Real-world NOx-emissions from various Non-Road Mobile Machinery and vehicles

Measurement and monitoring results

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Samenvatting

Namens het Ministerie van Infrastructuur en Waterstaat heeft TNO emissiemetingen uitgevoerd om meer inzicht te krijgen in de praktijk NO_x-emissies van verschillende mobiele werk-en voertuigen. Qua emissienormering vallen de machines grotendeels onder de Europese Non-road mobile machinery (NRMM) wetgeving. De gemeten voertuigen vallen daarentegen onder de Euro-normering. Ten behoeve van de metingen werden 18 dieselaangedreven machines uitgerust met meetappatuur en in de praktijk gemonitord. Onder de machines waren bouwmachines, railmaterieel en wegdekreinigers.
Het overkoepelende doel van het programma was om ervaringen op te doen met opties voor emissiemonitoring van mobiele machines in de praktijk. Hierover is in 2023 en 2024 gepubliceerd [1, 2]. In deze rapportage ligt de focus met name op de emissie-resultaten.

De variatie in de gemeten NO_x-emissies tussen machinecategorieën is groot. De variatie is met name afhankelijk van de vermogensklasse, de emissieklasse, de aanwezigheid van Selectieve Katalytische Reductie (SCR), de werking van de SCR en de inzet van de machine. De meetdata laat zien dat machines met een motor zonder SCR-systeem, oudere motoren en die met eenvoudigere emissiereductiesystemen, aanzienlijk hogere emissies hebben dan nieuwere machines met SCR.

In het algemeen laten de metingen zien dat de effectiviteit van SCR-systemen voor NO_x-reductie sterk afhangt van de machine-inzet en bijbehorende motorbelasting. De SCR werkt optimaal bij matige tot hoge motorbelasting, waarbij de uitlaatgastemperatuur hoog genoeg is. Bij een lage motorbelasting, zoals stationair draaien, neemt de effectiviteit van de SCR sterk af, wat leidt tot verhoogde NO_x-emissies. Dit heeft een grote impact op de gemiddelde NO_x-emissies. Voor de meeste gemeten machines werkte het SCR-systeem het grootste deel van de tijd effectief. Echter, tijdens 7-30% inactiviteit (SCR niet op bedrijfstemperatuur), namen de NO_x-emissies aanzienlijk toe, met een bijdrage van 66-94% aan de totale NO_x-emissies.

De meeste gemonitorde machines hadden een gemiddelde NO_x-uitstoot in lijn met de verwachte emissieniveaus op basis van de wettelijke emissielimietwaarde. Enkele gemonitorde machines/voertuigen (dieselaangedreven passagierstrein & twee wegdekreinigers) lieten NO_x-emissies zien die in de praktijk hoger waren dan de wettelijke limietwaarde die geldt voor een typegoedkeuringstest. Vermoedelijk kwam dat door het niet goed functioneren van het SCR-systeem (ondanks voldoende motorbelasting). Er is momenteel geen effectieve controle op de NO_x-praktijkuitstoot van dergelijke machines tijdens reguliere inzet waarin deze verhoogde emissies zichtbaar worden.

De slechte prestaties van SCR bij lage motorbelasting en de matige algehele prestaties die op sommige machines zijn gemeten, veroorzaken een grote variatie in NO_x-emissies tussen machines tijdens praktijktinzet.

[1] TNO 2024 R11077 - Opties voor monitoring van de NOx-emissies van mobiele werktuigen
[2] TNO 2023 R10553 - Pilot project Emissie Monitoring en Periodieke Keuring (EMPK) van bouwmachines

De metingen laten zien dat de EU-typegoedkeuringstest voor NRMM onvoldoende controle biedt over NO_x-emissies bij lage motobelasting, het wordt daarom aanbevolen om in dergelijke emissietesten meer rekening te houden met lage motorbelasting. Daarnaast wordt aanbevolen om strengere NO_x-emissielimieten in te voeren voor de machines met een motorvermogen onder de 56 kW en boven de 560 kW. Ook kunnen maatregelen worden aangemoedigd om langdurig stationair draaien te verminderen. Tot slot kunnen mogelijkheden onderzocht worden voor controle op de emissieprestaties en controle op de werking van de SCR in de praktijk.

