Real-world NO_x emissions of Stage V NRMM

R. Vermeulen[1], J. Demuynck [2], P. Paschinger[1], D. Bosteels[2]*

[1]TNO, The Hague, the Netherlands, robin.vermeulen@tno.nl

[2]Assocation for Emissions Control by Catalyst, AECC aisbl, Brussels, Belgium, joachim.demuynck@aecc.eu

Abstract

This work investigates the real-world NO_x emissions of stage V engines used in a variety of Non-Road Mobile Machinery (NRMM) applications. The purpose is to understand the real-world usage patterns in the fleet and resulting emissions under a variety of operating conditions. The monitoring data of thirteen Stage IV and V machines is analysed. Tail pipe NO_x emissions were measured during real-world operation with Smart Emissions Measurement Systems (SEMS).

It is observed that engine load patterns vary between machines, even when they are of the same type. In general, the average engine load is relatively low or can have intermittent periods of working and stand-by periods. A variety in real world average emissions performance can be observed. Several machines have average NO_x emissions below the limit, some are around the limit and others are significantly above the limit (which only applies for conditions as laid down in EU type approval procedures). It is to be noted that certification requirements and emission control technologies depend on the engine category. Not all machines are equipped with Selective Catalytic Reduction (SCR) for example. Impact on air quality is not only determined by the average emissions, as specific usages seems associated with higher emissions. The study therefore investigated the distribution of emissions as well, based on the Stage V In-Service Monitoring (ISM) post-processing procedures. In contrast to Euro 6/VI for on-road vehicles which has requirements for testing In-Service Conformity with PEMS, Stage V for NRMM includes testing with Portable Emissions Measurement Systems (PEMS) for monitoring purposes only, called In-Service Monitoring (ISM).

For five out of eight of the monitored Stage IV and V machines ($56 \leq P < 130$ kW and $130 \leq P \leq 560$kW, respectively), real-world NO_x emissions are reasonably low, in the range of the limit value, due to the usage of Selective Catalytic Reduction (SCR) systems. There are, however, events with higher emissions, which are often categorised as non-working event or invalid window in the ISM procedures. For three of the eight machines of these categories higher emissions are observed during the monitoring programme. Real-world NO_x emissions of low powered (<56 kW) and high-powered (>560 kW) categories are high due to the higher NO_x limits, which do not require the use of SCR.

Overall, a discrepancy between engine-certified and application-related real-world NO_x emission has been identified. This should be handled in future NRMM emission legislation to further improve local air quality.

Introduction

NRMM (Non-Road Mobile Machinery) is a broad category of machinery which includes mobile machinery and transportable equipment which are not primarily used for transporting people or goods over the road and most of which are fitted with an internal combustion engine (diesel mainly). As such, the machinery is to be regarded as a source of pollutant and greenhouse gas emissions. For instance, NRMM in the construction sector can be a significant contributor to local air pollution (NO_x, PM), acidification and eutrophication of nearby nature reserves (NO_x, NH_3). EU regulation has become more stringent over time with the aim to reduce pollutant emissions of the engines for most power categories. The regulation uses standardized tests to verify the emissions under controlled laboratory conditions. In-service emissions are only checked by means of monitoring with PEMS (Portable Emissions Measurement System), but this is limited to a selective part of the operation of the machinery.

Objectives
The objectives of the study at hand were to increase the understanding of real-world NO_x of stage IV/V engines applied in NRMM. More specifically, their usage patterns, dependencies of the emissions, fleet composition and contributions to total emissions were investigated. Furthermore, possible opportunities for improving regulatory requirements were identified and emissions put in perspective with air quality contributions. Finally, hot spots (largest contributing categories) and possible white spots in knowledge and data were identified.

Approach
The approach taken was to collect and analyse the real-world emissions and usage data which was measured on a number of Stage IV and V certified NRMM in the testing programs conducted by TNO for the Dutch Ministry of Infrastructure and Water management and Connekt.

Non-Road mobile Machinery

In the Netherlands
To be able to show the significance of emissions from NRMM and to get a view of the fleet of NRMM, the situation in the Netherlands was used as an example. In the Netherlands, the EMMA model [1] is used to estimate annual emissions. Presently, eighty-seven different types of machines are considered in the model, from chainsaws to pile drivers. Probably, there are still types in-use which are not identified and included. Regarding the fleet of NRMM in the Netherlands, it should be noted that there are large uncertainties in terms of numbers and types of NRMM due to lack of registration, e.g., a large underestimation was unveiled by the mandatory registration of 350,000 agricultural tractors, which is almost five times the initially estimated number of 71,000. Also, there is a large uncertainty of the usage of the machinery.

