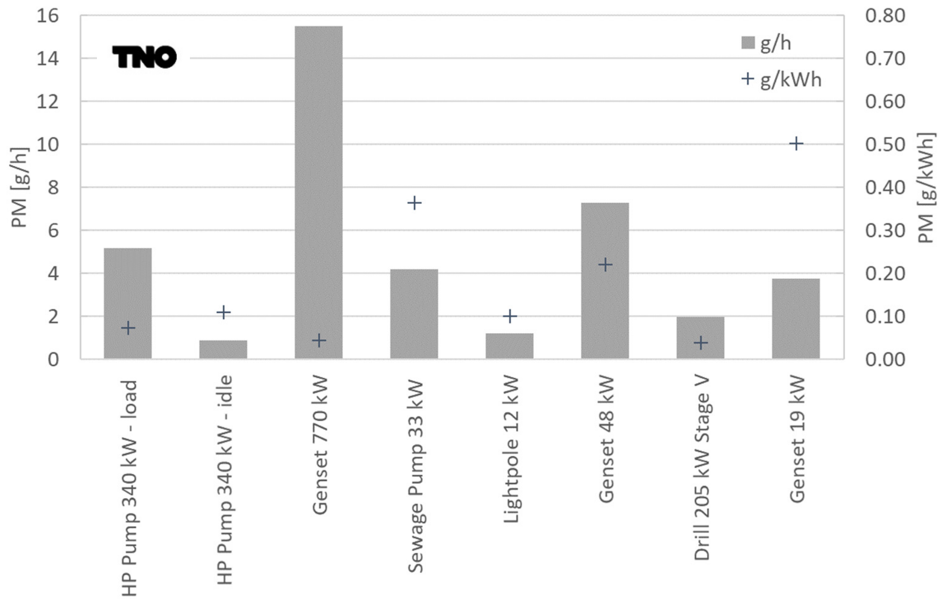

Figure 12: Spot measurements of the PM mass emissions of stationary machines at the construction site in g/h and g/kWh. The high pressure pump was measured at low and high load.

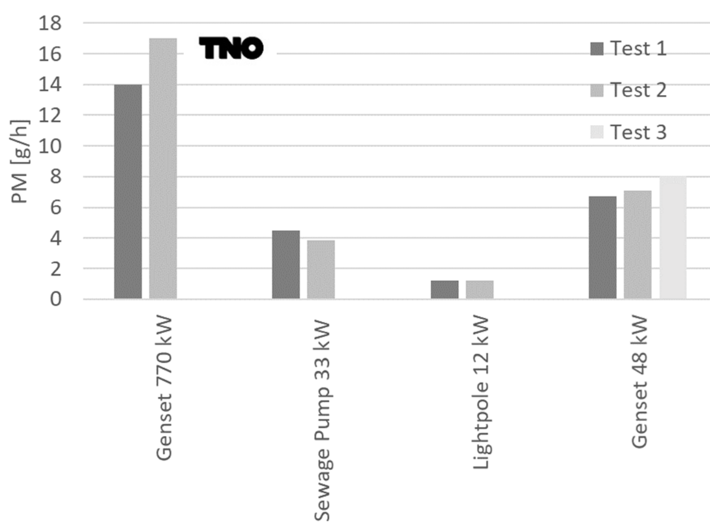

Figure 13: Spot measurements of the PM mass emissions of stationary machines at the construction site in g/h showing duplicate and triplicate repetitions of the PM measurement. The repetitions show the variation for PM measurement in the field. The maximum difference between two duplicates was 19%.

Table 6: Emissions results of the machinery tested at the construction site.

	Pmax kW	Approx[1]. Load, % of Pmax [%]	NO [g/h]	NO_2 [g/h]	NO_x [g/h]	CO [g/h]	CO_2 [kg/h]	HC [g/h]	PM [g/h]
HP pump 340kW load	340	21%	463	7	470	88	49	6	5.2
HP pump 340kW idle	340	2%	87	12	98	0	6	3	0.9
HP pump 340 kW SCR load	340	21%	5	4	8	10	47	6	n.a.
HP pump 340 kW SCR idle	340	2%	1.6	1.1	3	4	6	3	n.a.
Genset 770kW	770	46%	4012	130	4143	1425	227	8	14.0
Sewage Pump 33kW	33	35%	52	17	69	174	8	2	4.2
Lightpole 12 kW	12	99%	74	6	80	26	9	1	1
Lightpole 12kW lights off	12	17%	38	10	49	70	4	1	n.a.
Genset 48kW	48	23%	98	5	103	187	23	2	7.3
Drill 205 kW Stage V	205	24%	7	0.4	8	2	34	3	2.0
Genset 41kW	41	66%	138	2	140	92	19	0.0	n.a.
Genset 19kW	19	39%	45	5	50	35	5	1	3.8

[1] As available on the engine display, estimated from the applied electrical load or from fuel consumption calculated from engine speed and lambda (from O_2 concentration) for non-turbo engines.