Hieronder volgen de belangrijkste bevindingen van de metingen in meer detail.

Effectiviteit van SCR-systemen is afhankelijk van machine-inzet

Bij de meeste machines met SCR-systemen worden de NO_x-emissies van de dieselmotor effectief gereduceerd bij matige tot hoge motorbelastingen en uitlaatgastemperaturen. Zo vertoonden alle gemonitorde Stage V asfaltspreidmachines, uitgerust met SCR, emissieniveaus onder de 20 gram per uur. Daarentegen vertoonde een Stage V-wals zonder SCR, en met een drie keer lager motorvermogen dan die van de asfaltspreid-machines, NO_x-emissies van meer dan 40 gram per uur. De meetdata toont aan dat machines met een SCR lage NO_x-emissies hebben wanneer deze boven de 20% motorbelasting werken. De NO_x-emissies nemen aanzienlijk toe bij lage motorbelasting (zoals stationair draaien) en lage temperaturen. Dit komt omdat SCR-systemen dan hun effectieve werkingsgebied niet kunnen bereiken. Dit bleek bijvoorbeeld bij de gemonitorde asfaltfreesmachines, waarbij langdurig stationair draaien leidde tot hoge emissies. Een asfaltfreesmachine met twee Stage V-motoren vertoonde verschillende emissieniveaus tussen deze twee motoren. De motor die onder hoge motorbelasting draaide, stootte gemiddeld 1,3 gram NO_x per liter brandstof uit, terwijl de andere motor, die bij lagere belastingen draaide, 2,8 gram NO_x per liter brandstof uitstootte. Dit verschil benadrukt de beperkingen van de huidige SCR-technologie wanneer machines voornamelijk met een lage motorbelasting worden gebruikt.

Twee gemonitorde Stage IIIB-motoren in een dieselaangedreven passagierstrein zijn ook uitgerust met SCR. De gemiddelde NO_x-emissies van deze treinen waren tijdens de monitoring in de praktijk hoger dan de limietwaarde. De data bevestigde dat de motoren binnen het juiste temperatuurbereik van de SCR werkten. De NO_x-concentraties bleven echter boven de 300 ppm, wat wijst op een slechte werking van de SCR. Dezelfde trend werd waargenomen bij twee kleinere wegdekreinigers met een Euro VI-motor. De monitoringgegevens suggereren dat het SCR-systeem op deze gemonitorde wegdekreinigers niet effectief functioneerde, ondanks voldoende motorbelasting. Daarentegen vertoonde een grote wegdekreiniger met een Euro VI-motor juist wel lage NO_x-emissies.

Hoge variatie in NOx-emissies tussen machinetypes

De NO_x-emissies varieerden sterk tussen verschillende typen mobiele machines en werktuigen. Zo had de gemonitorde diesellocomotief, met een oudere motor zonder SCR, een gemiddelde NO_x-emissie van 1450 gram per uur. In tegenstelling tot de best presterende asfaltspreidmachine, die een gemiddelde NO_x-emissie had van 11 gram per uur.

Een ander voorbeeld betreft twee asfaltfreesmachines: een met een enkele grote Stage V-motor en de andere met twee minder grote Stage V-motoren. De machine met de enkele motor heeft een motorvermogen van meer dan 560 kW, waar de emissielimieten minder streng zijn en een SCR niet nodig is om de emissielimieten te halen. Daarentegen zijn de twee kleinere motoren van de andere machine, elk met een vermogen onder de 560 kW, uitgerust met SCR vanwege de strengere eisen.