Annual NO_x emissions [Figure 1] are at approximately the same level compared to inland shipping, somewhat higher than passenger cars, light-, or heavy-commercial vehicles and about 44 % of total traffic NO_x emissions. Annual PM_{10} emissions of NRMM [1] are as high as the total of road traffic. Annual NO_x emissions are estimated to decrease slightly from 2022 to 2030 due to the substantial increase of the share of stage V engines. This includes some growth of the fleet. The EMMA model estimates that the contribution to total NO_x emissions is highest for medium powered categories (75–560 kW). With this category becoming cleaner due to Stage V NO_x limits and the applied emissions abatement systems (mainly SCR) the contribution may shift to the lower power category with less stringent emissions limits. This may account for particulate matter as well.

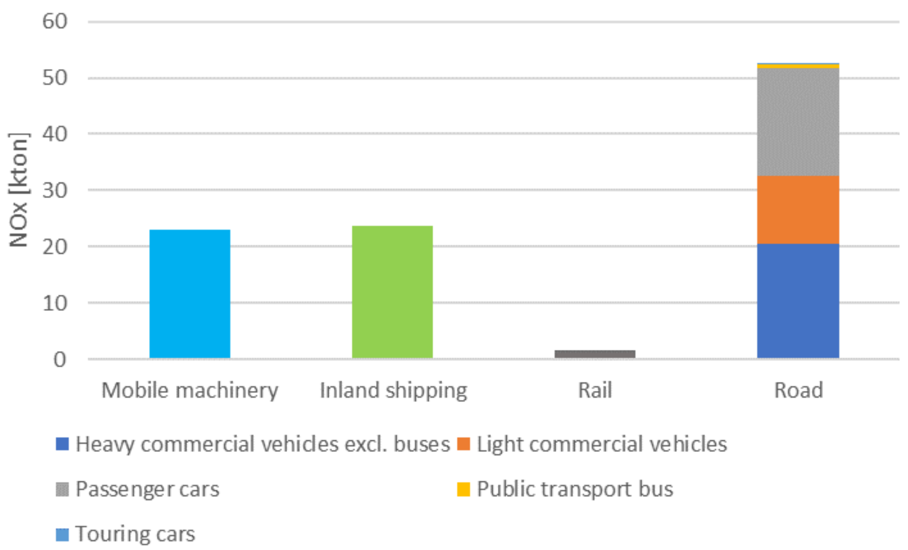

Figure 1: Total annual NO_x emissions in the Netherlands per sector for the year 2021.

EU Regulation

The EU NRMM Regulation [2] defines emission limits for NRMM for different power ranges and applications. It also lays down the procedures engine manufacturers must follow in order to obtain type-approval of their engines – which is a prerequisite for placing their engines on the EU market. The Regulation defines which applications fall under the scope. In scope are applications such as NRE (Non-Road Engines), NRG (Non-Road Gensets), IWP (Propulsion engines of Inland Waterway Vessels), RLL (Rail Locomotives) and RLR (Railcars). Test cycles for engine tests are to be conducted on an engine test bed. They consist of a transient test, the NRTC, and several steady-load tests, such as the NRSC (mode tests C1, E2, E3, etc). Emissions limits are differentiated by net power categories, with for each power category a different set of limits for the substances CO, HC, NO_x, PM (Particulate Matter) and PN (Particulate Number). For Stage V the power categories between 19 kW and 560 kW have more stringent PM and PN limits and the power categories between 56 and 560 kW also have a more stringent NO_x limit. In-service monitoring was initially applicable for NRE v/c 5 and 6 ($56 \leq P < 130$ kW and $130 \leq P \leq 560$kW, respectively) but is extended to lower and higher power categories as well, entering into force December 2022. For the power categories with more stringent limits the requirements lead to application of a DPF (Diesel Particle Filter) to comply to the respective PM and PN limits and SCR (Selective Catalytic Reduction) to comply to the NO_x limits.

