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Improving Real-World Emissions of Mobile Machinery

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Summary

Pollutant emissions from Non-Road Mobile Machinery (NRMM) have decreased over time. However, road-vehicle emissions have declined much faster. This is the result of stringent Euro standards, advanced aftertreatment technologies and comprehensive in-use monitoring. For NRMM, these elements are less developed. This contributes to a situation where a relatively small, but intensively used, NRMM fleet produces particulate mass exhaust emissions comparable to those of the much larger Dutch road-vehicle fleet. For NO_x, road traffic still emits more overall, but the difference is narrowing.

In the light of these developments, TNO carried out a study to identify the required improvements for future NRMM emission standards. This study is performed on behalf of the Dutch Ministry of Infrastructure and Water Management. An important part of the research was the assessment of real-world emissions of NRMM. To assess real-world emissions, TNO analysed an extensive new dataset of real-world NRMM emissions. The dataset covers around 90 machines measured between 2025 and 2026. Most of these new data originate from a monitoring programme where Topsector Logistiek and TNO collaborated. In addition, datasets were obtained from measurement programmes carried out by TNO on behalf of the Dutch Ministry of Infrastructure and Water Management.

The analysis shows that current Stage V emission legislation does not ensure consistently low real-world NO_x-emissions. Stage-IV and -V engines have Selective Catalytic Reduction (SCR) to lower NO_x-emissions for engines between 56 and 560 kW. However, the real-world effectiveness of SCR strongly depends on exhaust temperature. This directly relates to engine load. Machines with high shares of low-load operation, such as cranes, frequently operate below the required temperature range. Emissions are therefore higher. Machines that operate more continuously at moderate loads, such as hydraulic excavators, rollers and pavers, show more stable and lower NO_x-emissions.

Although Stage IV and Stage V machines are subject to the same legislative NO_x-emission limits, the analysis shows differences in real-world performance. Across the full dataset, Stage V machines show lower average NO_x-emissions and less variability. However, the variation within each Stage category is substantial. The analysis does not determine the cause of these differences. It is unclear whether they result from engine generation and emission stage or from deterioration effects. There were substantially more data available for Stage V compared to Stage IV. Therefore, the Stage V results are more robust. Additional Stage IV data would therefore be valuable to further strengthen the comparison.

A particularly important observation concerns the 56 kW threshold for Stage V engines. For engines with a power above 56 kW, the emission limit is much stricter. Machines with engines just below this engine power threshold (40-56 kW) emit 4-5 g/kWh NO_x in real-world use. Machines just above it (85-100 kW) emit below 0.5 g/kWh. This difference is driven by the presence of an SCR. Even in absolute terms (g/h), the SCR-equipped machines emit two to three times less NO_x despite their higher power demand. This shows that the 56 kW threshold creates a structural difference in emission behaviour. Effectively it leaves small and medium-sized machinery without effective NO_x-control. The same is true for machines with an engine power above 560 kW.

The report also examines particulate matter (PM) and particle number (PN) emissions from three small (below 19 kW) Stage V machines (a generator, light pole, and wellpointing pump). None of these machines are required to use diesel particulate filters (DPFs). All three machines meet the Stage V mass limit of 0.4 g/kWh. However, they emit high numbers of ultrafine particles, between 1×10^{14} and 6×10^{14} #/kWh. This is far above the PN limit applied to larger engines (above 19 kW). Particle-size measurements show that nearly all emitted particles are below 100 nm. A substantial fraction is even smaller than 23 nm. These ultrafine particles are of particular concern for public health. Their high occurrence points to a regulatory gap for machines below 19 kW and above 560 kW. PN limits do not apply in these categories. The >560 kW category was not measured in this study.

Ammonia (NH_3)-emissions were also evaluated. Although average NH_3-levels remain below the 10 ppm limit (as used in the Euro VI road-vehicle framework), significant fluctuations occur. This is especially at low exhaust temperatures and during (very) high-temperature events. These events may indicate urea overdosing or incomplete conversion in the SCR catalyst. As SCR use expands in the NRMM fleet, NH_3-emissions become increasingly relevant.

The results of this study show that current Stage V emission requirements leave substantial room for improvement. Improvements necessary to upgrade NRMM emission standards from Stage V towards a potential Stage VI include:

1. Removing differences in NO_x- and PM/PN limits between engine power classes, and introducing a limit for NH_3;
2. Ensuring that low-load operating conditions are adequately covered in the test procedure;
3. Introducing in-use emission performance monitoring and checking, including anti-manipulation provisions.

These improvements would reduce real-world emissions throughout its useful life. With NRMM emissions expected to grow in relative importance as other sectors lower emissions, there is a clear need for a Stage VI standard that ensures robust, durable, and verifiable emission control across the entire NRMM fleet. These improvements remain necessary in parallel with ongoing electrification. Zero-emission NRMM is not yet widely applicable across all sectors in Europe. Therefore, diesel-powered machinery is expected to remain in use for the foreseeable future.

Contents

1 Introduction

Pollutant emissions of Non-Road Mobile Machinery (NRMM) have gradually decreased over time. However, the reduction rate is considerably less than for road vehicles, as has been illustrated in an earlier study by TNO for the Dutch Ministry of Infrastructure and Water Management[1]. Important reasons for this slower pace are notable differences between the type approval requirements of NRMM and road vehicles. These differences concern the testing methods, test conditions and the stringency of emission limits but also a lack of enforcement on in-use performance and durability requirements. Compared to the extensive Euro 7 type approval framework that is currently being implemented for passenger cars and trucks, the mobile machine type approval requirements fall short on each of these aspects.

The aforementioned study showed that PM-emissions from a relatively small NRMM fleet have become comparable to those of the much larger road-vehicle fleet in the Netherlands. For NO_x, road traffic still dominates, but the difference is narrowing.

This is increasingly causing problems, particularly in densely populated urban areas where air quality is already poor, leading to a wide range of national and local initiatives to cut emissions. These include bans on older NRMM emission Stage classes, requirements for the use of zero-emission NRMM, and various measures in between. Therefore, there is a growing need to address the issue at its source by targeting the shortcomings of the current type approval framework and proposing amendments that result in a substantial reduction of NRMM emissions under real-world conditions.

Although the uptake of zero-emission NRMM is progressing, it does not yet provide a full alternative to the existing diesel fleet. Requirements for zero-emission machinery are currently limited to specific sectors. In the Netherlands, for example, these requirements mainly apply to the construction sector. In many other applications, electrification remains limited. This is especially true for high-power machinery and operations in remote or grid-constrained locations. In addition, the uptake of zero-emission NRMM is currently limited in most European Member States. As a result, diesel-powered machinery will continue to play a significant role in the coming decades. Further tightening of emission standards therefore remains necessary and effective. Even during the transition to zero-emission, improved emission control for combustion-engine NRMM is essential.

The type approval requirements and emission limits for NRMM engines are laid down in the UNECE Regulation No. 96 (from here onwards referred to as UNECE R96)[2]. Implementation of this Regulation in Europe is laid down in Regulation (EU)2016/1628[3].

[1] Refer to https://www.government.nl/documents/reports/2025/07/04/proposal-for-amendments-to-unece-r96
[2] Refer to https://unece.org/DAM/trans/main/wp29/wp29regs/2018/R096r3am2e.pdf. Note that UNECE R96 aims at the approval of engines for NRMM with regard to pollutant emissions, which excludes the emissions of CO_2
[3] (EU) 2016/1628 is the main regulation (https://eur-lex.europa.eu/eli/reg/2016/1628/oj).
Note that there are several implementing regulations under this, such as the technical test procedure details in (EU) 2017/654, the in-service monitoring in (EU) 2017/655 (with amendment (EU) 2017/987), administrative details in (EU) 2017/656 (with amendments in (EU) 2018/988) and the UNECE R49 and UNECE R96 approval in (EU) 2021/1398.

The focus for a proposal of amendments to the type approval requirements and emission limits will be at the level of UNECE R96.

The Dutch Ministry of Infrastructure and Water Management first raised the issue of high NRMM emissions during the 90th GRPE meeting in January 2024, to gain support for amending UNECE R96[4]. This was followed by the TNO study which aimed to propose a concrete set of amendments[1].

The present underlying report builds directly on that study, on behalf of the Dutch Ministry of Infrastructure and Water Management. It further expands the knowledge base by incorporating additional insights and results from several recent emission measurement campaigns in the Netherlands. These new data are used to substantiate and complement the proposed amendments to the current NRMM type-approval legislation. Within UNECE R96, the most recent emission limit framework is referred to as 'Stage V'. The findings presented in this report support the introduction of a more stringent next step, provisionally referred to as 'Stage VI'.

A key development supporting this assessment is the availability of a substantially larger dataset of real-world emissions. In 2025 and 2026, many new measurements of construction machinery were completed, resulting in a dataset covering approximately 90 mobile machines. Most of these new data originate from a monitoring programme where Topsector Logistiek and TNO collaborated[5]. The data of this monitoring programme were anonymised before analysis. In addition, datasets were obtained from measurement programmes carried out by TNO on behalf of the Dutch Ministry of Infrastructure and Water Management. The majority of the machines included in the dataset are Stage V machines, followed by Stage IV machines, enabling a robust evaluation of the real-world emission performance of Stage V technology.

In addition to these datasets, particulate matter measurements were performed on three mobile machines without diesel particulate filters. The results of these measurements provide valuable supplementary input, particularly for identifying potential technological gaps and informing further improvements envisioned under a future Stage VI framework.

Readers guide

This report builds on earlier TNO research and presents new real-world emission data collected in 2025-2026. The document is structured as follows.

- Chapter 2 - NO_x-performance of Stage IV and V machines with SCR (56-560 kW): Presents long-term NO_x-monitoring data, including distributions per machine type, load dependence, comparison between Stage IV and V, and temperature-resolved analysis of SCR effectiveness.
- Chapter 3 - Comparative analysis of Stage IV and Stage V real-world emissions: Including effects of engine load on emissions.
- Chapter 4 - NO_x-emissions of Stage V machines below 56 kW and above 560 kW: Evaluates machines without SCR, compares g/kWh and g/h behaviour, and analyses the impact of the legislative thresholds at 56 kW and 560 kW.

[4] See informal document GRPE-90-24, https://unece.org/sites/default/files/2024-01/GRPE-90-24e.pdf

[5] TNO en Topsector Logistiek bundelen krachten voor betere emissie-inzichten mobiele werktuigen - Topsector Logisitek

- Chapter 5 - Particulate matter and particle number emissions: Describes the measurement setup and presents PM, PN, and particle-size results for three non-DPF Stage V machines (generator, light pole, wellpointing pump).
- Chapter 6 - Ammonia emissions: Summarises measured NH_3 concentrations, identifies conditions leading to NH_3-slip.
- Chapter 7 - Potential amendments for Stage VI: Proposes improvements to emission limits, test procedures, monitoring requirements, and durability provisions.
- Chapter 8 - Conclusions and recommendations: Summarises the key findings and provides advice for further development of NRMM emission legislation.

2 Real-World NO_x-emissions of Stage IV and V machinery (56-560 kW)

This chapter analyses the NO_x-emission performance of Stage IV and Stage V machinery between 56 and 560 kW using long-term measurements. It presents machine-type distributions, g/kWh and g/h results, as well as load-resolved patterns.

2.1 Measurement equipment

This section describes the measurement method and equipment used. As noted in the introduction, the majority of the newly obtained data originate from a monitoring programme in which Topsector Logistiek and TNO collaborated.[6] The data of this monitoring programme were anonymised before analysis. Within this programme, external companies installed their own emission measurement systems on behalf of Topsector Logistiek. These are largely based on similar hardware as the TNO-developed Smart Emission Measurement System (SEMS). SEMS is a compact and robust emission monitoring system designed for long-term, real-world operation of diesel engines. For this reason TNO developed, on behalf of Topsector Logistiek, an installation manual.[7] For quality assurance, TNO validated multiple installations performed by each external company and systematically reviewed the resulting measurement data for every individual machine. In addition, datasets were obtained from measurement programmes carried out by TNO on behalf of the Dutch Ministry of Infrastructure and Water Management. For these campaigns the TNO SEMS was applied. For consistency, all measurement devices used in this study are referred to as SEMS, regardless of whether they are TNO-developed systems or externally implemented variants.

Figure 2.1 displays that SEMS consists of a central data logger equipped with 4G connectivity, connected to several sensors and data sources. A combined NO_x/O_2-sensor is installed in the exhaust line downstream of the aftertreatment system, enabling continuous measurement of NO_x- and O_2-concentrations in the exhaust gas. Based on the measured O_2-concentration, CO_2-emissions can be derived. Where applicable, an NH_3-sensor can be added downstream of the SCR catalyst as an optional component.

To obtain relevant engine and operating data, SEMS can interface with the machine's on-board data via an inductive CAN sensor, as shown in Figure 2-1. This allows parameters such as engine speed, torque, and fuel consumption to be logged. These engine signals can be used to convert the measured exhaust gas concentrations (expressed in parts per million) into mass-based emission values (grams). However, most of time a mass air flow (MAF) sensor was mounted upstream of the engine intake to convert ppm's to grams.

[6] TNO en Topsector Logistiek bundelen krachten voor betere emissie-inzichten mobiele werktuigen - Topsector Logisitek
[7] Installatiehandleiding NOx-monitoring op non-road machinery

Vehicle position and operation are recorded via the SEMS-integrated GPS antenna, while all sensor signals are collected by the data logger, which is powered through the machine's electrical system via a relay box. Once installed, the SEMS operates fully autonomously and does not interfere with normal machine operation. Data are recorded at a frequency of 1 Hz. After the machine is switched off, the recorded data are automatically transmitted to a central server via the 4G connection.

Following installation, the measurement equipment remains on the machine for an extended period, typically several months. For each machine, approximately 100 to 300 operating hours of data are collected, providing a representative dataset of emissions under real-world operating conditions and typical use patterns. The minimum amount of data applied as a threshold is 30 hours in total and 1 hour per day.