Beide machines werden gedurende ongeveer hetzelfde aantal bedrijfsuren gemonitord. De NO_x-emissies van de machine met de enkele grote motor (zonder SCR) kwamen in totaal uit op 134 kg voor de gehele periode, terwijl de machine met twee kleinere motoren (met SCR) slechts 16 kg uitstootte – een verschil van ruim een factor acht. De CO_2-emissies waren vergelijkbaar, wat duidt op een vergelijkbare motorbelasting. Dit laat de effectiviteit zien van een goed functionerend SCR-systeem.

Emissiemonitoring belangrijk voor inzicht in praktijkemissies

Ten behoeve van de monitoring is gebruik gemaakt van het TNO Smart Emissions Measurement System (SEMS). Hiermee worden emissies van de machines gemeten. Deze praktijkmonitoring biedt essentiële inzichten die standaard laboratoriumtests vaak missen, zoals de hoge NO_x-emissies die zijn gemeten tijdens stationair draaien en bij lage motorbelasting. Nieuwere machines leveren vaak zelf gegevens die kunnen worden uitgelezen ten behoeve van de monitoring en het berekenen van de uitstoot. Vaak is echter het uitlezen van deze (CAN-bus) gegevens complex en is de bruikbaarheid beperkt. Zo kan vanwege het gebrek aan standaardisatie de beschikbaarheid van gegevens tussen machines erg verschillen. Het uitrusten van een machine met een Mass Air Flow (MAF)-sensor lijkt een veelbelovend alternatief om dit te verhelpen, omdat de berekening van emissies niet meer afhangt van de beschikbaarheid van gegevens van de CAN-bus. Met een MAF-sensor kan de uitlaatgasstroom op een universele manier worden bepaald. Dit vereenvoudigt de monitoring en verbetert de nauwkeurigheid van de gegevens. Verder onderzoek is echter nodig om de haalbaarheid van MAF-sensoren in praktische toepassingen te testen, vooral voor machines met een hoog motorvermogen en grotere inlaatdiameters.

Een andere vereenvoudigde optie voor het berekenen van de uitstoot is door alleen data van de (externe) NO_x-sensor te gebruiken. Met deze gegevens kan de NO_x/CO_2-verhouding worden berekend. Hiermee kunnen de emissieniveaus van een machine worden benaderd. De berekeningsmethode is eenvoudig; de NO_x-concentraties worden gedeeld door de CO_2-concentraties. Hierbij zijn geen CAN-bus-signalen nodig. De NO_x/CO_2-ratio toont duidelijk het verschil in emissieniveaus, de werking van de SCR-katalysator en de emissies bij verschillende motorbelastingen. Vanwege de eenvoud, en de onafhankelijkheid van CANbus-signalen, is de meting van de NO_x/CO_2-verhouding een interessante optie voor vereenvoudigde emissiemonitoring. Deze optie wordt momenteel in meer detail onderzocht.

Implicaties voor beleid en regelgeving

De resultaten benadrukken de noodzaak voor Europese emissie-eisen die de werkelijke gebruiksomstandigheden van NRMM weerspiegelen, vooral voor machines die vaak bij lage belastingen of in stedelijke omgevingen worden gebruikt.

Belangrijke beleidsimplicaties zijn:

- Het verbeteren van Europese emissietesten, waarbij rekening moet worden gehouden met lage motorbelastingen waar SCR-technologie minder effectief is;
- Het tevens opnemen van lage motorlast in de Europese eisen voor de In-Service Monitoring voor NRMM;
- Het introduceren van strengere NO_x-emissielimieten voor machines met een motorvermogen onder de 56 kW en boven de 560 kW;
- Het bevorderen van maatregelen die langdurig stationair draaien en lage-belastingsomstandigheden verminderen;
- Het onderzoeken van mogelijkheden voor controle op de emissieprestaties en controle op de werking van de SCR in de praktijk.