Measuring real word emissions: method

To be able to determine real world emission levels of NRMM, the emissions and usage data of the NRMM were measured using a Smart Emissions Measurement System (SEMS). SEMS is a sensor-based system developed by TNO [3], [4]. SEMS has been used in various programmes to measure and analyse the tailpipe NO_x, NH_3 and CO_2 emissions of various mobile sources. Moreover, the fuel consumption during daily operation and a range of vehicle/engine parameters are monitored. The purpose is to characterize the typical operation and real world emissions of the vehicles or machinery. In this way, for the group of test subjects, weeks up to months of data were collected per subject. The SEMS uses a calibrated (periodically checked and adjusted) automotive NO_x sensor which is combined with an O_2 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 1 Hz.

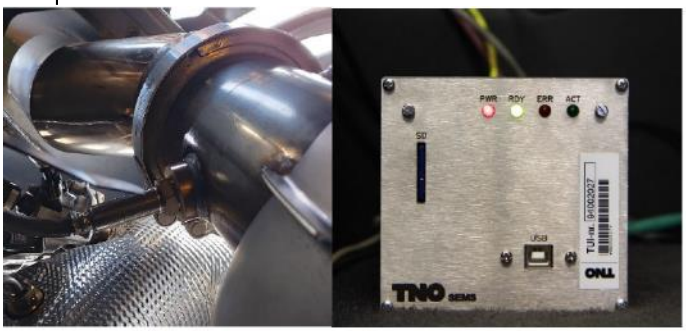

Figure 2: Smart Emissions Measurement System (SEMS). Left, emissions sensors in the tail pipe of an NRMM. Right, SEMS data recorder and transmitter to read, store and transmit sensor data, engine data and GPS data to a central server.

Mass emissions and instantaneous engine power are calculated combining sensor data and engine and vehicle data, such as manifold air flow, fuel rate, engine torque, engine speed and sensor O_2 concentration where available. Depending on availability of signals, the best of the following methods is chosen in terms of expected accuracy: carbon-balance, mass air flow and fuel flow, speed-density, emission-over-CO_2 ratio and estimate of specific fuel consumption.

Data from four projects was collected [5], [6] and [7] and reprocessed to calculate and depict emissions and usage parameters of thirteen NRMM used in real operation in their daily duty. In the programmes fifteen individual machines fulfilled the criterion of having either stage IV or V certification. Two machines were rejected from the sample because one ran only for a very short duration (3 h) during a long test period and another one had a faulty NO_x sensor signal. In Table 1 an overview is given of the machinery which was used in the analysis.

Table 1: Overview of measured Stage IV and V NRMM available for analysis.

Type	Brand	Type	Power [kW]	EU NRMM Stage	Machine running hours at beginning of test	Total test hours
Excavator	Kubota	KX027-4	18.5	V (IID)	1716	8
Excavator	Hitachi	ZX85US-6	42.4	V (NRE-v-4)	n.a.	83
Excavator	Takeuchi	TB290-2	51.6	V (NRE-v-4)	1648	163
Excavator	Takeuchi	TB 2150 R	85	V (NRE-v-5)	2322	53
Wheeled Excavator	Takeuchi	TB295W	85	V (NRE-v-5)	n.a.	45
Excavator	Caterpillar	326	152	IV (R)	n.a.	144
Wheel loader	Volvo	L70h	127	IV (R)	3635	211
Wheel loader	Caterpillar	950M	171	V (NRE-v-6)	405	468
Asphalt Roller	Bomag	174AP-4AM	55.4	V (NRE-v-4)	2665	587
Paver	Dynapac	SD2500C	129	V (NRE-v-5)	2096	275
Pile driving rig	ABI	TM18/22B	563	V (NRE-v-7)	888	516
Terminal Swap body transporter	Kamag	PM	115	V (NRE-v-5)	4390	1278
Tractor	Valtra	N4	114	IV (R)	n.a.	55.3