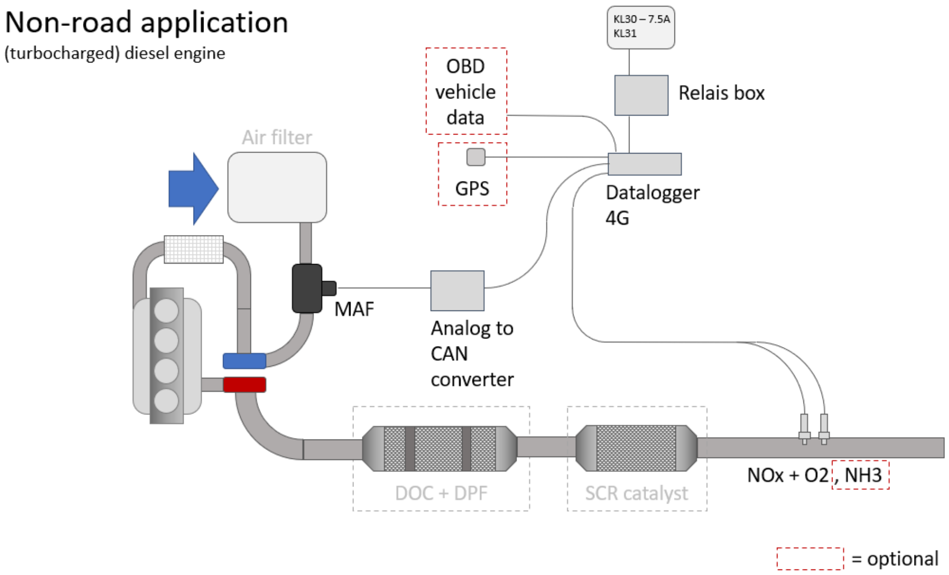

Figure 2-1: Schematic overview of the Smart Emission Measurement System (SEMS) installed on a non-road mobile diesel engine.

2.2 Stage V and IV-engines between 56 - 560 kW

In this analysis, the NO_x-emissions (grams per kWh and grams per hour) of various types of non-road mobile machinery were calculated and compared. The energy-specific emissions (g/kWh) primarily reflects emission control effectiveness relative to useful work. It shows how efficiently NO_x is reduced per unit of energy. The absolute emissions (g/h) shows the total NO_x mass emitted per operating hour, which is strongly influenced by engine size and engine load, in addition to emission control performance.

The results presented in Figure 2-2 and Figure 2-3 using boxplots illustrate both the distribution and the level of the measured emissions per machine type. Measurements from Stage IV and Stage V machines are benchmarked against the legislative Stage IV/V NO_x-emission limit for the power class 56-560 kW, shown by the red horizontal reference line. It should be noted that this emission limit applies under test conditions prescribed in emission legislation, whereas the results shown here are based on real-world operation.

The boxplots depict the statistical distribution of daily average NO_x-emissions. The coloured box represents the interquartile range (the central 50% of the data), with the horizontal line indicating the median value and the dot showing the mean. The whiskers indicate the range of the smallest and largest data points, while individual points outside this range represent outliers, i.e. exceptionally high or low daily emission levels. This representation allows both the central tendency and the variability within and between machine categories to be assessed.

As shown in Figure 2-2 and Figure 2-3 the dataset covers a broad range of machine types, including loaders, tractors, cranes, excavators, rollers, and dumpers. For most categories, emission measurements were obtained from multiple machines, as shown by the number of machines shown in parentheses on the x-axis. The machines operate under a wide variety of real-world duty cycles, which contributes to the observed variation in emission performance. In addition, an aggregated category showing the average daily emissions per machine for all machines is included at the right-hand side of the figure.

Figure 2-2 demonstrates that several machine categories exhibit a wide spread in NO_x-emissions (in g/kWh). In particular, loaders, mobile cranes, tractors, piling rigs, crawler cranes, and concrete processing equipment show high variability and frequent outliers. Upon further inspection of the data this variability can reflect both day-to-day variations in operating conditions for individual machines (e.g. concrete processing) and performance differences between machines within the same category (e.g. tractors). In multiple categories, measured NO_x-emissions regularly exceed the legislative limit line. This does not necessarily indicate non-compliance. The limit is defined for specific test conditions, whereas these measurements reflect real-world use.

By contrast, machine types such as asphalt rollers, pavers/finishers, hydraulic excavators, and dumpers generally show lower NO_x-emissions with a relatively narrow spread, indicating more stable emission performance. The category “Average per machine” shows a comparatively high mean value. This is largely driven by a small number of machine categories with very high emission peaks that increase the overall average mean value despite lower median values across most machines.

Figure 2-3 complements this analysis by presenting the same data in terms of absolute NO_x-emission rates (g/h). The g/h results also show pronounced differences between machine categories, including the effect of engine power demand. Several examples illustrate this effect: crawler cranes, piling rigs, and road milling machines exhibit the highest daily median NO_x emission values. For road milling machines, this is primarily associated with sustained high-load operation, whereas crawler cranes and piling rigs already showed elevated NO_x emissions when expressed in g/kWh. Loaders and tractors provide a further example, displaying moderate median daily emission rates in g/h, consistent with their g/kWh performance. Conversely, the mobile crane illustrates how interpretation changes between metrics, showing only moderate NO_x emissions in g/h despite relatively high g/kWh values. This indicates operation at comparatively low average engine loads.

A key factor influencing the observed variation in NO_x-emissions is the effectiveness of the SCR aftertreatment system, which reduces NO_x-emissions through the use of AdBlue. SCR performance strongly depends on achieving sufficient exhaust gas temperatures, which are typically only reached at higher engine loads. Consequently, machines operating at higher average load factors tend to show lower NO_x-emissions (in g/kWh) but higher AdBlue consumption. In the following section, NO_x-emissions are therefore analysed explicitly as a function of engine load.

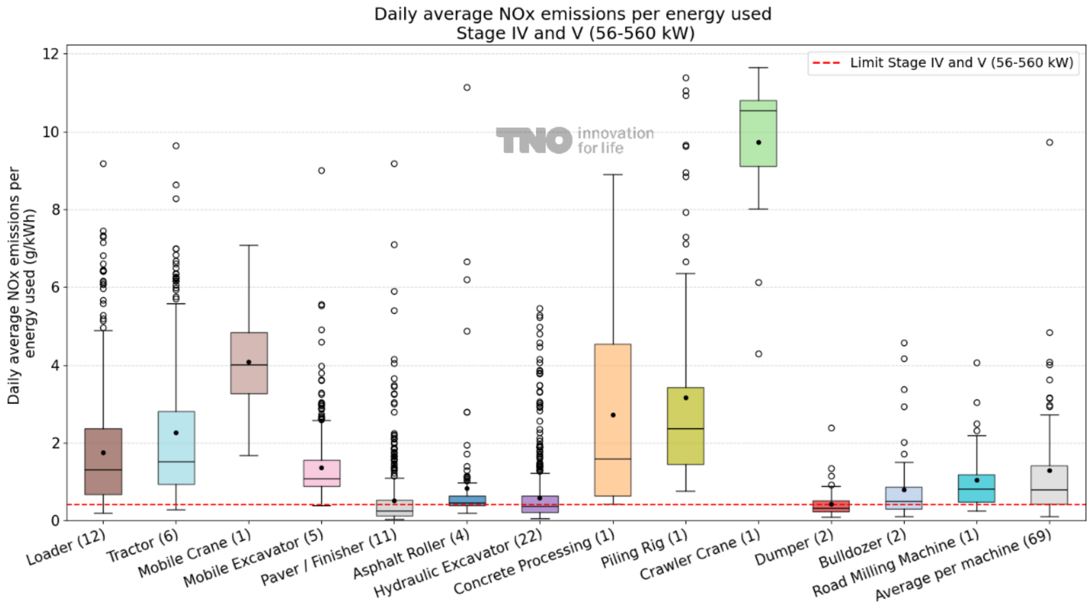

Figure 2-2: Distribution of daily average NO_x-emissions **(g/kWh)** for different types of non-road mobile machinery (Stage IV and V, 56-560 kW).

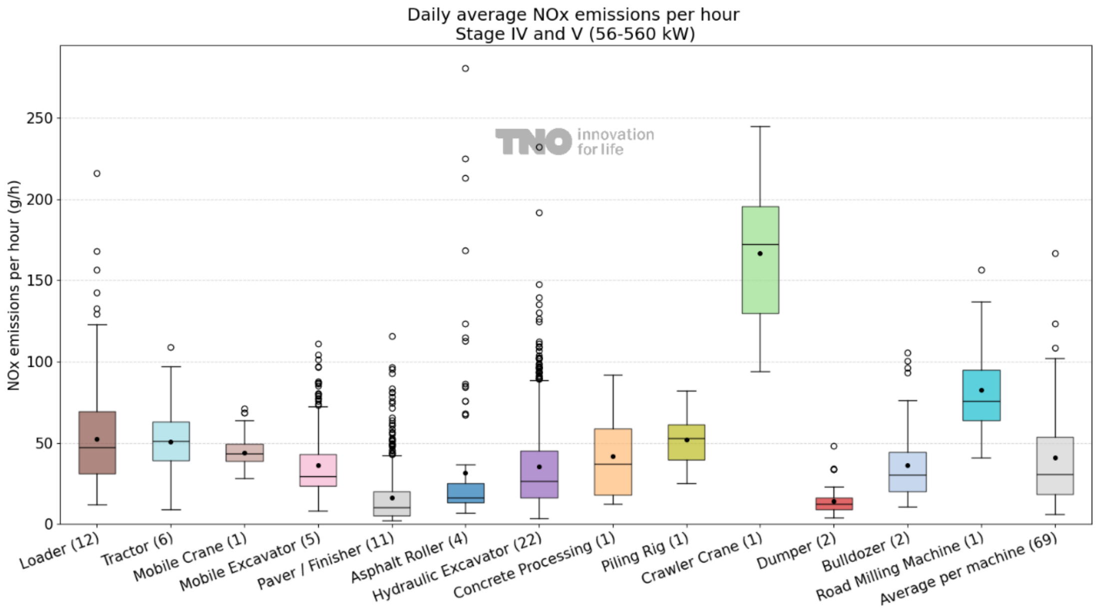

Figure 2-3: Distribution of daily average NO_x-emissions **(g/h)** for different types of non-road mobile machinery (Stage IV and V, 56-560 kW).

2.2.1 NO_x-emissions as a function of engine load

Figure 2-4 presents the average NO_x-emissions per unit of energy (g/kWh) for Stage IV and Stage V machines, shown as boxplots for different engine load bins. Each load bin represents the average engine load over a full operating day, calculated from real-world measurements.

Figure 2-4 shows a pronounced decrease in average NO_x-emissions per unit of energy (g/kWh) with increasing engine load. In the lowest load ranges (0-5% and 5-10%),

NO_x-emissions are highest and exhibit a wide spread, indicating large variability between measurements under low-load operation. In the 10-15% and 15-20% load bins, emission levels decrease but still show considerable variability.

From the 20-25% load bin onwards, NO_x-emissions drop substantially and the distributions become more compact, indicating a transition to more stable emission behaviour. In the intermediate load range between 25% and 35%, median NO_x-emissions are low and variability continues to decrease, although a limited number of outliers are still observed.

At higher load levels (approximately 35-40% and above), median NO_x-emissions reach their lowest values and the spread of the measurements is minimal. This reflects effective and stable operation of the SCR aftertreatment system at higher exhaust gas temperatures. In the highest load bins (45-60%), NO_x-emissions remain low across nearly all measurements, with only a few isolated outliers.

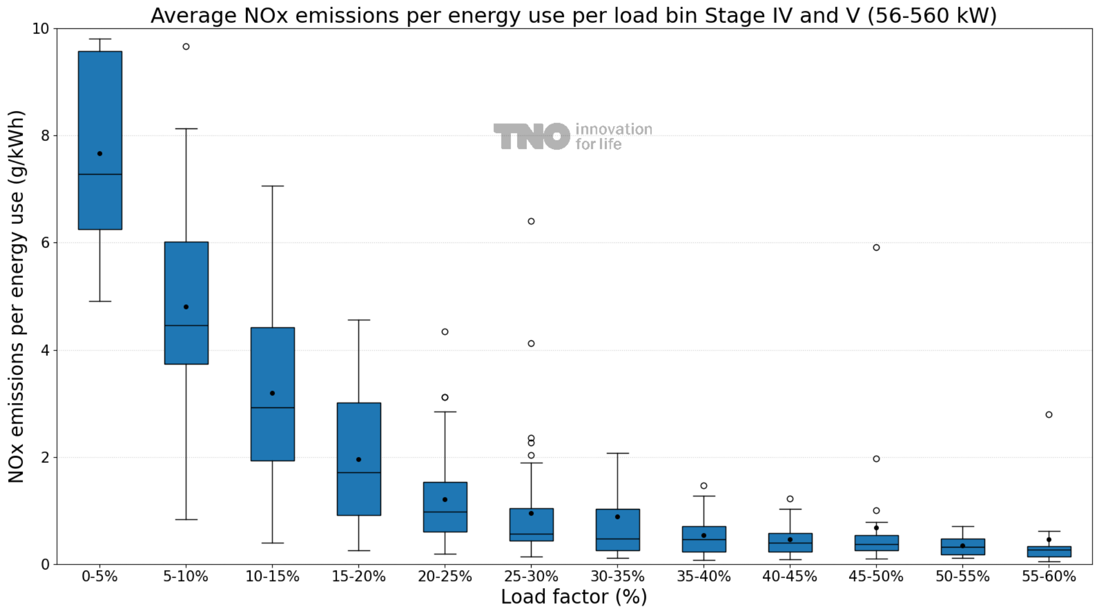

Figure 2-4: Daily average NO_x-emissions per unit of energy (g/kWh), broken down by load bins for Stage IV and Stage V machines (56-560 kW).

3 Comparative analysis of Stage IV and Stage V real-world emissions

Stage IV and Stage V machines are subject to the same legislative NO_x-emission limit. However, Stage IV machines are generally older and have often accumulated a higher number of operating hours. This section examines whether there are systematic differences in real-world NO_x-emissions between these two Stage classes. The number of operating hours were not directly available for all machines and therefore not part of the analysis.

Within both Stage IV and Stage V, further subcategories exist within the power range of 56-560 kW. For Stage IV, these are categories Q and R, where category R includes engines with a rated power below 130 kW and category Q includes engines above 130 kW.
For Stage V, the corresponding subcategories are NRE 5 (<130 kW) and NRE 6 (>130 kW). These subcategories are analysed and illustrated separately.

Since machines equipped with either Stage IV or Stage V engines could be placed on the market in the transition period between 2019 and 2022, machines from these intermediate years were excluded from the analysis to avoid overlap between regulatory stages.