Summary

On behalf of the Dutch Ministry of Infrastructure and Water Management, TNO conducted emission measurements to gain more insight into the real-world NO_x emissions of various mobile machines and vehicles. In terms of emission regulations, the machines largely fall under the European Non-Road Mobile Machinery (NRMM) legislation, whereas the measured vehicles fall under the Euro standards. In this study, a total of 18 diesel-powered machines, engines, and vehicles were measured and evaluated, covering construction equipment, rail machinery, and road surface cleaners. The overarching goal of the program was to gain experience with options for emission monitoring of mobile machines during real-world usage. Publications on this topic were released in 2023 and 2024[3, 4]. This report primarily focuses on the emission results.

The variation in measured NO_x emissions between machine categories is significant. This variation mainly depends on the engine power class, the emission class, the presence of an Selective Catalytic Reduction (SCR) system, the functioning of the SCR, and machine usage. The measurement data show that machines with engines without an SCR system, older engines, and those with simpler emission reduction systems have considerably higher emissions than newer machines equipped with SCR.

In general, the measurements indicate that the effectiveness of SCR systems for NO_x reduction strongly depends on machine operation and the corresponding engine load. The SCR functions optimally at moderate to high engine loads, where the exhaust gas temperature is sufficiently high. At low engine loads, such as idling, its effectiveness decreases significantly, leading to increased NO_x-emissions, contributing substantially to average NO_x-emissions. For most of the measured machines, the SCR system operated effectively most of the time. However, during 7-30% inactivity (SCR not on operating temperature), the NO_x-emissions increased significantly, contributing to 66-94% of the total NO_x-emissions.

Most of the monitored machines had average NO_x emission levels in line with the regulatory emission limit. However, some monitored machines/vehicles (the diesel passenger train and two road surface cleaners) showed NO_x emissions in real-world operation, exceeding the regulatory emission limit (which applies during type approval. This exceedance was likely the result of a malfunctioning of the SCR system (despite sufficient engine load). There is currently no effective monitoring of the real-world NO_x emissions in place of such machines during regular operation.

The poor low load performance of SCR and the poor overall performance measured on some of the machines cause a high variability of NO_x-emissions between machines in the field.

The measurements demonstrated the lack of control of NO_x emissions at low load operation by the EU type approval tests for NRMM. It is therefore recommended to improve the tests by including low load usage in the test procedure.

[3] TNO 2024 R11077 - Opties voor monitoring van de NOx-emissies van mobiele werktuigen
[4] TNO 2023 R10553 - Pilot project Emissie Monitoring en Periodieke Keuring (EMPK) van bouwmachines

Moreover, it is recommended to implement stricter NO_x emission limits for machines with an engine power below 56 kW and above 560 kW. Also practices should be encouraged that reduce prolonged idling and low load usage of NRMM. Finally, measures can be taken to improve SCR system monitoring during real-world operation.

Below the findings of the measurement programme are described in more detail.

Effectiveness of Selective Catalytic Reduction (SCR) systems

Most of the machines with SCR systems effectively reduce NO_x emissions when they are operating at moderate to high engine loads and exhaust temperatures. For example, all monitored Stage V pavers, equipped with SCR, have emission levels below 20 grams per hour. In contrast, a Stage V roller without SCR and with an engine power which is three times lower than that of the pavers, exhibited NO_x emissions exceeding 40 grams per hour. Data showed that machinery with SCR, had low average NO_x emissions when operating consistently above 20% engine load, where SCR performance was working properly.

NO_x emissions increase substantially at low engine loads and temperatures, where SCR systems cannot reach their effective working temperature. In the monitoring data this was observed at the asphalt milling machines, where extended idling led to high emissions. One of the asphalt milling machines is equipped with two Stage V engines. This machine demonstrated varying emissions levels between the two engines. The engine operating under a high load emitted an average of 1.3 grams of NO_x per litre of fuel, while the other engine, running at lower loads, emitted 2.8 grams of NO_x per litre of fuel. This variability underscores the limitations of current SCR technologies for machinery frequently used in low-load applications.