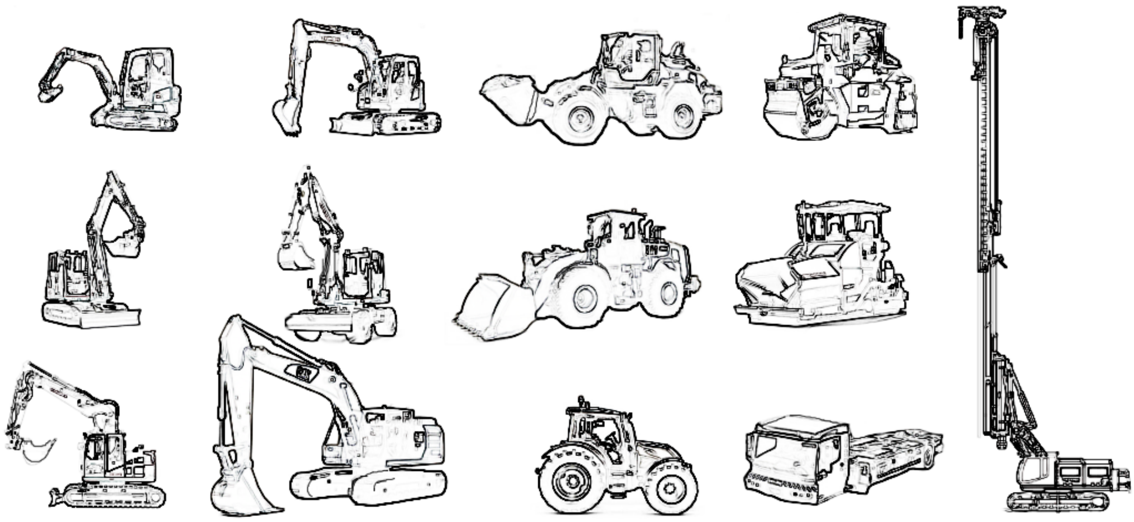

Figure 3: Representation of the types of NRMM that were part of the analyses.

NO_x emissions of 13 Stage IV and V NRMM

EU emissions regulation aims to limit the brake specific emissions, but for air quality the time-based emissions are important. Therefore, for the thirteen NRMM both the average work specific as well as the average hourly mass emissions were determined, see Figure 4 and Figure 5, respectively. Real-world NO_x emissions of cat. NRE 5 and 6 ($56 \leq P < 560$ kW), which all use SCR, are reasonably low in most regular cases such as excavators and wheel loaders: 0.2 – 1.8

g/kWh, but are higher for some other regular cases, the wheeled excavator (2.4 g/kWh) and the tractor (IV, 1.7 g/kWh) and are high for a special case, the swap body transporter (6.7 g/kWh).

Real-world NO_x emissions of the monitored low powered cat. 2 (8 ≤ P < 19 kW) and 4 (37 ≤ P < 56 kW) are high due to the higher NO_x limits which do not require the use of SCR. The same may apply for NRE-1 and 3 which have not been monitored. Real-world NO_x emissions of a category NRE-7 machine, the pile driving rig, are very high (7.3 g/kWh) due to the higher NO_x limit which does not require the use of SCR and are also high in g/h due to the high power of the engine and running at low load.

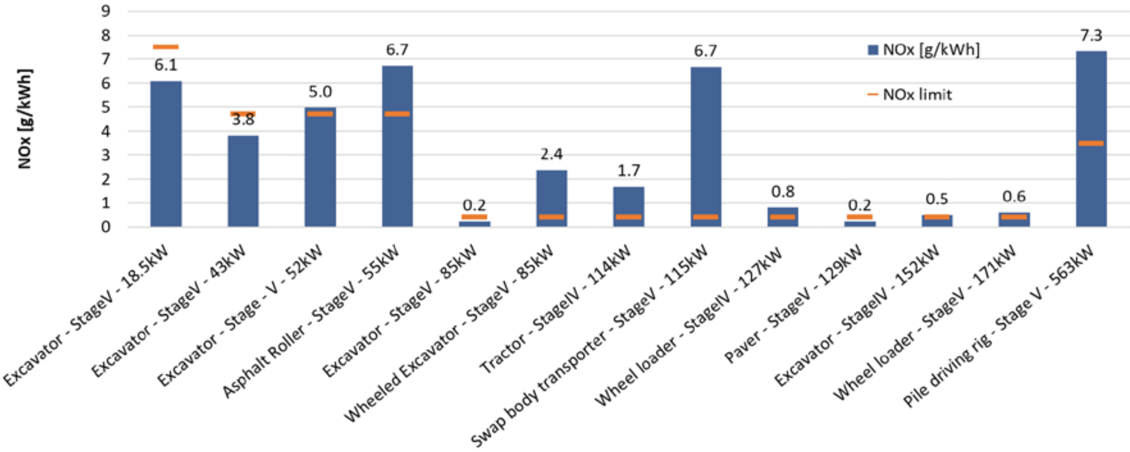

Figure 4: Average work specific NO_x emissions of thirteen NRMM in real world operation and the NO_x limit according to the EU NRMM Regulation which applies for the prescribed laboratory test cycles.