Figure 3-1 presents the daily average NO_x-emissions per unit of energy (g/kWh) for the different Stage categories (Stage IV Q, Stage IV R, Stage V NRE 5, and Stage V NRE 6) within the 56-560 kW power class. Across all subcategories, Stage V machines show clearly better emission performance than Stage IV machines. The median NO_x-emissions for the Stage V categories are substantially lower, and the spread of the data is smaller, indicating more consistent real-world performance.

Within Stage IV, category Q exhibits the largest variability and the highest mean NO_x-emissions. Although the median value for Stage IV Q is lower than that of Stage IV R, the overall distribution indicates less stable emission behaviour. In contrast, both Stage V categories show lower and more stable emissions. Stage V NRE 5 has higher median and mean values than Stage V NRE 6, while Stage V NRE 6 consistently shows the lowest NO_x-emissions of all categories considered.

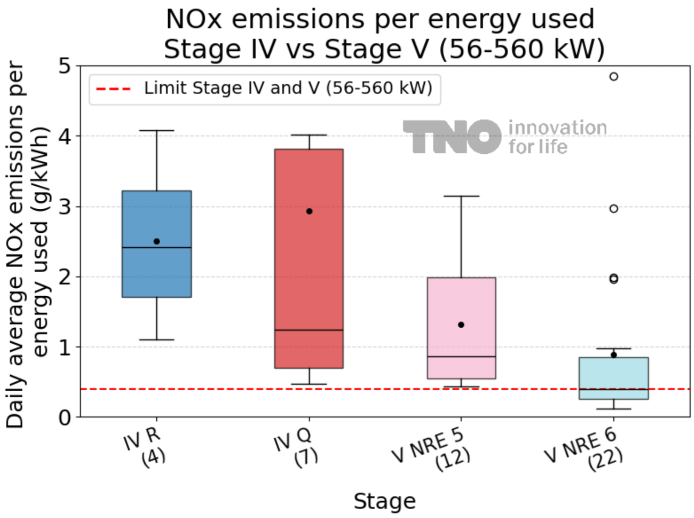

Figure 3-1: Daily average NO_x-emissions per unit of energy (g/kWh) for Stage IV and Stage V non-road mobile machinery within the power range 56-560 kW.

3.1 Dependence of NO_x-emissions on engine load for Stage IV and Stage V machines

Figure 3-2 presents the median NO_x-emissions per unit of energy (g/kWh), shown per engine load bin and Stage subcategory (Stage IV R and Q, and Stage V NRE 5 and NRE 6). Each load bin represents the average engine load over a full operating day.

Figure 3-3 shows the number of measurement days per engine load bin and Stage subcategory, providing important context for the interpretation of Figure 3-2. The data coverage differs substantially between categories. The Stage V subcategories include considerably more measurement days than Stage IV, most notably Stage V NRE 6, which has the highest number of data points across nearly all load bins, particularly between 15% and 40% load. The Stage IV subcategories (R and Q) have markedly fewer measurement days, especially at higher load levels (>30%). In contrast, Stage V NRE 5 has relatively few measurement days in the lowest load bins. Therefore, the comparison between the Stage-classes should be interpreted with caution.

Across the entire load range, a clear and consistent decrease in median NO_x-emissions is observed with increasing engine load in Figure 3-2. At low load levels (0-15%), NO_x-emissions are highest for all categories. From approximately 20-25% load onwards, median emissions decrease sharply and stabilize at low levels at higher loads.

Figure 3-2 shows differences both between the Stage classes and between the individual subcategories. Up to an engine load of approximately 20%, Stage IV R performs comparably to or slightly better than Stage IV Q. Beyond this point, Stage IV Q consistently shows lower median emissions than Stage IV R.

Within Stage V, NRE 6 performs best across the full engine load range, exhibiting the lowest median NO_x-emissions in nearly all load bins. Stage V NRE 5 shows clearly higher median values than NRE 6.

The uneven distribution of data, as displayed by Figure 3-3 implies that differences between Stage IV and Stage V, as well as between individual subcategories, should be interpreted with caution. Part of the observed differences may be related to differences in machine deployment and load patterns. While the figures generally show that Stage V, and especially NRE 6, exhibits lower median NO_x-emissions, the limited data coverage for Stage IV and for some load bins does not yet allow for robust quantitative conclusions.

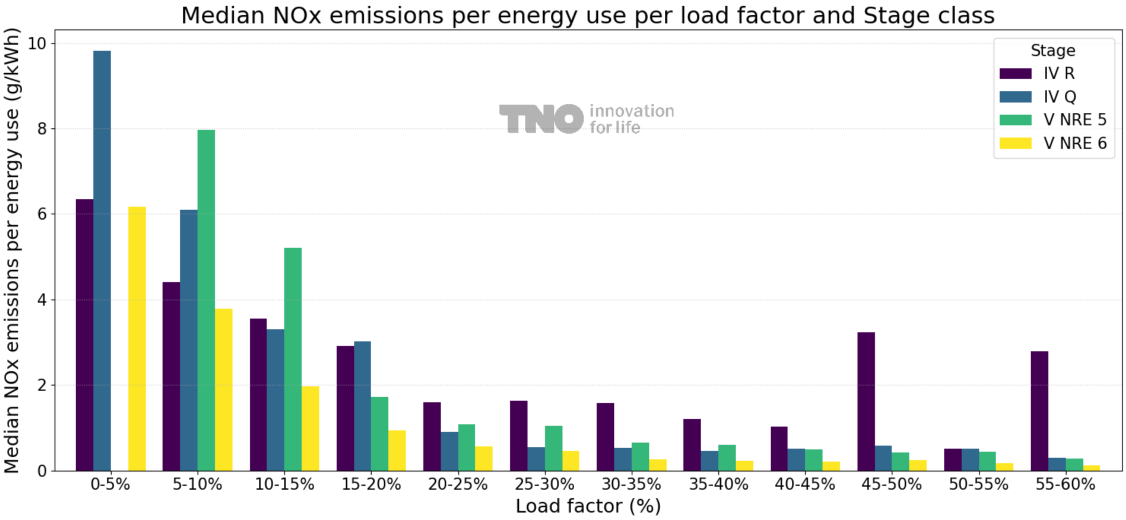

Figure 3-2: Median NO_x-emissions per unit of energy (g/kWh), shown per engine load bin and Stage subcategory (Stage IV Q, Stage IV R, Stage V NRE 5, and Stage V NRE 6).

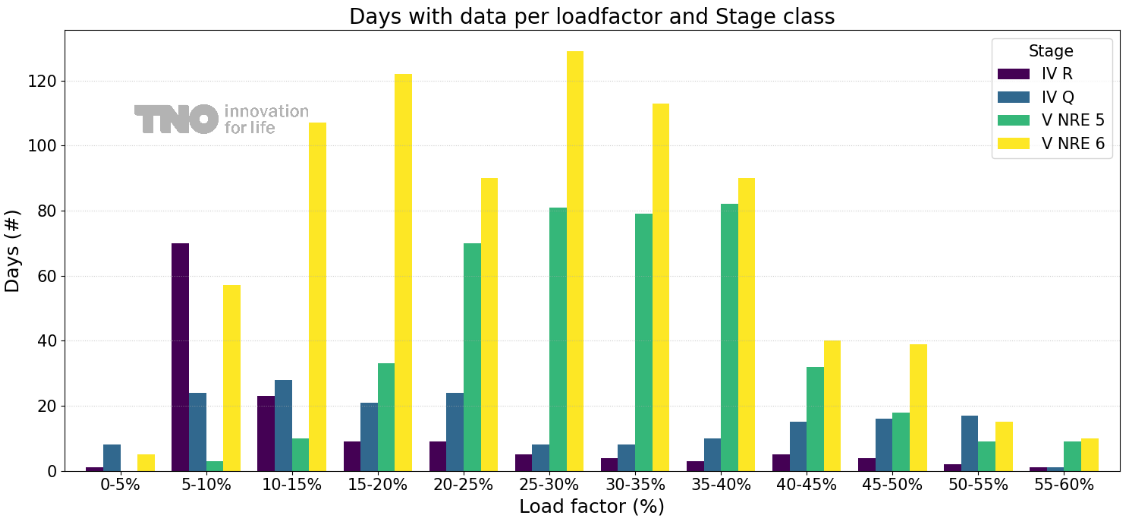

Figure 3-3: Number of measurement days per engine load bin and Stage subcategory (Stage IV Q, Stage IV R, Stage V NRE 5, and Stage V NRE 6).

3.2 Comparison of equivalent Stage IV and Stage V pairs

To enable a more detailed comparison between Stage IV and Stage V emission performance, a targeted dataset of six hydraulic excavators was selected. These machines form three comparable pairs, each consisting of a Stage IV and a Stage V machine within the same power category. This paired approach allows differences in emissions to be attributed primarily to the engine generation, emission stage and potential deterioration effects, rather than to machine type or rated power.

For each manufacturer, one Stage IV machine was matched with an equivalent Stage V machine. In the case of Komatsu, both the machine and the engine are of the same type, with the Stage V version representing an updated engine generation. For Caterpillar and Volvo, the machines are identical or closely comparable, and the engines are based on the same engine block design, albeit from a newer generation for the Stage V variants.
All selected machines fall within the power range of approximately 120-200 kW and are representative of hydraulic excavators commonly used in construction and earth-moving applications. An overview of the measured machines, including manufacturer, model, rated power, and emission stage classification, is provided in Table 3-1.

Table 3-1: Overview of hydraulic excavators measured for the comparison between Stage IV and Stage V emission performance.

Machine name	Type	Make	Model	Power (kW)	Stage
CAT_323___NGMDNRE5	Hydraulic Excavator	Caterpillar	323	129	V (NRE 5)
CAT_323FL_NGMDST4R	Hydraulic Excavator	Caterpillar	323FL	122	IV R
VOL_EC250E_ NGMDNRE6	Hydraulic Excavator	Volvo	EC250EL	168	V (NRE 6)
VOL_EC250E_ NGMDST4Q	Hydraulic Excavator	Volvo	EC250EL	160	IV Q
KOM_HB365L_NGMDNRE6	Hydraulic Excavator	Komatsu	HB365LC-3E0	202	V (NRE 6)
KOM_HB365L_NGMDST4Q	Hydraulic Excavator	Komatsu	HB365LC-3	202	IV Q

The results presented in Table 3-2 show a clear difference in NO_x-emission performance between Stage IV and Stage V excavators, although the magnitude of these differences varies between manufacturers. Evaluating both work-specific emissions (g/kWh) and absolute emission rates (g/h) provides a consistent basis for comparison under real-world operating conditions. In addition to the overall average, g/kWh values are reported for engine loads above 20 %, as this range better reflects the operating conditions considered under current emission legislation.

For the Caterpillar machines, average NO_x-emissions are 0.68 g/kWh for the Stage IV excavator and 0.35 g/kWh for the Stage V excavator. At engine loads above 20 % of rated power, this difference remains. These differences are reflected in the absolute emission rates as well, with 43.1 g/h for the Stage IV machine and 20.8 g/h for the Stage V machine. The Volvo excavators exhibit the largest difference between emission stages. The Stage IV machine shows an average NO_x emission of 0.80 g/kWh, whereas the Stage V machine achieves 0.10 g/kWh, with similarly low values observed at higher engine loads.

This difference is also evident in absolute terms, with average NO_x emissions of 64.2 g/h for the Stage IV machine compared to 8.9 g/h for the Stage V machine. It should be noted, however, that the Volvo Stage V excavator also exhibits considerably lower pollutant emissions than the other Stage V machines in the dataset, which likely contributes to the magnitude of the observed Stage IV-V difference. For the Komatsu, the results are the other way around. Average NO_x emissions are 0.33 g/kWh for the Stage IV machine and 0.39 g/kWh for the Stage V machine. Emissions are closely aligned at engine loads above 20 % power. The higher overall emissions of the Stage V are also driven by a greater share of operation at low-load conditions. This difference is consistent with the average absolute emission of 27.9 g/h for Stage IV and 32.6 g/h for Stage V. The Komatsu Stage IV engine performs best among the Stage IV machines in this comparison. This may be the result of a well performing EGR (Exhaust Gas Recirculation) system. In contrast, the Stage V engine shows the highest emissions among the Stage V engines in this comparison. Nevertheless, it remains below the 0.4 g/kWh emission limit.

Table 3-2: NO_x-emission performance between Stage IV and Stage V excavators.

	CAT_323		Vol_EC250E		KOM_HB365L	
	Stage V (NRE5)	Stage IV (R)	Stage V (NRE6)	Stage IV (Q)	Stage V (NRE6)	Stage IV (Q)
Monitoring time [h]	496	332	132	173	381	279
NO_x [avg g/kWh]	0.35	0.68	0.1	0.8	0.39	0.33
NO_x [avg g/kWh >20% power]	0.21	0.53	0.09	0.78	0.21	0.21
NO_x avg [g/h]	20.8	43.1	8.9	64.2	32.6	27.9
NO_x avg [g/l_fuel]	1.43	2.74	0.41	3.69	1.57	1.3

3.2.1 Dependence of engine load

Figure 3-4 shows the average NO_x-emission rates in grams per hour as a function of engine load for the Stage IV and Stage V excavators. For the Caterpillar 323, the Stage V machine exhibits consistently lower NO_x-emissions than the Stage IV machine across almost the entire load range, with the difference becoming more pronounced at higher engine loads. The Volvo EC250E displays the largest difference between emission stages. NO_x-emissions from the Stage IV machine increase strongly with engine load, whereas the Stage V machine maintains very low emission levels over the full load range. For the Komatsu HB365L, the NO_x-emission levels of the Stage IV are generally somewhat lower than those of the Stage V machines. However, this difference is not consistent across the engine load range. This finding is in line with the average NO_x-emissions discussed previously.