4 Conclusions

TNO has carried out an emissions measurement program to determine the real-world emissions of a selection of mobile machines with 2 excavators, a mini excavator, 2 wheel loaders, a transport cooling unit and stationary machinery such as pumps and generator sets. From results of the tested machinery the following can be concluded:

The measured large Stage IV (3) and V (1) mobile machines (power >= 56 kW), all equipped with SCR, emit 0.5 to 0.8 g/kWh NO_x which is cleaner than the measured Stage IIIB machines (2) which emit 2.8 to 4.9 g/kWh. All machines were tested in real-world operation.

The Stage IV and V machines still emit more than the Stage IV and V limit of 0.4 g/kWh which accounts for the formal engine test of the type approval procedure.

The machines operate a lot in stand-by mode, about 35% of the total running time. This means that the engine is running but no work is produced. NO_x emissions during stand-by mode represent 26 to 42% share of the total NO_x emissions. For instance, when the engine would be stopped after two minutes, by adaptation of the driver's behavior (turning off the engine) or using a start-stop system, 22 to 33% of NO_x emission would be avoided.

The ammonia slip of the Stage IV and V machines equipped with SCR was generally low in real-world operation, with average ammonia concentrations in the exhaust of 1 to 8 ppm. On an official motor test for Stage V, the average ammonia concentration should not exceed 10 ppm.

Small mobile machines (power < 56 kW) are very dirty. A refrigerated trailer unit (driven by a small diesel engine) emits on average 52 g/h NOx, which is 1.5 times as much for NO_x and more than 10 times as much for particulate matter than the Euro-VI trucks that drives in front of it.
The tested 2.5 t mini-excavator emits 36 g/h on average, which is about the same level as a large Stage IV excavator and a large Stage V wheel loader. The reason of the high NO_x emissions is that non-stringent emission requirements apply to small mobile machines, even for Stage V engines with a power lower than 56 kW.

Most of the measured stationary machines (pumps and generator sets) are very dirty. The reason is that these machines had to comply with old and non-stringent very flexible emissions standards. In case of low powered (<19 kW) or high powered engines (>560 kW), even no emission limit applied. Many small dirty sources that run for many hours together can emit a lot. But also a single large machine can emit a lot on its own. A large generator with a 770 kW engine, out of the scope of the EU emissions regulation, had NO_x emissions of 4.1 kg/h during operation and in this case emits about as much NO_x as 100 large mobile machines or 100 Euro VI trucks.

A pump with a dirty diesel engine, fitted by the owner with an emission reduction system for NO_x, shows very low NO_x emissions, lower than the level of the Stage V standard. A Stage V engine equipped with SCR, as used on a drilling rig, is very clean as well. This indicates that the Stage V limit for stationary engines and the emissions abatement technology SCR can be very effective.

In this study, measurements were carried out on a limited number of mobile machinery and stationary sources on a construction site. This provides a first indication of the level of real-world NO_x and particulate matter emissions of these sources. More measurements are needed to obtain a complete and reliable picture of the emissions of the very broad NRMM and stationary engine categories.

Acknowledgements
Acknowledgments go to all companies which provided their machinery for the emission tests.

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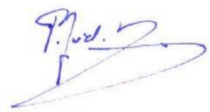
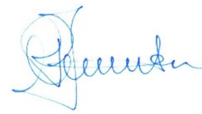
6 Signature

The Hague, 11 February 2021

TNO





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A Overview of EU Stage norms

Source: https://dieselnet.com, December 2020.

Table 7: NO_x and in some cases HC+NO_x emission standards for non-road diesel engines.