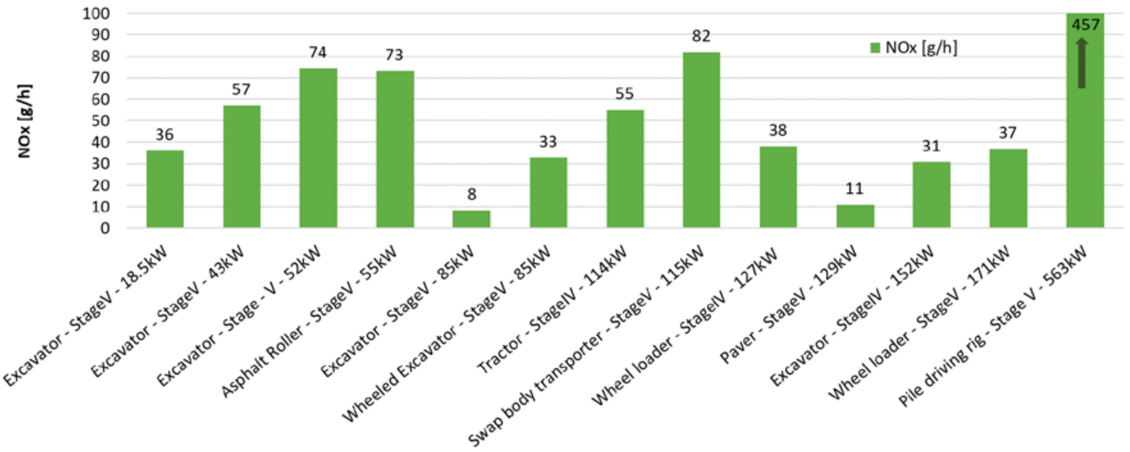

Figure 5: Average hourly NO_x emissions of thirteen NRMM in real world operation. Time-based NO_x emissions are relevant for contribution to local air pollution, acidification and eutrophication of nearby nature reserves.

Impact on local air quality is not only determined by the average emissions. The study at hand therefore looked into the distribution of emissions, as well. The data is analysed according to the Stage V In-Service Monitoring (ISM) procedures, using the Moving Average Windows (MAW) methodology. This method averages emissions in a window with a fixed amount of engine work of which the duration is thus determined by the level of engine power. Criteria are defined to exclude MAW (invalid MAW, e.g. average engine power <20%), short sequences and non-working events (e.g. average engine power <10%, take off from the ISM evaluation. Figure 6 illustrates the frequency of the MAW NO_x values measured for the wheeled excavator of 85 kW and the swap body transporter. The blue bars represent the data which remains after applying the ISM procedure (containing working events and valid MAW), the orange bars show data which are excluded (among others: short sequences <1 NRTC work, non-working events (<10% engine power, cold starts, instrument checks, less common ambient conditions, working events after long non-working events) and invalid MAW with engine power <20%). The example of the wheeled excavator shows that 42 % of the MAWs are in the lowest NO_x bin. A long tail is however observed, with some MAWs going up to 10 g/kWh and where higher fractions of MAW are excluded. For the swap body transporter almost all MAW are excluded. The peak of the distribution lies around 7 g/kWh. Figure 7 shows that the ISM method leads to different shares of valid, invalid MAW and exclusions depending on the NRMM and its usage. The pile driving rig and swap body transporter have a low share of valid MAW. Both NRMM run at a very low power of about 11 % of maximum rated power on average. Also, the wheeled excavator which shows 48 % of valid MAW runs at a low average power of 16 %.