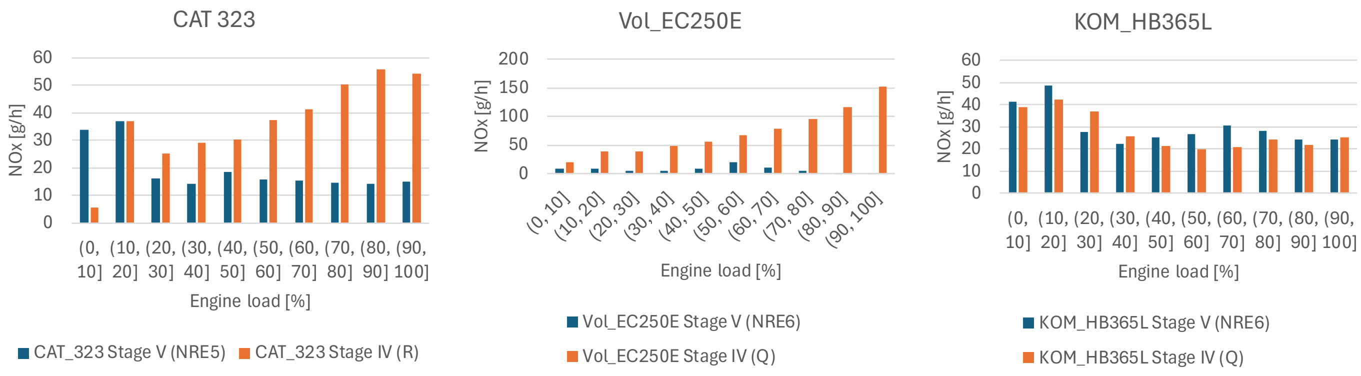

Figure 3-4: Average NO_x-emission rates (g/h) as a function of engine load for the paired Stage IV and Stage V excavators from Caterpillar (CAT 323), Volvo (EC250E), and Komatsu (HB365L). The figure illustrates load-dependent differences in NO_x emissions between emission stages and shows engine-specific performance characteristics under real-world operating conditions.

3.2.2 Functioning of the SCR

The relationship between exhaust gas temperature, NO_x-emissions after the SCR catalyst, and the share of operating time provides additional insight into the observed Stage IV and Stage V emission differences. The graphs in Figure 3-5 show NO_x-concentration downstream of the aftertreatment system as a function of exhaust gas temperature, together with the corresponding operating time distribution.
For the evaluated excavators, a clear operating region can be identified around exhaust gas temperatures of approximately 250-320 °C, where a large share of the operating time is accumulated. Within this temperature range, NO_x concentrations after the catalyst are consistently low, indicating effective operation of the exhaust aftertreatment system. This behaviour is particularly evident for the Volvo Stage V machine, where NO_x-levels remain near zero over the dominant temperature range. This explains the very low average NO_x-values observed both in g/kWh and g/h. In contrast, the Stage IV machines show higher NO_x-concentrations over a broader exhaust temperature range. Although these machines also spend a significant fraction of operating time at exhaust temperatures around 280-320 °C, NO_x-reduction at these temperatures is less effective, resulting in substantially higher downstream NO_x-levels. This effect is especially pronounced for the Volvo Stage IV excavator, which exhibits elevated NO_x-concentrations even within temperature ranges typically favourable for NO_x-control. This contributes to the large difference observed between the Stage IV and Stage V variants.

For the Caterpillar excavators, the Stage V machine demonstrates a distinct reduction in NO_x-emissions once exhaust gas temperatures exceed approximately 250 °C, coinciding with the primary operating region. The Stage IV machine, by contrast, shows increased NO_x-concentrations across much of the same temperature range, which is consistent with the higher average NO_x-emissions observed in both work-specific and absolute terms. The Komatsu machines display similar temperature-NO_x characteristics between emission stages. Both Stage IV and Stage V variants show decreasing NO_x concentrations with increasing exhaust gas temperature, and the main operating regions largely overlap. However, the Stage V machine operates slightly more often outside the optimal SCR temperature range.

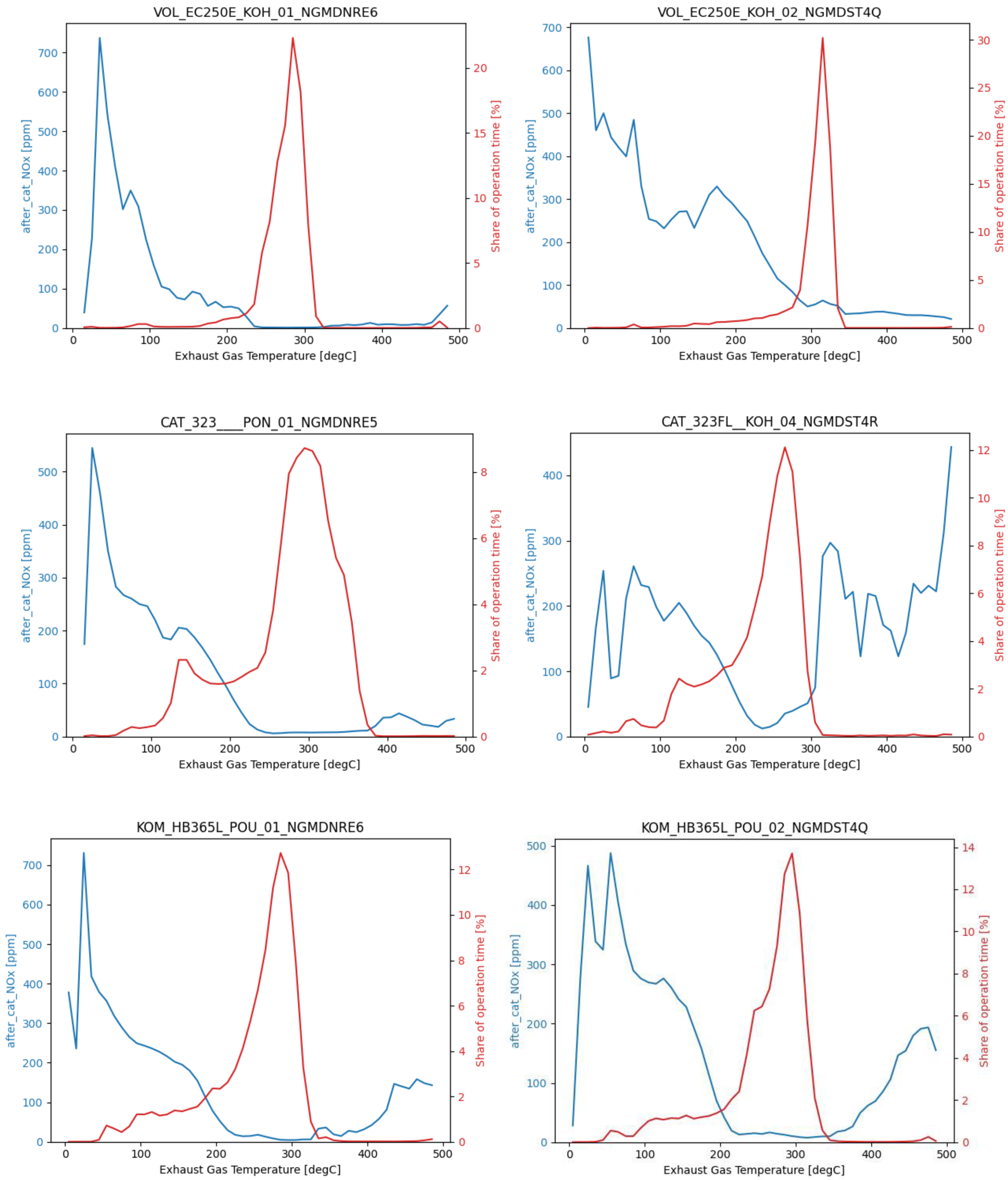

Figure 3-5: Distribution of exhaust gas temperature and corresponding NO_x concentration downstream of the aftertreatment system for the evaluated Stage IV and Stage V excavators. The blue lines show average NO_x concentration after the catalyst, while the red line indicate the share of operating time as a function of exhaust gas temperature. The plots illustrate differences in temperature-resolved NO_x control effectiveness between emission stages and manufacturers under real-world operating conditions.

3.3 Conclusion on Stage V versus Stage IV

Stage IV and Stage V machines are subject to the same legislative NO_x emission limits. However, the analysis shows differences in real-world emission performance. Across the full dataset, Stage V machines generally exhibit lower median NO_x emissions, with less variation. These differences are most pronounced at medium and high engine loads, where the SCR aftertreatment system operates effectively. Data coverage is however limited, particularly for Stage IV machines and certain load ranges. Moreover, the analysis does not determine the cause of these differences. It is unclear whether they result from engine generation and emission stage or from deterioration effects.

4 Real-World NO_x-emissions of Stage V machinery below 56 kW and above 560 kW

This chapter examines the real-world NO_x-emissions of Stage V machines below 56 kW, which operate without SCR. Results are compared with the SCR-equipped 56-560 kW class to identify the impact of the current regulatory threshold. Also for this category, the majority of the newly obtained data originate from the earlier mentioned monitoring programme in which Topsector Logistiek and TNO collaborated. The same measurement equipment is applied as described in paragraph 2.1.

4.1 Emission performance of Stage V <56 kW

The real-world NO_x-emission performance of Stage V machines with a rated power below 56 kW is evaluated using both energy-normalised emissions (g/kWh) and absolute emission rates (g/h), see Figure 4-1 and Figure 4-2.

The applicable legislative emission limit for this group is 4.7 g/kWh for NO_x + THC, determined under type-approval test conditions. No SCR is needed to comply with this emission limit. The results shown here represent real-world performance rather than compliance test outcomes and are not expected to directly align with the legislative limit.

The g/kWh results show substantial variability across machine types. Hydraulic excavators and pavers/finishers generally exhibit median daily average NO_x emissions below the legislative limit, indicating comparatively effective emission control under real-world operation. In contrast, asphalt rollers, and most notably generator sets, display higher median emissions and a wider spread, including several pronounced outliers. Compared with earlier results for Stage V machines in the 56-560 kW range equipped with SCR, the machines below 56 kW clearly show higher median NO_x-emissions and greater variability. This pattern is consistent with the absence of NO_x-aftertreatment systems in this lower power class.

The g/h results provide complementary insight by illustrating the absolute NO_x mass emitted during operation. Hydraulic excavators and asphalt rollers show median emission rates of approximately 35-45 g/h, with moderate variability. Pavers/finishers operate at somewhat higher but relatively stable emission levels, around 60-70 g/h, reflecting their higher average engine loads, although these results should be interpreted with caution due to the limited number of machines. The generator sets show the largest spread, with median emissions around 50 g/h and maximum values exceeding 140 g/h, indicating prolonged operation under elevated and variable loads. Tool carriers (comparable configuration as a wheel loader) exhibit the highest median absolute emission rates, around 100 g/h, consistent with their typically high and continuous power demand.

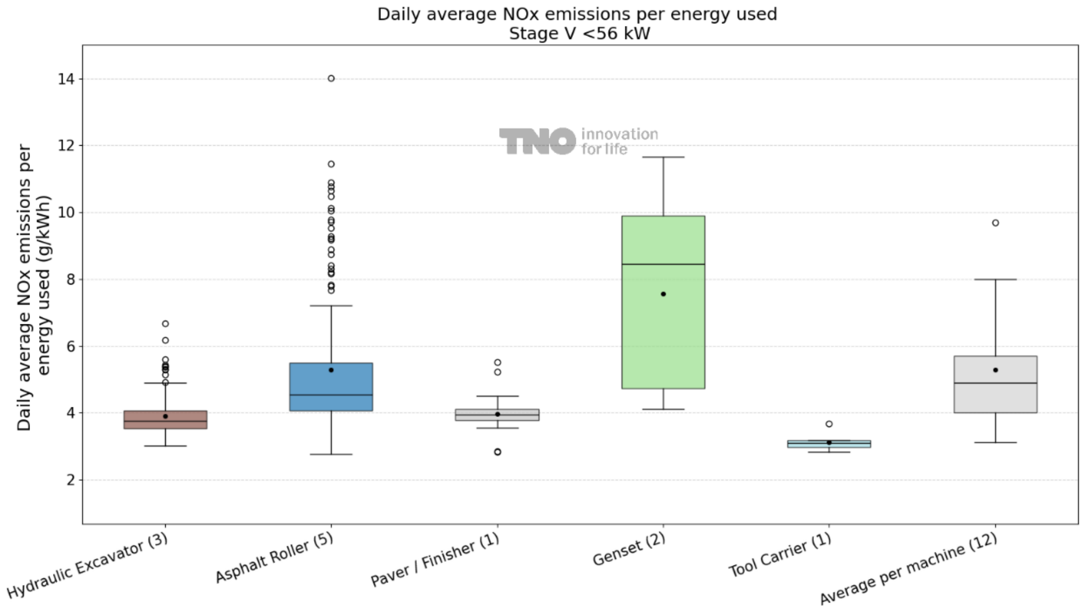

Figure 4-1: Daily average real-world NO_x emissions per unit of energy (g/kWh) for Stage V non-road machinery with a rated power below 56 kW, shown per machine type.

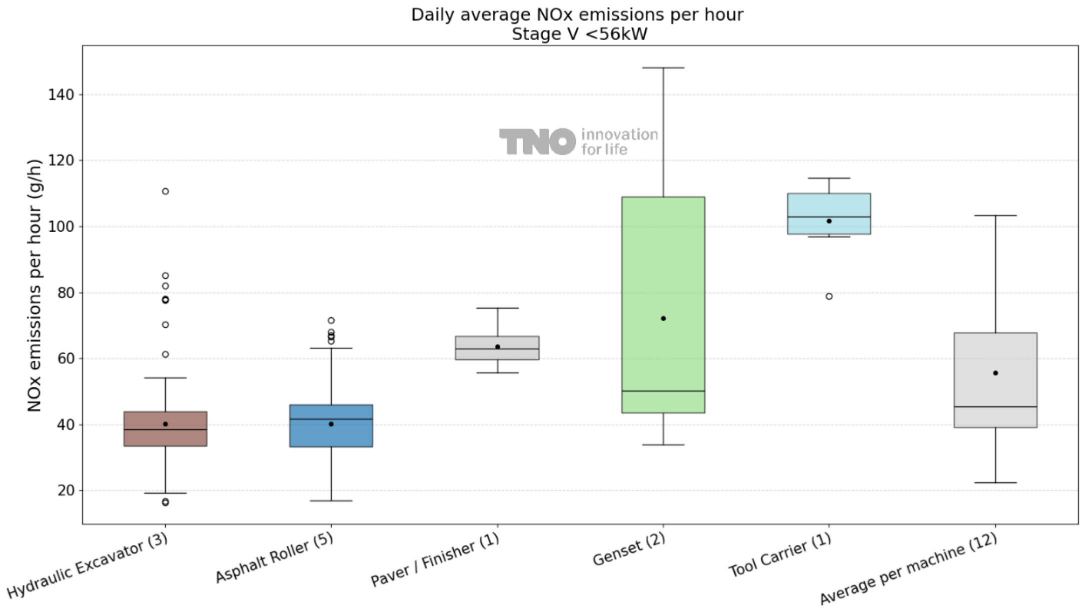

Figure 4-2: Daily average real-world NO_x emission rates per operating hour (g/h) for Stage V non-road machinery with a rated power below 56 kW, shown per machine type.