Two Stage IIIB engines in diesel-powered passenger trains are also equipped with SCR. However, their average NO_x-emissions were during the monitoring period higher than the regulatory limit value. The measurements confirm that the engines operate within the correct SCR-temperature range, yet NO_x concentrations remain above 300 ppm, indicating poor SCR performance. The same trend was observed for two smaller road surfacecleaning vehicles with an Euro VI engine. The monitoring data suggests that the SCR system on these monitored road cleaners did not function effectively, despite of having sufficient engine load. In contrast, a large highway road surface cleaner with an Euro VI engine demonstrated low NO_x-emissions.

High variability in emissions across machinery types

NO_x emissions varied widely between different NRMM types. For example, the monitored dieselloc, with on older engine without SCR, showed average NO_x emissions of 1450 grams per hour. In contrast the best performing paver showed average NO_x emissions of 11 grams of NO_x per hour.

Another example involves two asphalt milling machines: one with a single large Stage V engine and the other with two smaller Stage V engines. The machine with the single engine has an engine power rating above 560 kW, where emission limits are less stringent and SCR is not required. In contrast, the other machine's two smaller engines, each with a power rating below 560 kW, are equipped with SCR due to a more stringent emission limit. Both machines were monitored for approximately the same number of operating hours. The NO_x emissions for the machine with the single large engine (no SCR) totaled 134 kg over the entire period, while the machine with two smaller engines (with SCR) emitted only 16 kg, a difference by a factor of eight. CO_2 emissions were similar, indicating comparable engine loads.

Emission monitoring for insights in real-world emissions

The study used TNO's Smart Emissions Measurement System (SEMS) for long-term and short-term monitoring, capturing emissions data directly from the machinery.
This real-world monitoring approach provided critical insights that lab-based tests often miss, such as the high NO_x emissions observed during idling or low load conditions.

While the CANbus connection used in TNO's SEMS system provided valuable data, reliance on CANbus signals is challenging due to the lack of standardisation and inconsistent data availability across machinery. The study suggests that equipping a machine with a Mass Air Flow (MAF) measuring sensor could be a promising alternative to the CAN-bus connection. The MAF enables a more direct determination of exhaust flow without needing CANbus data, simplifying monitoring and enhancing data accuracy. However, further research is necessary to test MAF sensors' feasibility in real-world applications, particularly for high-power machinery with larger intake diameters.

Another alternative, which reduces complexity of NO_x emissions monitoring,is to use the data provided by the (external) NO_x-sensor only. With these data, the NO_x/CO_2 ratio can be calculated. This allows useful conclusions to be drawn about the emission levels of a machine. The calculation method is very simple, as it only involves dividing the measured NO_x concentrations by the CO_2 concentrations, for which no CANbus signals are required. The NO_x/CO_2 ratio clearly shows the distinction in emission levels, the functioning of the SCR catalyst and emissions under varying engine loads. Due to its simplicity and independence from CANbus signals, this ratio is an interesting option for simplified emission monitoring. This is being investigated in more detail.

Implications for policy and regulation

The results underscores the need for European emission regulation that better reflects the real-world operating conditions of NRMM, especially for machinery which are frequently used at low loads or in urban settings.

Key policy implications are:

- Improving European emissions tests for non road engines accounting for low-load conditions where SCR technology is presently less effective;
- Include low-load conditions in In-Service Monitoring for NRMM;
- Introduce more stringent NO_xemission limits for NRMM categories with an engine power below 56 kW and above 560 kW;
- Encouraging practices that reduce prolonged idling and low-load operation as this could improve SCR performance and lower emissions;
- Investigating possibilities for inspection on emission performance and SCR-functioning in real-world circumstances.