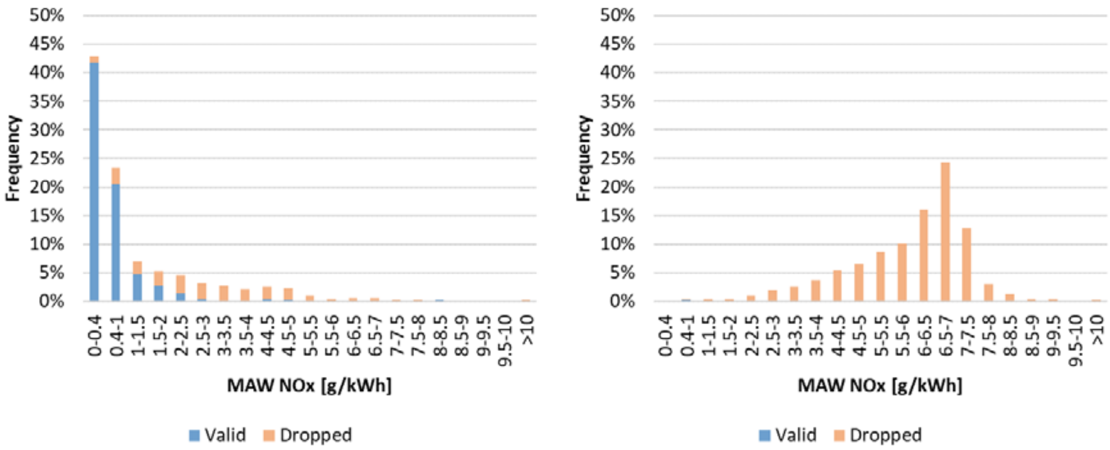

Figure 6: Examples of the distribution of work specific NO_x emissions in Moving Averaging Windows (MAW) of two NRMM. The graphs show valid MAW (blue) and dropped data (orange, either invalid MAW or excluded data according to the in-service monitoring rules).

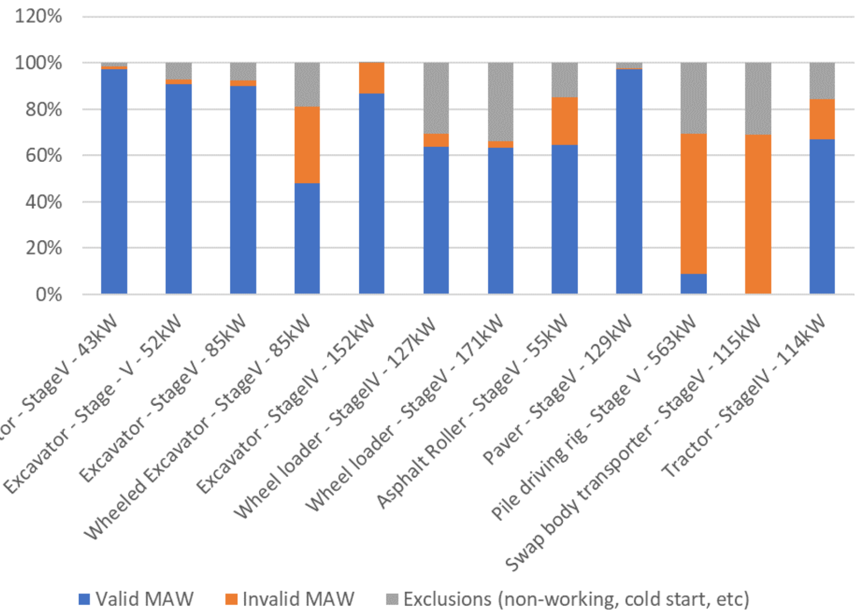

Figure 7: Shares of valid and invalid Moving Averaging Windows (MAW) and exclusions (non-working events, cold starts) after applying the calculation rules for in-service monitoring.

Analysis of the distribution of engine power reveals that for most machines the power distribution is on the low side, with a high share below 30 % of maximum engine power. With exception of four machines, most machines show a distribution of exhaust gas temperatures above 200°C which indicates that for those applications SCR working temperatures is reached most of the times, despite the in some cases lower loads below 30 %. The small excavator (18.5 kW, no SCR) shows larger shares of low exhaust gas temperatures, and so do the swap body transporter (115 kW, SCR) and the pile driving rig (563kW, Exhaust Gas Recirculation – EGR – only) which resulted in high NO_x emissions.

Figure 11 shows the percentage of total NO_x emissions that can be avoided by switching it off in idle. For instance, on average 18 % of total NO_x can be avoided by switching off the engine after 5 minutes of stand-by, with the variation being between 3 to 44 %.