4.2 Comparison of NO_x-emissions of different power classes

Under Stage V emission legislation, non-road mobile machinery (NRMM) with a rated power of 56 kW or higher and up to 560 kW is equipped with a Selective Catalytic Reduction (SCR). For NRMM with a rated power below 56 kW or above 560 kW, the installation of an SCR system is not necessary under the current regulatory framework, as compliance with the emission limits can be achieved without NO_x aftertreatment in this power range.

Figure 4-3 compares real-world NO_x emissions of all measured Stage V non-road mobile machinery across three power classes: machines with rated power below 56 kW, 56-560 kW, and above 560 kW. The results are shown both as energy-specific emissions (g/kWh) and as absolute emission rates (g/h), highlighting the influence of machine size and power category on emission behaviour.

The g/kWh results (left graph) show a pronounced difference between the power classes. Stage V machines in the 56-560 kW range exhibit the lowest median NO_x-emissions per unit of energy, with a relatively narrow spread. This reflects the use of SCR aftertreatment in this power category and its effective operation under typical medium-to-high load conditions. By contrast, Stage V machines below 56 kW show substantially higher median g/kWh values and greater variability, including several high outliers. This indicates less effective NO_x control, which is consistent with the absence of SCR systems in this power class. Machines above 560 kW also show higher median g/kWh values than the SCR-equipped 56-560 kW group. However, there is less variability than the <56 kW category. This might be the result of less measured machines above 560 kW.

The g/h results (right graph) provide a complementary perspective by showing the absolute NO_x mass emitted during operation. Here, the ordering between power classes is different. Absolute NO_x-emissions are significantly higher for the largest engine size, with machines above 560 kW showing by far the highest average emission rates, exceeding 500 g/h. This reflects sustained operation at very high power levels. Machines in the 56-560 kW range show much lower average emission rates (around 35 g/h), while machines below 56 kW exhibit moderate absolute emissions (around 55 g/h).

In general Stage V machines in the 56-560 kW power range perform best in terms of g/kWh as well as g/h due to effective SCR aftertreatment. Although in some cases their absolute emissions can exceed those of smaller machines. These results demonstrate the strong influence of the 56 kW and 560 kW regulatory threshold on Stage V emission behaviour.

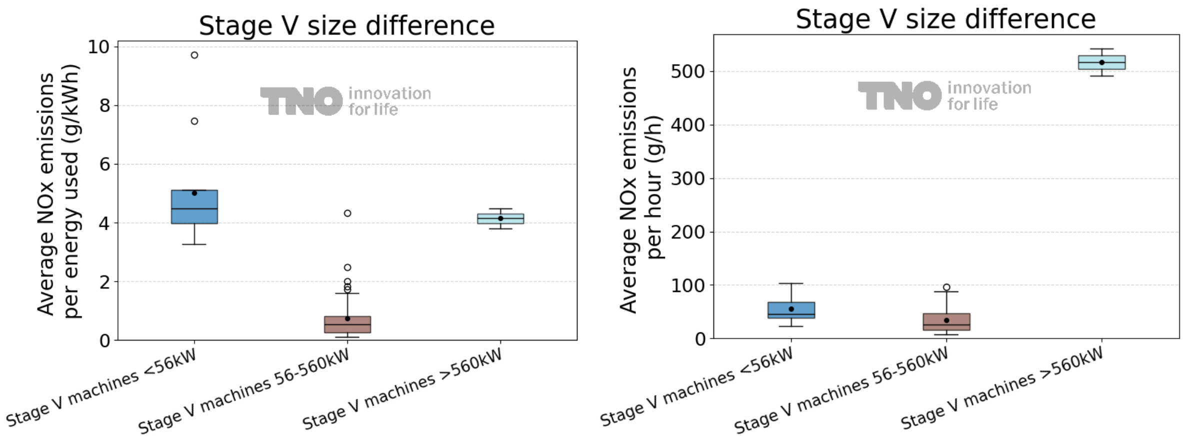

Figure 4-3: Daily average real-world NO_x-emissions per unit of energy (g/kWh)(left) and per operating hour (g/h) (right) for Stage V non-road mobile machinery, grouped by rated power class (<56 kW, 56-560 kW, and >560 kW).

4.3 Real-world NO_x-emissions of Stage V machines around the 56 kW threshold

As mentioned in the previous section, the absolute emissions in grams per hour are dependent on the delivered engine power. Larger engines therefore generally show higher absolute emissions (within the same power class). Despite this, the dataset shows that the <56 kW Stage V machines still exhibit average absolute NO_x-emissions around 1.5 times higher than those of the 56-560 kW class, based on all measured machinery. This shows that the absence of SCR systems below 56 kW has a clear and measurable impact on real-world NO_x emissions, outweighing the effect of lower rated power.

To enable a more like-for-like comparison, the analysis is refined in the following section by focusing specifically on machines with rated power closest to the Stage V regulatory threshold of 56 kW. For the <56 kW category, machines in the 40-56 kW range are selected; for the >56 kW category, machines in the 85-100 kW range are chosen to represent the lower end of the SCR-equipped class (lower engine powers were not available in the dataset). In both groups, only hydraulic excavators and rollers are included.

Figure 4-4 present the real-world NO_x-emissions of Stage V hydraulic excavators and rollers in the 40-56 kW and 56-100 kW power ranges, expressed respectively as energy-specific emissions (g/kWh) and absolute hourly emissions (g/h).

The g/kWh results show a clear and systematic difference between the two power classes. Machines in the 40-56 kW range exhibit NO_x-emissions around 4-5 g/kWh. By contrast, machines in the 56-100 kW class show significantly lower values, generally below 0.5 g/kWh, and only limited variability. This large difference directly reflects the presence of SCR systems in the >56 kW category, enabling effective NO_x reduction under real-world conditions.

The g/h results provide additional insight into the real-world emission impact. Machines in the 40-56 kW range emit approximately 45-50 g/h on average per day, while the SCR-equipped machines in the 56-100 kW range emit only 15-20 g/h, despite their higher rated power.

The consistently lower g/h emissions of the 56-100 kW group show that effective aftertreatment more than compensates for the higher engine power.

The comparison around the 56 kW threshold confirms that SCR-equipped Stage V machines achieve substantially better NO_x-control, both in g/kWh and in grams per hour. Machines below 56 kW show higher NO_x-emissions, confirming that the 56 kW Stage V threshold constitutes a significant distinction in real-world NO_x behaviour

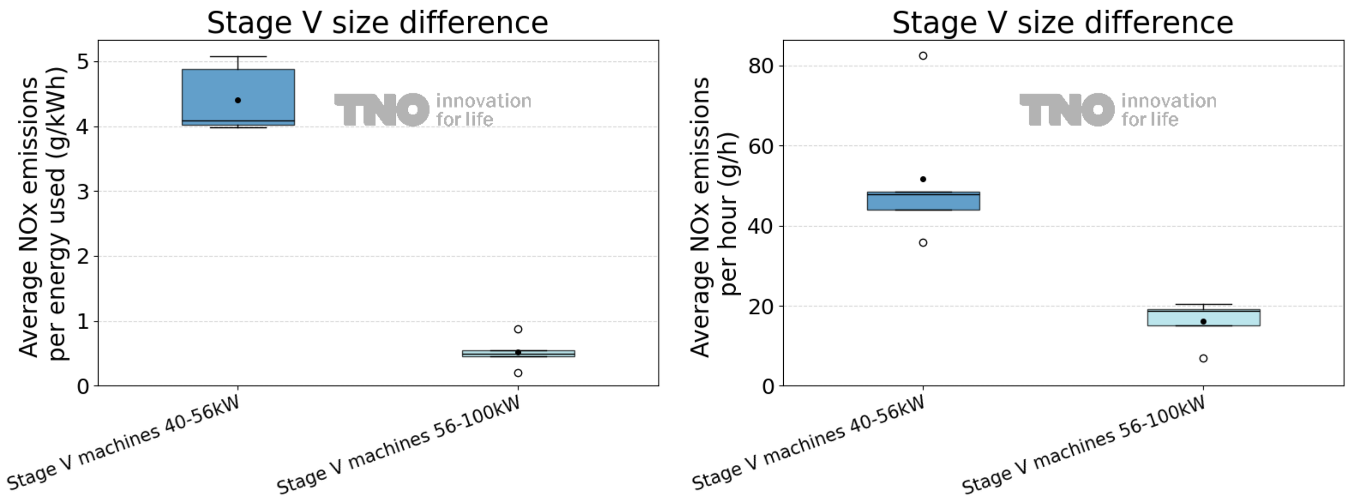

Figure 4-4: Daily average real-world NO_x emissions per unit of energy (g/kWh) for Stage V machines in the 40-56 kW and 56-100 kW power classes (left graph). Daily average real-world NO_x emission rates per hour (g/h) for Stage V machines in the 40-56 kW and 56-100 kW power classes (right graph).

5 Particle emissions from small non-DPF Stage V engines

In addition to the NO_x-measurements, particulate matter (PM) measurements were carried out on three mobile machines that are not equipped with diesel particulate filters (DPFs). These measurements were conducted on behalf of the Ministry of Infrastructure and Water Management. These measurements provide valuable input for the discussion on future Stage VI emission requirements, as modern Stage V machines below 19 kW and above 560 kW are currently not required to have a DPF. As a result, engines in these power classes emit notable levels of particulate mass and number in real-world operation.
The measurements presented here therefore characterises in-use particulate emissions of these machine categories.

5.1 Measurement equipment

For these measurements, several specialised instruments were used to quantify the particle number, particle size distribution, and particle mass in the exhaust gas.

To measure particle number (PN) of the machinery, the Horiba OBS-ONE PN unit or the TSI NPET were employed. Both instruments operate according to the Condensation Particle Counter (CPC) principle and are capable of detecting particles in the size range of 23 nm to 1000 nm. These instruments provide real-time PN data, enabling accurate assessment of ultrafine particle emissions.

The particle size distribution was determined using the Dekati ELPI+, a real-time particle spectrometer that measures particles from 6 nm to 10 µm. This wide measurement range makes it possible to characterise both ultrafine and coarse particulate fractions.

For particle mass (PM) determination, a TNO-developed filter measurement setup was used. In this configuration, a controlled fraction of the exhaust gas is diluted with clean, dry air and drawn through a sampling filter. Prior to sampling, the appropriate dilution ratio and loading duration are established to ensure that the filter receives a representative and analytically suitable particle load for subsequent gravimetric analysis. The sampling filters are replaced at each test point.

During the tests, NO_x and O_2 concentrations were simultaneously measured. This was done using the so-called “BOEM kit” equipment. These measurements allow the particulate data to be linked to gaseous emission behaviour. A Mass Air Flow (MAF) sensor was included upstream of the engine to enable conversion of concentration-based data into mass-based emission values.

Figure 5-1 provides an overview of the complete measurement setup. After intake air passes through the MAF sensor and enters the engine, the exhaust stream is sampled in parallel by the various measurement systems for particle number, particle size distribution, particle mass, and gaseous emissions.

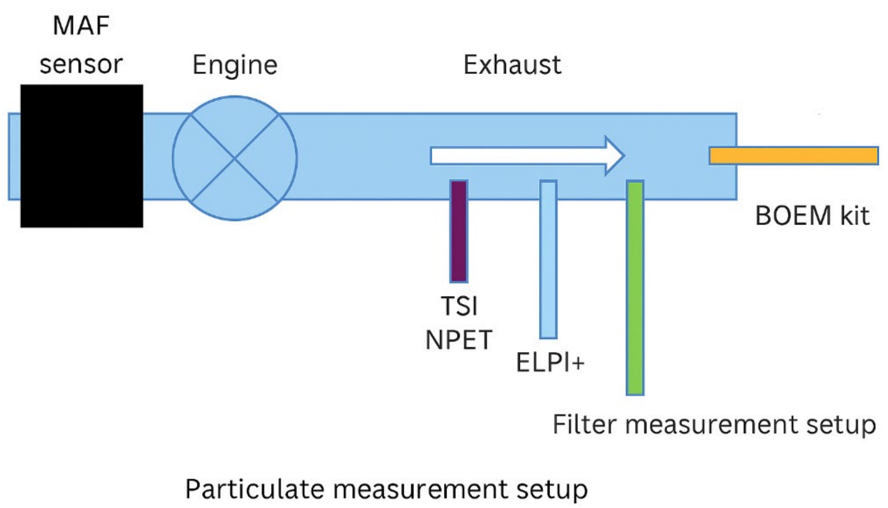

Figure 5-1: Schematic overview of the particulate measurement setup used for real-world testing. Intake air passes through a MAF sensor before entering the engine. Downstream of the engine, exhaust samples are taken by a TSI NPET, ELPI+, and a filter measurement setup, with a BOEM kit located at the end of the exhaust line for auxiliary measurements.

5.2 Measured machinery and test conditions

For the particulate and gaseous emission measurements, three mobile machines without diesel particulate filters (DPFs) were selected, see Table 5-1. These machines represent typical Stage V equipment in the lower power classes where DPFs are not required under current legislation (<19 kW).

The machines differ in operating characteristics and load-control possibilities, which influenced the test approach. The generator (18.9 kW, Stage V NRE 2) was tested using a load bank, allowing the engine load to be varied across the measurement cycles. This provided stable and repeatable conditions for evaluating particulate emissions under different steady-state load points.

For the light pole (3 kW, Stage V NRE 1), engine load was varied by switching on and off different numbers of lamp units. This method enabled load steps representative of practical operation while remaining simple and repeatable for testing purposes.

For the wellpointing pump (5.5 kW, Stage V NRE 1), engine load could not be varied, as the pump operates at a nearly constant load determined by the pump activity. To evaluate fuel effects, the pump was tested with both standard diesel and HVO.

All machines were tested with both a cold engine start and a warm engine start. All warm-condition cycles were repeated at least three times to ensure repeatability and to capture measurement variability under representative operating conditions.

Table 5-1: Overview of measured machines.