	Stage I		Stage II	Stage II	Stage II	Stage II		Stage IIIA	Stage IIIA	Stage IIIA			Stage IIIB	Stage IIIB	Stage IIIB	Stage IV					Stage V[2]	Stage V[2]
Net power [kW]	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020 2022
0-8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.5[1]	
8-19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.5[1]	
19-37	-	-	8						7.5[1]												4.7[1]	
37-75	9.2					7				4.7[1]												
37-56															4.7						4.7[1]	
56-75														3.3								
75-130	9.2				6				4[1]													
56-130														3.3		0.4						0.4
130-560	9.2			6				4[1]					2			0.4					0.4	
>560	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.5	
	Stage II for CS engines effective 2007.01, Stage IIIA 2011.01 (19-37 and 75-130) and 2012.01 (37-75)																					
	[1]combined HC+NOx limit																					
	[2]Transitional provision and exception with a period of 24 months. Production within 18 months after effective date and put on market within 6 month later. Category 5 are exempt: effective date is January 1st 2020 followed by the 24 month period. Due to Covid-19 pandemic in July 2020 the effective date was extended from 2020 to 31-12-2021 for engines < 56 kW and >130kW, the same effective date as for engines 56 to 130kW which wasn't changed.																					

Ammonia limit as of Stage III 25ppm over test cycle, for Stage V this is 10 ppm with exception of category RRL.

Cat.	Net Power	Date*	CO	HC	NO_x	PM
	kW		*g/kWh*			
Stage I						
A	130 ≤ P ≤ 560	1999.01	5	1.3	9.2	0.54
B	75 ≤ P < 130	1999.01	5	1.3	9.2	0.7
C	37 ≤ P < 75	1999.04	6.5	1.3	9.2	0.85
Stage II						
E	130 ≤ P ≤ 560	2002.01	3.5	1	6	0.2
F	75 ≤ P < 130	2003.01	5	1	6	0.3
G	37 ≤ P < 75	2004.01	5	1.3	7	0.4
D	18 ≤ P < 37	2001.01	5.5	1.5	8	0.8
* Stage II also applies to constant speed engines effective 2007.01						

Stage III A/B emission standards for nonroad diesel engines							
Cat.	Net Power	Date†	CO	HC	$HC+NO_x$	NO_x	PM
	kW		*g/kWh*				
Stage III A							
H	130 ≤ P ≤ 560	2006.01	3.5	-	4	-	0.2
I	75 ≤ P < 130	2007.01	5	-	4	-	0.3
J	37 ≤ P < 75	2008.01	5	-	4.7	-	0.4
K	19 ≤ P < 37	2007.01	5.5	-	7.5	-	0.6
Stage III B							
L	130 ≤ P ≤ 560	2011.01	3.5	0.19	-	2	0.025
M	75 ≤ P < 130	2012.01	5	0.19	-	3.3	0.025
N	56 ≤ P < 75	2012.01	5	0.19	-	3.3	0.025
P	37 ≤ P < 56	2013.01	5	-	4.7	-	0.025
† Dates for constant speed engines are: 2011.01 for categories H, I and K; 2012.01 for category J.							

Stage IV emission standards for nonroad diesel engines						
t.	Net Power	Date	CO	HC	NO_x	PM
	kW		*g/kWh*			
Q	130 ≤ P ≤ 560	2014.01	3.5	0.19	0.4	0.025
R	56 ≤ P < 130	2014.1	5	0.19	0.4	0.025

Stage V emission limits for engines in nonroad mobile machinery (category NRE).

Cat.	Ign.	Net Power	Date[1]	CO	HC	NO_x	PM	PN
		kW		g/kWh				*1/kWh*
NRE-v/c-1	CI	P < 8	2019	8	7.50[a,c]		0.40[b]	-
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.6	7.50[a,c]		0.4	-
NRE-v/c-3	CI	19 ≤ P < 37	2019	5	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-4	CI	37 ≤ P < 56	2019	5	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-5	All	56 ≤ P < 130	2020	5	0.19[c]	0.4	0.015	1×10^{12}
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.5	0.19[c]	0.4	0.015	1×10^{12}
NRE-v/c-7	All	P > 560	2019	3.5	0.19[d]	3.5	0.045	-
[a] HC+NOx								
[b] 0.60 for hand-startable, air-cooled direct injection engines								

[1]Transitional provision and exception with a period of 24 months. Production within 18 months after effective date and put on market within 6 month later. Category 5 are exempt: effective date is January 1st 2020 followed by the 24 month period.

Engines above 560 kW used in generator sets (category NRG) must meet standards shown in Table 5 (NRSC and NRTC test cycles).

Category	Ign.	Net. Power	Date	CO	HC	NO_x	PM	PN
		kW		g/kWh				1/kWh
NRG-v/c-1	All	P > 560	2019	3.50	0.19[a]	0.67	0.035	-
[a] A = 6.00 for gas engines								