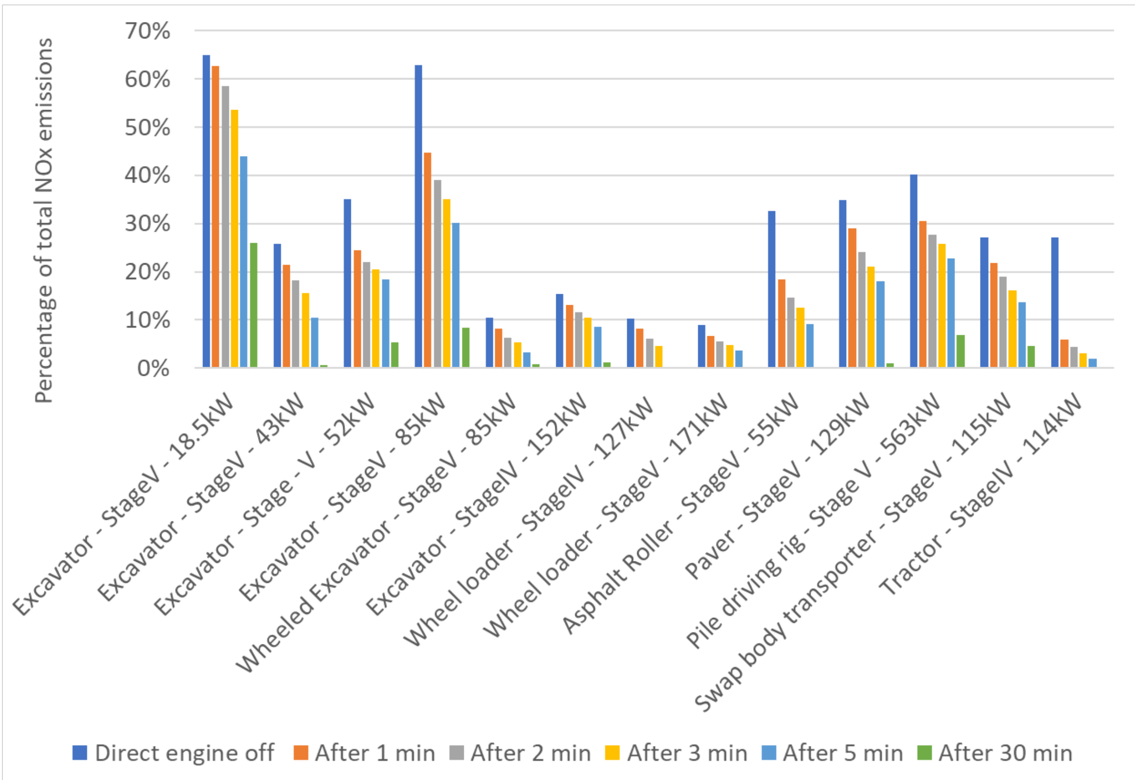

Figure 8: Percentage of total NO_x emissions which can be avoided when the engine is switched off at different times after a working event.

Discussion

Engine load patterns vary between machines of the same type and between different types of machines. Analyses of the engine loads patterns showed that in general the average engine load is relatively low or can have intermittent periods of working and stand-by events. Despite the low power, with a few exceptions most tested NRMM are able to maintain sufficiently high SCR working temperatures to reduce engine out NO_x emissions for most of the running time, in the case NRMM are equipped with SCR. Generally, on average higher or temporarily higher NO_x emissions for these NRMM are caused by average low load operation, intermittent load operation and high stand-by shares of the engine, which aren't controlled by NRMM test cycles.

NRMM in the low power (<56 kW) and high power (>560 kW) categories have less stringent NO_x limits, hence SCR is not needed to comply to the EU Regulation. This results in high absolute emissions for the low power categories (P<56 kW) and very high NO_x emissions for the high powered NRMM (>560 kW). Absence of a PN limit and a less stringent PM limit for the engine category 'P < 19 kW and P > 560 kW', might not require the use of a DPF which probably results in high PN and PM emissions. Engine power sizing is pushed to categories with less stringent

NO_x and/or PN/PM limits, e.g., >560 or <19 kW/<56 kW where no emissions abatement is needed to achieve the test cycle emission limits. For example, several machines were identified with an engine power just outside the boundary (e.g., 18.5, 55 and 563 kW).