ID	Type	Power (kW)	Stage	Fuel
BRE_R8887_NSTDNRE2	Generator	18.9	V (NRE 2)	Diesel
GEN_R7457P_NSTDNRE2	Light Pole	3	V (NRE 1)	Diesel
CLA_SUPERS_NSTDNRE1	Wellpoint pump	5.5	V (NRE 1)	Diesel

5.3 Measurement results - particle emissions

In this paragraph, the particle emissions results are described of the three machines. For context, the legislative particle mass limit for Stage V engines below 19 kW is 0.4 g/kWh (during type-approval test). No legislative particle number (PN) limit exists for this power class. In contrast, non-road engines between 19 kW and 560 kW must be equipped with a DPF due to a significantly lower PM limit of 0.015 g/kWh in combination with a stringent PN limit of 1×10^{12} #/kWh. Due to the varied applications of the machines tested, not all type-approval load points of the Stage V legislative procedure could be followed in this measurement programme.

5.3.1 Generator

Although the generator's diesel engine has a maximum mechanical power of 19 kW, the electrical output of the generator was limited to 12 kW. As a result, the measurement programme included load points of 2, 5, 7, 9, and 12 kW, representing the majority of the usable load range of the generator in practice. The measurements at 7 kW and 12 kW were repeated at least three times to ensure repeatability.

Figure 5-2 shows the PM-emissions for the generator at the available load points. PM-emissions in g/kWh are highest at very low load (2 kW), reaching approximately 0.16 g/kWh. The g/kWh emissions decrease substantially as load increases, stabilising in the range of 0.05-0.08 g/kWh for loads above 5 kW. However, the cold-start measurement at 7 kW shows a temporary increase in emissions. While the measured PM values remain well below the Stage V type-approval limit of 0.4 g/kWh for engines below 19 kW, they would exceed the much lower Stage V particulate mass limit of 0.015 g/kWh that applies to engines above 19 kW, which require a DPF.

The right graph in Figure 5-2 expresses the same measurements as absolute PM mass emissions per hour. Unlike the g/kWh trend, PM in g/h increases with load, ranging from 0.3-0.35 g/h at low load to 0.5-1.0 g/h at higher load points.

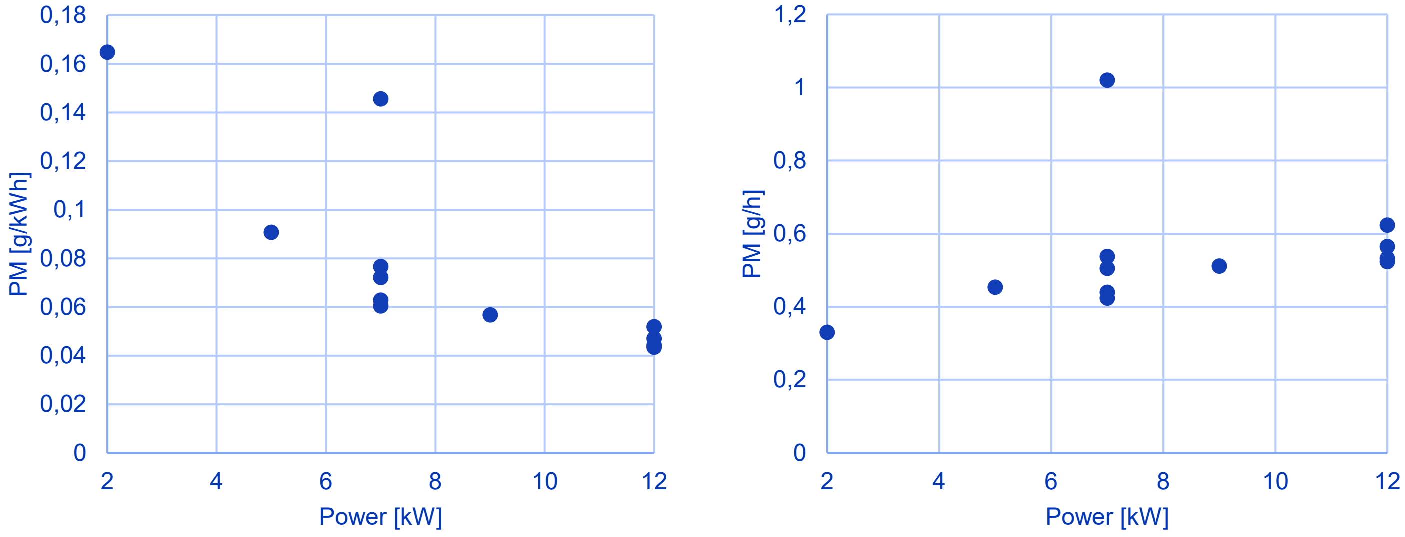

Figure 5-2: Particulate mass (PM) emissions in g/kWh (left) and g/h (right) for the generator measured at different load bank power levels.

Figure 5-3 presents PN emissions in #/kWh. At lower and medium loads (2-7 kW), PN values range between 2.0×10^{14} and 2.3×10^{14} #/kWh, decreasing to 1.0×10^{14}-1.2×10^{14} #/kWh at the highest loads (9-12 kW). All values are orders of magnitude above the PN limit of 1×10^{12} #/kWh applicable to >19 kW Stage V engines with DPFs, clearly reflecting the absence of particulate filtration in this power category.

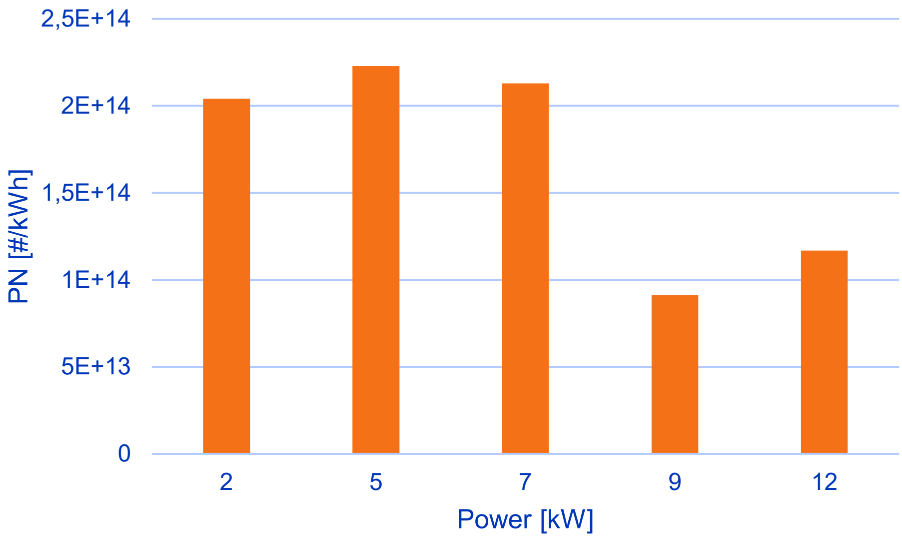

Figure 5-3: Particle number (PN) emissions in #/kWh for the generator at different load bank settings.

Figure 5-4 shows the ELPI+ size-resolved PN emissions for the 7 kW load point. The majority of emitted particles fall within the ultrafine fraction (<100 nm). The comparable PN values for <100 nm and <235 nm indicate that virtually all particles are smaller than 100 nm. This size distribution is typical for diesel engines.

This demonstrates that, although total mass emissions remain below the Stage V PM limit for this power class, number-based emissions are dominated by ultrafine particles that are not captured by the PM mass metric.

When comparing the ELPI+ and NPET particle number results (expressed in #/kWh), it becomes clear why the ELPI+ reports higher values. The NPET is a CPC-based instrument that only counts particles larger than 23 nm, as required by the Stage V regulatory method. All particles smaller than 23 nm are therefore excluded from the NPET measurement. The ELPI+, on the other hand, measures particles from 6 nm upward, capturing a much larger share of the ultrafine particle spectrum. Because the generator emits many particles below 23 nm, the ELPI+ naturally reports higher PN values. In addition, the ELPI+ is more sensitive to shifts in particle size distribution, which can further increase differences.

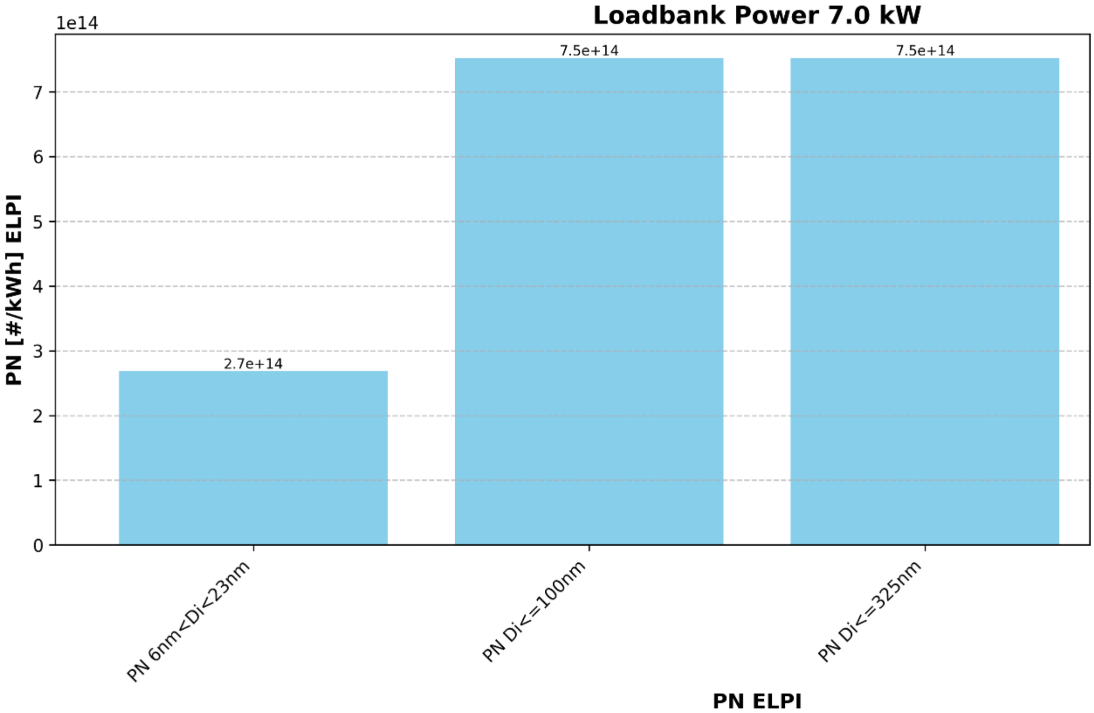

Figure 5-4: Particle number size distribution of the generator at 7 kW load, measured using the ELPI+. Most emitted particles are smaller than 100 nm.

5.3.2 Light pole

Following the generator measurements, the light pole was tested at different load levels by switching on an increasing number of lights. Figure 5-5 present the particulate mass emissions (PM) in g/kWh (left) and g/h (right) for the available operating points. The number of lights switched on only slightly changes the engine load, as the lighting system represents a relatively small share of the generator’s total electrical capacity.

The left graph in Figure 5-5 shows that the PM-emissions per unit of energy remain within a relatively narrow range across all load levels. With 0 to 4 lights on, the PM values lie between 0.07 and 0.12 g/kWh, showing only limited sensitivity to engine load. Overall magnitude remains well below the Stage V PM limit of 0.4 g/kWh applicable to engines below 19 kW.

As displayed in right graph of Figure 5-5, the absolute PM-emissions (g/h) increase moderately with higher electrical load. PM varies from 0.10 g/h at low load to approximately 0.15-0.25 g/h when four lights are active. This increase reflects higher fuel consumption at increased load. The highest value with 4 lights on was measured during cold start of the engine. Absolute PM-emissions are lower than those of the generator, which is consistent with the substantially smaller engine size.

The data analysis shows that the measured PN values for the light pole fall between 2.6×10^{14} and 5.6×10^{14} #/kWh, which is somewhat higher than the generator emissions. These values are far above the Stage V PN limit of 1×10^{12} #/kWh that applies to engines between 19 kW and 560 kW (which require a DPF), illustrating again that small non-DPF engines can emit very high numbers of ultrafine particles.

The ELPI+ size distribution for the light pole is broadly similar to that of the generator. The majority of particles fall below 100 nm, confirming that ultrafine particles dominate the emissions. However, compared with the generator, the fraction of particles below 23 nm is slightly smaller.

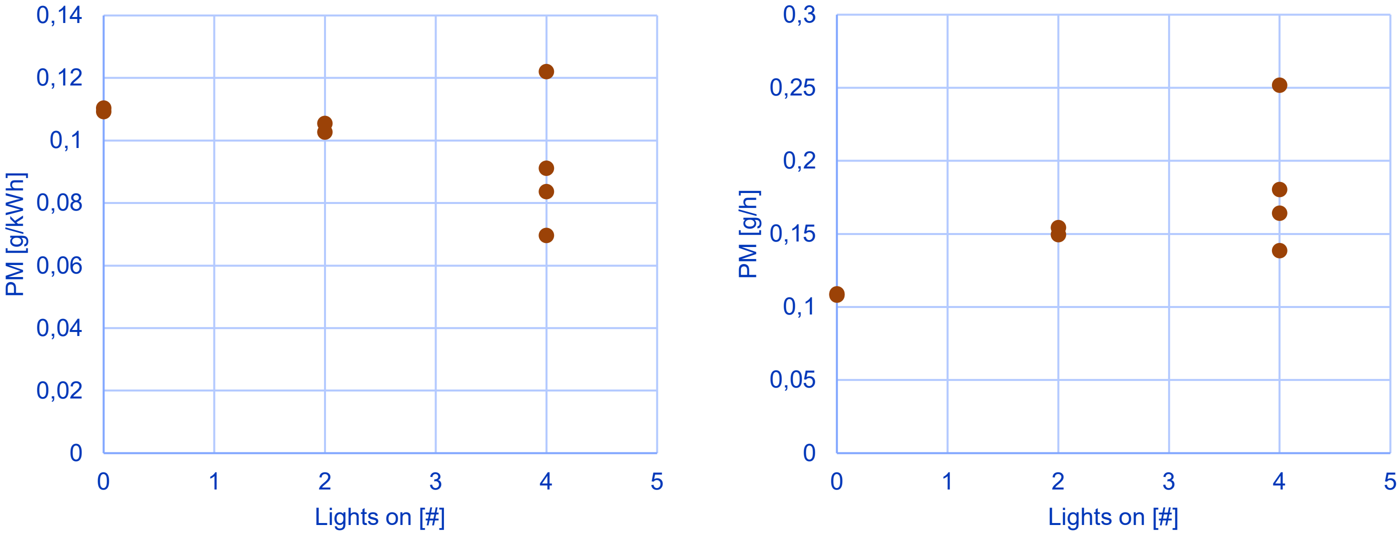

Figure 5-5: Particulate mass (PM) emissions in g/kWh (left) and g/h (right) for the light pole as a function of the number of lights switched on.

5.3.3 Wellpoint pump

The wellpointing pump was tested under steady-load operation, first on diesel and then on HVO, with multiple repetitions. As with the generator and light pole, both PM and PN were measured. Because the pump operates at an essentially fixed mechanical load, the results show less variation than for the other machines.

During testing, several measurement points exhibited elevated PM-emissions. Most of these were cold-start events, during which the PM-emissions were two to ten times higher than during warm operation. One high-emission event occurred with a warm engine, though the cause could not be determined. This unexplained result showed PM values approximately four times higher than the average and is therefore excluded from the boxplots for clarity. In practical operation, pumps often run continuously for long periods (24/7), which makes cold-start emissions largely irrelevant for real-world exposure.

In this section box plots are shown. In the three figures below, the boxplots show the interquartile range (IQR), the median, the mean (× symbol), and the typical variation of repeated warm-engine measurements. The whiskers represent the range of normal observations.

Figure 5-6 shows the particulate mass emissions per unit of energy for both fuels. The boxplots show slightly higher PM-emissions for diesel (median around 0.15 g/kWh) compared to HVO (median around 0.11-0.12 g/kWh). The diesel results also show a wider spread, reflecting the sensitivity of PM to combustion conditions. All results remain below the Stage V PM limit of 0.4 g/kWh (some cold start events and one outlier exceeded this limit), although they are clearly above the much stricter PM limit (0.015 g/kWh) applicable to engines above 19 kW that require a DPF.

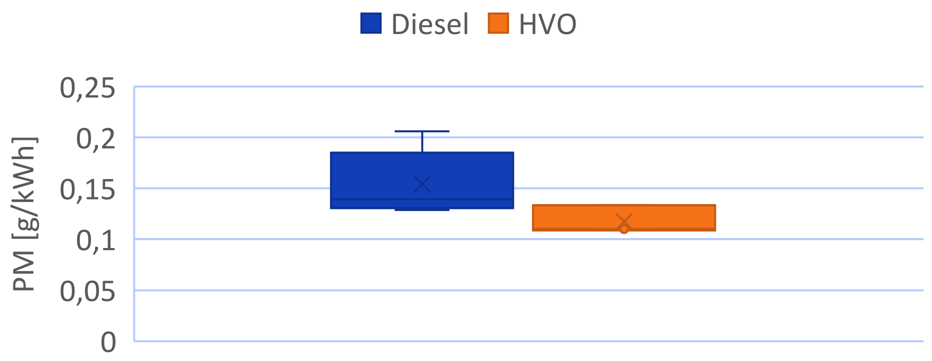

Figure 5-6: Particulate mass (PM) in g/kWh for the wellpointing pump running on diesel and HVO.

Figure 5-7 presents the same PM results expressed as absolute mass per hour. As expected for a constant-load engine, the spread is similar to the g/kWh results. Diesel produces PM-emissions around 0.12-0.18 g/h, while HVO shows lower emissions, typically 0.10-0.12 g/h.

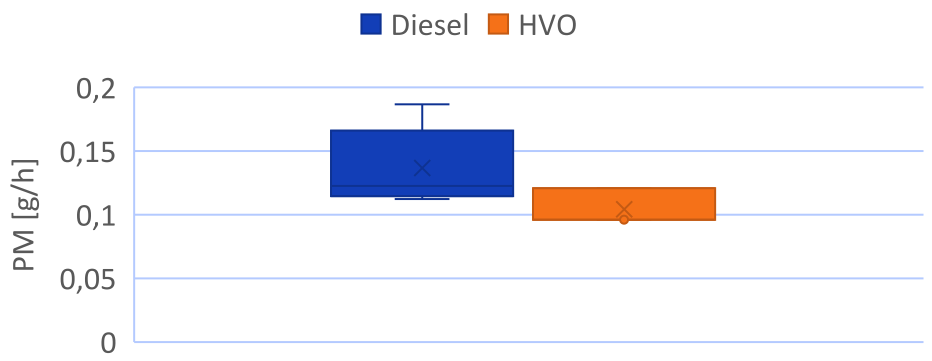

Figure 5-7: Particulate mass (PM) in g/h for the wellpointing pump on diesel and HVO.

Figure 5-8 shows the PN emissions for diesel and HVO. PN values for the pump operating on diesel range between 1.4×10^{14} and 1.8×10^{14} #/kWh, while HVO results fall slightly lower, around 1.1×10^{14}-1.2×10^{14} #/kWh. Although HVO reduces particle number emissions compared with diesel, all PN values are orders of magnitude above the Stage V PN limit for engines between 19 and 560 kW (1×10^{12} #/kWh), highlighting the effect of operating without a DPF.

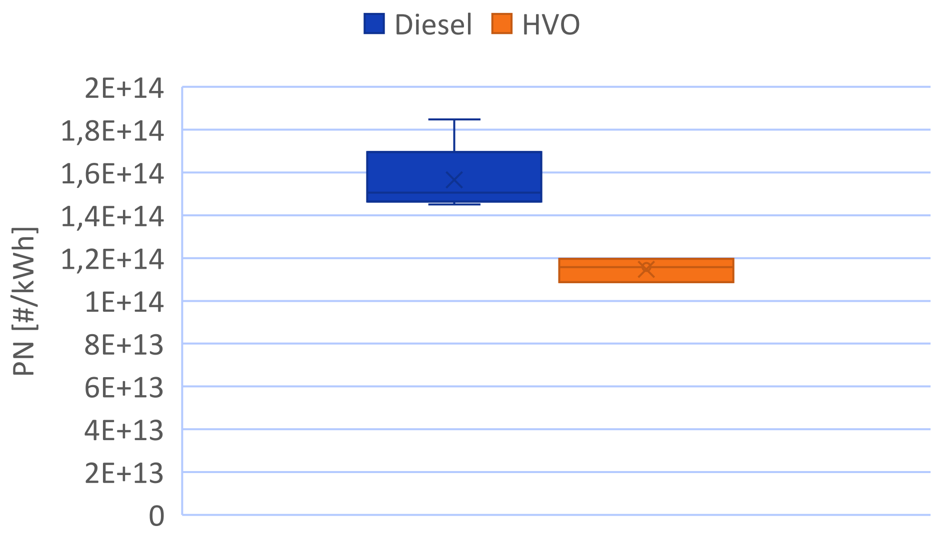

Figure 5-8: Particle number (PN)-emissions in #/kWh for the wellpointing pump using diesel and HVO.

5.3.4 Summary across different machines

Across the three non-DPF Stage V machines, the generator, light pole and wellpointing pump, clear and consistent patterns emerge. All machines show PM mass emissions well below the Stage V limit of 0.4 g/kWh, but they would exceed the much lower Stage V particulate mass limit that applies to engines above 19 kW, which require a DPF. Moreover, very high particle number (PN) emissions are shown, in the range of 10^{14} #/kWh, far above the PN limit that applies to larger engines equipped with DPFs.

The generator shows strong load effects: PM per kWh is highest at low load, while absolute PM increases with load. Its particle size distribution is dominated by ultrafine particles (<100 nm), with a large fraction below 23 nm. The light pole produces similar PM levels at all load settings. PN emissions are slightly higher than the generator, and the size distribution is again dominated by ultrafine particles, though with somewhat fewer particles <23 nm. The wellpointing pump shows stable emissions under warm, steady operation. HVO consistently reduces both PM and PN compared with diesel. Cold-start events cause short-term PM spikes (2-10 times higher than the average), but these are not relevant for typical 24/7 pump operation. One unexplained high warm-engine measurement (≈4× the normal PM level) was excluded.

6 Ammonia emissions from SCR-equipped NRMM

Within discussions amongst legislators on effective emission control, it has been suggested that a limit for ammonia (NH_3) should be introduced for non-road mobile machinery (NRMM). Currently, Stage V machines have no limit value for NH_3. Due to the application of Selective Catalytic Reduction (SRC) technology in Stage IV and Stage V machines, the NH_3-emissions have increased via NH_3 slip due to an incomplete reaction of the urea solution (AdBlue) injected into the SCR. When a machine injects more AdBlue than the amount that is able to react with the available NO_x in the SCR, then the excess AdBlue will cause NH_3 slip from the exhaust. Therefore, there is an increased risk of substantial NH_3 emissions in modern Stage V machines.

As a reference, Euro VI heavy-duty on-road diesel vehicles have had an emission limit for NH_3 in the World Harmonised Stationary Cycle (WHSC) and the World Harmonised Transient Cycle (WHTC) since 2013. The current NH_3 limit for Euro VI vehicles is set at a maximum average NH_3-concentration of 10 parts per million (ppm) during the test cycles. From 2028, this limit will be changed to 0.06 g/kWh under the Euro 7 legislation for heavy-duty diesel vehicles.

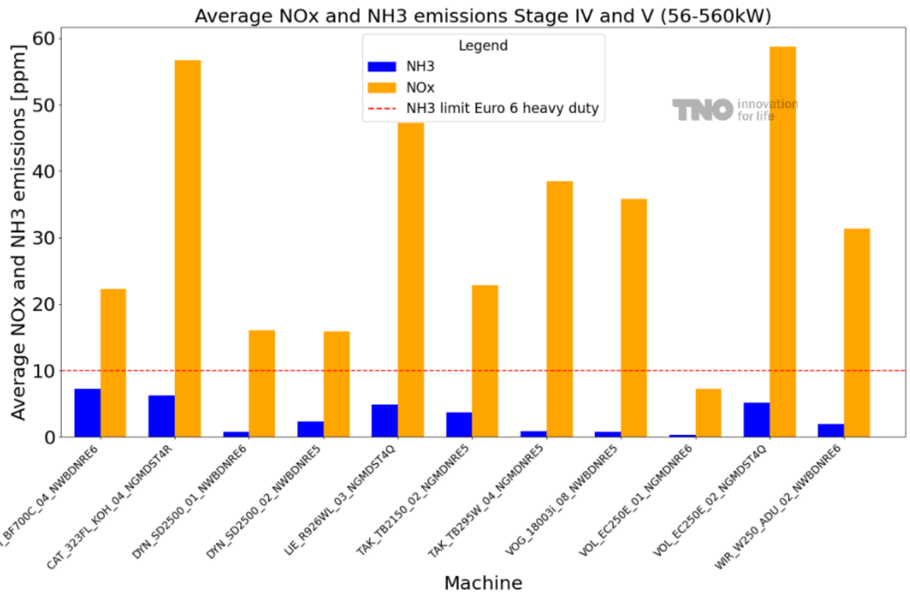

Figure 6-1: A comparison of average NH_3 and NO_x concentrations of NRMM measured by TNO. The line shows the Euro VI NH_3 emission limit.

6.1 Measured NH_3-concentrations in NRMM

In Figure 6-1 measured NH_3-concentrations of 11 Stage IV and Stage V machines are displayed alongside measured NO_x-concentrations. It is observed that the measured machines stay well below the Euro VI limit of 10 ppm.

Figure 6-2 shows how much variation was observed amongst the NH_3-measurements for each machine. Although the machines, on average, stay below the Euro VI limit, it is observed that the variation in the measurements and the number of outliers is large meaning one should be careful with the interpretation of these results.

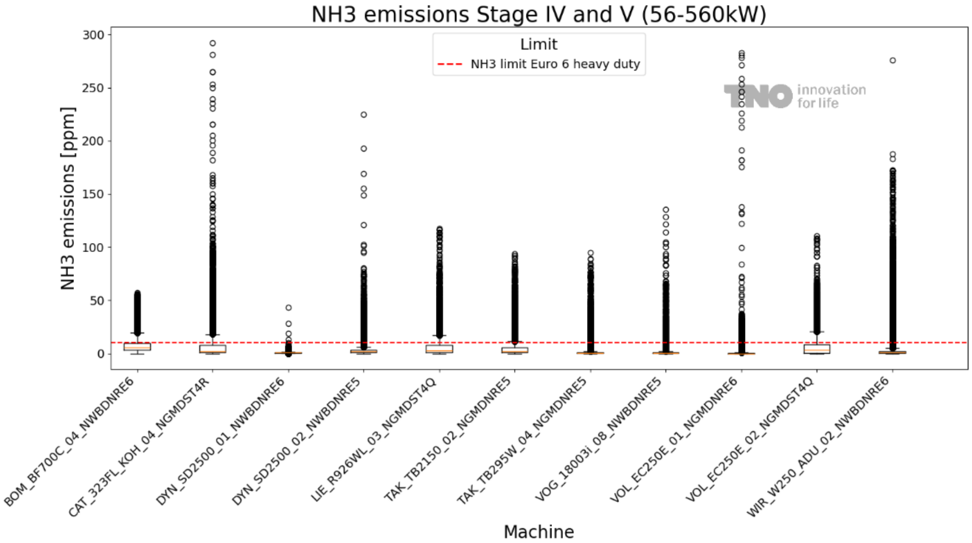

Figure 6-2: Variation of the NH_3 concentrations of the machines during the measurements in a box plot.

6.2 NH_3 slip at lower and higher temperatures

In Figure 6-3 and Figure 6-4 the measured NH_3-concentrations of two Stage V machines are displayed as a function of exhaust gas temperature. In Figure 6-3 raised NH_3-concentrations are observed at exhaust gas temperatures (EGT) below 100 degrees Celsius. Because the SCR is too cold under these low load and low EGT conditions for the AdBlue to react well with the NO_x from the engine, typically high NO_x-emissions are observed under these conditions. Raised NH_3 concentrations at low EGT may be an indication of the AdBlue dosing to be too high under low temperature conditions. The second machine does not clearly show raised NH_3 concentrations at low temperatures.