Representativeness of test cycles, e.g. NRTC (Non Road Transient Cycle); test cycles do not cover the spread of usage in terms of engine load patterns observed. There is a lack of control of real-world emissions from normal (varying) usage with stand-by/idling, low load, intermitted loads, which are all not well-covered in test cycles. The high average load over the test cycle does not require low temperature SCR light-off. The NRTC has higher speeds and loads than the WHTC test used for on-road heavy-duty engines. For NRMM this results in faster reaching the operating temperatures for exhaust aftertreatment in the test cycle. The transient operation of NRTC does resemble the typical part of transient engine operation of certain construction machinery while working, such as wheel loaders and excavators. In real use, working events can however be followed or preceded by stand-by or non-working events, which aren't included in test cycles and which according to ISM rules are excluded from monitoring. ISM is limited to conditions comparable to the NRTC, i.e., working events with well-functioning SCR and high load, which excludes low load and idling and which is only applicable for medium powered NRE. However, stand-by NO_x emissions and NO_x from intermittent load cycles can be significant. For multiple machines which were monitored, a substantial part of the real-world data needed to be excluded because it was considered as a non-working event or not valid. The absence of signals from on-board control units makes it difficult to calculate the engine load in some cases. Furthermore, the calculation method of engine power is not always clear due to lack of standardization.

Conclusions

NRMM contributes significantly to the total PM and NO_x emissions. Due to the lack of stringent emission limits for the low and high-powered engines, the incomplete coverage of normal operation of NRMM in test procedures and the use of older machinery with a long lifetime, the contribution of NRMM will remain significant in the upcoming years. In contrast, the emissions of road transport will decrease further due to the effective Euro VI- step E and Euro 6d and introduction of Euro 7.

There are many NRMM types. For the ones tested, usage patterns vary significantly.

For the latest generation of NRMM (Stage IV with SCR and Stage V) real-world NO_x emissions vary from 0.2 to 7.3 g/kWh and depend on usage and the NRE power category. The large variation is caused by:

- The applicable type-approval test procedures which only partly covers normal conditions of use, but does not cover typical use such as stand-by, intermittent load and low load operation. As a result, NRMM regulation does not consider a substantial share of the real working conditions. The ISM evaluation also excludes substantial test data of normal use, such as low engine load conditions and stand-by/idle. This while NRMM often remain on one location to do their work for a period of time, hence all usage and related emissions matter for local air-quality and nitrogen oxides deposition.
- The fact that higher NO_x emissions are allowed for Stage V NRE in the low and high-power categories. Similar issues for control of PM/PN emissions are expected for NRE in the low and high-power categories with absence of a PN and a stringent PM limit.

This can be tackled by more stringent NO_x limits for P<56 kW and >560 kW, a PN limit for low (<19 kW) and high-powered engines (>560 kW), better coverage of real-world usage in tests and for ISM, extension of window of control, covering a larger part of real-world usage, including low load operation, among other items.
Technical solutions include automatic engine shut off, NO_x abatement for low and high-powered diesel engines (EGR, SCR), increasing low temperature SCR performance, introduction of DPF for low and high-powered diesel engines and electrification depending on the use case.

Acknowledgements

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Sources and References

[1] Hulskotte, Ir. J.H.J., Verbeek, Ir. R.P., Emissiemodel Mobiele Machines gebaseerd op machineverkopen in combinatie met brandstof Afzet (EMMA), TNO rapport TNO-034-UT-2009-01782_RPT-ML, November 2009

[2] Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016, on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC (Text with EEA relevance)

[3] Heijne, V., Spreen, J., Smokers, R., Vermeulen, R., Ligterink, N., Stelwagen, U., Kadijk, G. (2016). Assessment of road vehicle emissions: methodology of the Dutch in-service testing programmes, TNO 2016 R11178, 20 October 2016.

[4] Vermeulen, van Goethem, SEMS operating as a proven system for screening real-world NO_x emissions, paper for the Transport and Air-Pollution Conference 2014, Graz, Austria

[5] Ligterink, N., Louman, R., Buskermolen, E., & Verbeek, R. (2018, October). Connekt Topsector logistiek, Use of construction machines and associated NO_x and CO_2 emissions.

[6] Vermeulen, R.J., Ligterink, N.E., van der Mark, P.J., Real-world emissions of non-road mobile machinery, TNO report TNO 2021 R10221, 11 February 2021

[7] Vermeulen, Paschinger, NRMM stage IV/V real-world NO_x emissions: status quo and perspectives, TNO 2023 P10252, 24 January 2023

[8] C.D. Desouza, D.J. Marsh, S.D. Beevers, N. Molden, D.C. Green, Real-world emissions from non-road mobile machinery in London, Atmospheric Environment, Volume 223, 15 February 2020

[9] C.D. Desouza, D.J. Marsh, S.D. Beevers, N. Molden, D.C. Green, A spatial and fleet disaggregated approach to calculating the NO_x emissions inventory for non-road mobile machinery in London, Atmospheric Environment: X Volume 12, December 2021, 100125