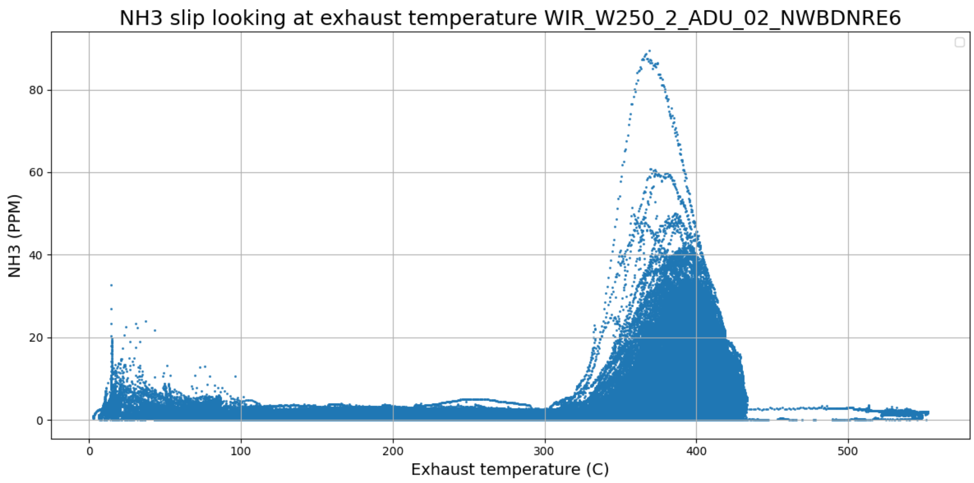

Figure 6-3: Measured NH_3-concentrations as a function of exhaust gas temperature of a Stage V 272 kW road milling machine engine.

Both Figure 6-3 and Figure 6-4 show raised NH_3-concentrations at higher exhaust gas temperatures. Possible explanations for this phenomenon include the rate of adsorption and desorption of NH_3 in the SCR[8], overdosing AdBlue and AdBlue deposit decompositions at high temperatures. Further research is needed to explain these observations in greater detail.

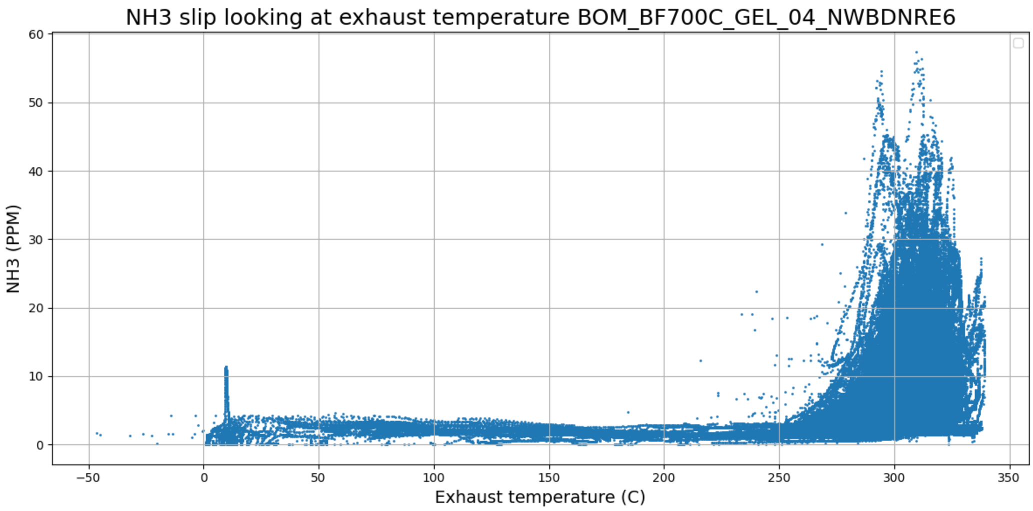

Figure 6-4: Measured NH_3 concentration as a function of exhaust gas temperature of a Stage V 140 kW engine of a paver/finisher. This machine also applies exhaust gas recirculation (EGR) alongside the SCR for NO_x reduction.

[8] See, for example: Study on Rates of NH3 Adsorption and Desorption in SCR on Various Engine Operation Conditions | MDPI

7 Identified gaps and potential amendments for Stage VI

This chapter synthesises the findings from all earlier chapters and translates them into potential amendments for a future Stage VI emission standard. This report has revealed a number of issues which lead to high pollutant emissions of NRMMs in real-world conditions. These elevated emissions are observed even for machines that comply with the requirements of the current Stage V emission regulation. This leads to a situation where NRMM emissions are playing an ever more prominent role in their impact on air quality. Considering that NRMM emissions do not decrease in the same rate as those of other emission producing sectors -such as transport- this problem is expected to worsen. This is calling for the need of a new Stage VI emission standard, for which the potential amendments will be identified in this section, building on the ones that were already recommended in the previous report[9]. Note that these amendments primarily target NRMM categories with diesel engines (referred to in UNECE R96 as Compression Ignition - CI), which fall in sub-category NRE.

There are three main areas identified where shortcomings of the Stage V standard are observed:

a) *Lack in stringency and consistency and absence of a limit for NH_3*
There is up to a factor of 10 difference in the stringency of emission limits for NO_x and particles between the power-classes regulated in Stage V of UNECE R96. Many NRMM fall in the power-classes below 56 kW (in the Netherlands this is more than 60% of the fleet), where particularly for NO_x the emission limits are much more relaxed. Similarly, all machines in the power classes below 19 kW benefit from relaxed PM emission limits. Also machines above 560 kW have less stringent limits for NO_x and PM/PN.

In addition, these large differences lead to the issue of 'power-bin hopping'[9], this is the effect that machines with an output power close to border between power-classes are type-approved at a slightly lower or higher power level to take advantage of the more relaxed emission limits. Manufacturers apply this strategy to circumvent additional costs for exhaust aftertreatment.

b) *Unrepresentative test conditions*
The engine load patterns applied during the type approval tests are not representative for all real-life use conditions of NRMM engines. Particularly the low-load and idle conditions which occur frequently in normal use (idling shares between 20 to 30% of the total operation time are often observed) are not sufficiently covered in the type approval test. These low-load operating conditions lead to high real-world NO_x-emissions due to the exhaust temperature being too low for the SCR catalyst to facilitate NO_x-conversion.

[9] Refer to https://www.government.nl/documents/reports/2025/07/04/proposal-for-amendments-to-unece-r96

c) *Absence of in-use performance monitoring and checking*
Once the NRMM engine has been put into service, there is no checking mechanisms in place to observe whether the engine is well-maintained, if it is not being tampered with or even if the exhaust aftertreatment systems are functioning well. NRMM users also have no possibility to monitor if the emission levels are in their normal range. In addition, the durability requirement covers on average only roughly the first nine years of the useful life, while in reality NRMMs are kept in service for a much longer time. Finally, these durability requirements are not verified on in-service engines.

For each of these shortcomings, potential amendments are identified in the following paragraph to address the respective issues.

7.1 Potential amendments

To arrive at a new generation of NRMMs having a low pollutant emission contribution throughout their useful life, the following amendments are proposed to be considered for a new Stage VI. These amendments are based on the main identified areas of shortcomings of the current Stage V standard of UNECE R96:

a) Lack of stringency

- *Increased stringency for NO_x-emissions*
  For sub-category NRE engines in the power-classes from 19 to 37 kW, from 37 to 56 kW and above 560 kW the emission limit should be reduced to 0.4 g/kWh, which is the required level for all engines from 56 to 560 kW. This ensures that all engines above a power output of 19 kW are equipped with a functional SCR-catalyst which considerably helps to cut down NO_x-emissions.
- *Increased stringency for PN-emissions*
  For sub-category NRE engines in the power-classes from 8 to 19 kW and above 560 kW the introduction of the same PN limit of 1 x 10^{12} #/kWh as for the power-classes in between would necessitate the application of a particulate filter to meet this limit. Consequently, the particle emissions for engines falling in these power-classes will reduce by more than 99%.
- *Introduction of a NH_3-limit*
  Evidence from the transport sector and measurements on NRMM engines equipped with SCRdeNO_x exhaust aftertreatment with urea injection reveals that considerable NH_3-emission levels may occur in the exhaust gases. There are technical possibilities to avoid this, such as the use of NO_x-sensors for accurate dosing of urea and application of a NH_3 slip catalyst. However, these solutions will only be installed if they are demanded by the legislation. Therefore, introduction of a NH_3 emission limit could be considered for those power-classes where the NO_x limit is low and thus requires application of SCRdeNO_x aftertreatment.

b) Unrepresentative test conditions

- *More emphasis on low-load and idle conditions*
  For the NRE engine sub-categories where a NO_x limit of 0.4 g/kWh is applicable (or will become applicable), there is a need to introduce a specific low-load and idle test cycle.

The objective of this is to ensure that during these conditions the SCRdeNO$_x$ catalyst (or any other deNO$_x$ technology) will continue to be sufficiently effective in their emission reducing capabilities. A potential candidate for such a test cycle is the Nonroad Low Load Cycle (nonroad LLC) applied by the California Air Resources Board[10]. Another approach -but assumed to be less effective- is to extend the control area for low-load operation, as currently the points that are randomly selected may not be chosen below 30% of the engine torque or 30% of the engine power.

c) **Absence of in-use performance monitoring and checking**

- *Introduction of on-board monitoring for NO$_x$-emissions*
  If the previous points leads to NO$_x$-sensors being applied on engines within the relevant power-classes, this also allows for the mandatory introduction of on-board monitoring of NO$_x$-emissions. This will help the operator to get real-time insight into the emission performance of the engine. If anomalies are observed, the operator is notified and can take action to correct these.
- *Introduction of in-service conformity (ISC)*
  Similar to the emission legislation for road vehicles, an in-service conformity requirement for the manufacturer could be introduced. This will help to ensure that engines keep fulfilling the emission limits, not only when they are new but also while being in service for a longer time. There is currently a durability period in place, however without any accountability as to whether engines actually fulfil this requirement in practice. The current In-Service Monitoring requirement in the European legislation is already seen as a prelude for a future In-Service Conformity requirement. This methodology could be used as a basis for an ISC test method.
- *Introduction of explicit anti-tampering/-manipulation*
  The introduction of explicit anti-tampering/-manipulation provisions is essential. These provisions should apply not only at the point of placing engines on the market, but also throughout their operational lifetime. Without such safeguards, emission control systems may be disabled, bypassed, or improperly maintained during use, undermining regulatory effectiveness. This need is particularly strong for NRMM, as there are currently no periodic technical inspection (PTI) or roadside inspection (RSI) regimes targeting emissions. As a result, there is limited to no oversight once machines are in service. In some Member States there is also no clear or specific national ban on owners and users of mobile machines switching off SCR catalysts and/or dismantling particulate filters. Anti-manipulation measures are therefore critical. In addition to anti-manipulation measures on the engines itself, these should also target users and owners of mobile machines, as well as and companies that manipulate these machines. Combined with in-service conformity, this helps to ensure that real-world emissions remain compliant over time.
- *Extended durability requirement*
  Currently, the emission durability period (EDP) is restricted to a maximum of 8000 hours for engines of 37 kW and higher, which is the equivalent of 333 full days.

[10] Refer to https://dieselnet.com/standards/cycles/llc-nr.php

Depending on the application there are engines currently in use which will reach this accumulated operation time within two years, for example in irrigation and drainage pumps. The durability should be extended to better reflect the real useful life of the NRMM engines.

Note that points of this proposed package are complementary to one another, meaning that the effectiveness of a new Stage VI class can only be guaranteed if all aspects are adequately addressed.

8 Conclusions and recommendations

This study shows that real-world emissions from Stage V NRMM remain high and often exceed expectations based on type-approval limits. Stage V machines equipped with an SCR show low NO_x-emissions at moderate engine loads. However, NO_x-levels remain elevated during low-load and idle operation due to insufficient exhaust temperatures for effective SCR conversion. In the power classes below 56 kW, the absence of SCR results in substantially higher and more variable NO_x-emissions, even though these machines have much lower rated power. This creates a structural difference in emission performance across the 56 kW threshold. The same is true for machines with an engine power above 560 kW.

Although Stage IV and Stage V machines are subject to the same legislative NO_x-emission limits, the analysis reveals differences in real-world performance. Across the full dataset, Stage V machines show lower average NO_x-emissions, reduced variability, and more consistent behaviour than Stage IV machines. At the same time, notable variation also exists within each Stage category, reflecting differences in engine sub power classes (all with SCR). Data coverage is however limited, particularly for Stage IV machines and certain load ranges. Moreover, the analysis does not determine the cause of these differences. It is unclear whether they result from engine generation and emission stage or from deterioration effects.

For particulate matter, all non-DPF machines tested comply with the Stage V mass limit, but they emit large quantities of ultrafine particles. Given that engines above 19 kW are already required to apply DPF technology under a strict PN limit, the data clearly show that extending PN control to the remaining power classes would deliver substantial emission reductions.

Ammonia (NH_3) emissions were also evaluated. Average NH_3-levels remain below the 10 ppm limit used in the Euro VI road-vehicle framework. However, significant fluctuations occur. This is especially at low exhaust temperatures and during (very) high-temperature events. These events may indicate urea overdosing or incomplete conversion in the SCR catalyst. The findings indicate that NH_3 slip may become a relevant concern as SCR use expands across NRMM categories.

Based on these findings, a potential future Stage VI framework should address several structural shortcomings of the current Stage V regulation. First, the stringency of NO_x and PN limits should be aligned across power classes to avoid regulatory gaps and eliminate incentives for power-bin hopping. Introducing a PN limit for engines below 19 kW and above 560 kW would ensure the application of DPF technology where it is currently absent. Incorporating an NH_3 limit would improve SCR performance and minimise undesirable side-effects of urea dosing.

Second, the test procedures should better reflect real-world operation by including dedicated low-load and idle cycles, ensuring effective emission control under conditions that dominate actual use.

Third, the absence of in-use monitoring and conformity provisions should be addressed by introducing on-board monitoring of NO_x-emissions and establishing an in-service conformity scheme to ensure that engines remain compliant throughout their operational life. In addition, explicit anti-tampering and anti-manipulation provisions should be introduced, covering both the placing on the market of new engines and their operation in real-world use. Finally, durability requirements should be extended to reflect real-world usage patterns, especially for machines that accumulate operating hours rapidly.

These improvements would reduce real-world emissions throughout its useful life. These improvements remain necessary in parallel with ongoing electrification. Zero-emission NRMM is not yet widely applicable across all sectors in Europe and diesel-powered machinery is expected to remain in use for the foreseeable future.

Signature

TNO ⟩ Mobility & Built Environment ⟩ The Hague, 19 May 2026

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