Contents

1 Introduction

Non-road mobile machinery (NRMM) comprises a diverse range of equipment employed across various sectors. Given this diversity and the considerable contribution of NRMM to national pollutant emissions (23.3 kton NO_x for all machinery, 10.2 kton NO_x for construction machinery in 2023), understanding NO_x emissions from these machines is crucial for refining the Dutch emission factors and models developed by TNO, thereby providing policymakers with robust data to inform future regulatory decisions for the NRMM sector. Moreover, the insights are relevant for machine-owners which are interested in possibilities for NO_x-reduction.

This report presents an in-depth analysis of NO_x emissions monitoring conducted over an extended period, often spanning several months, to capture a broad spectrum of real-world operating conditions. The overarching goal of the program was to gain experience with options for emission monitoring of mobile machines during real-world usage. Publications on this topic were released in 2023 and 2024[5] [6]. This report primarily focuses on the emission results.

By assessing emissions during real-world operations of various machines, valuable insights into their environmental impact are shown. This real-world approach offers a more accurate picture of emissions behavior than traditional laboratory testing, which often fails to account for the operational variability inherent in NRMM.

The emission measurement results are not directly converted into emission factors. Instead, previous measurement data and external findings are also considered when refining these factors. When new emission factors are determined, they will be discussed in the Task Force on Traffic and Transport of the national Pollutant Release and Transfer register (NL-PRTR) [7].

Alongside long-term monitoring, short-duration emission measurements were also conducted. These shorter assessments are effective for machines with relatively stable emissions, such as those operating at consistent engine loads or older models without advanced emission controls like Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) systems. In such cases, short-term measurements provide a reliable indication of emissions performance. The monitoring and measurements were performed on behalf of the Ministry of Infrastructure and Water Management.

In this study, a total of 18 machines, engines, and vehicles were evaluated, covering a range of equipment including construction machinery, rail equipment, and road surface cleaners. While most of the machines fall under NRMM, some are classified as road vehicles.
All machinery was assessed under real-world conditions to ensure the data accurately reflects typical usage scenarios. The following chapters provide a detailed analysis of NO_x emissions from construction machinery, rail equipment, and road surface cleaners, based on NO_x sensor data, where possible combined with CANbus system connections.

[5] TNO 2024 R11077 - Opties voor monitoring van de NOx-emissies van mobiele werktuigen
[6] TNO 2023 R10553 - Pilot project Emissie Monitoring en Periodieke Keuring (EMPK) van bouwmachines
[7] https://www.emissieregistratie.nl/

This report aims to enhance the understanding of NO_x-emissions across different types of machines and operational conditions. A particular focus is placed on evaluating the performance of SCR systems, widely used in newer machinery designed to meet stringent emissions standards. These systems play a crucial role in reducing NO_x emissions, yet their effectiveness is highly dependent on engine load and temperature—factors that vary considerably in NRMM applications. By monitoring various types of non-road mobile machinery with SCR systems, the report highlights their real-world performance and identifies limitations, particularly under low-load conditions where SCR systems may not reach optimal operating temperatures.

This report

In this report, the methodology and an overview of the specifications of the measured objects are given in Chapter 2. In Chapter 3, the NO_x-emission monitoring results of construction machinery are presented, including an overview of monitored machines and detailed emission levels. Chapter 4 discusses the emission performance of rail machinery and trains, providing monitoring results for diesel locomotives and passenger trains. Chapter 5 covers the monitoring results of road surface cleaners, with both overall and detailed findings for highway and city cleaners. The discussion of these results is found in Chapter 6, followed by the conclusions in Chapter 7.

2 Measurement equipment and measured machinery

This chapter describes the equipment used for the measurements and monitoring and provides an overview of the monitored machines during the project.

2.1 Emission monitoring

With monitoring, the emissions are assessed over a long period, typically several months. Therefore, a broad spectrum of real-world conditions can be assessed, as the machine is operated during their daily activities.

For real-time NO_x monitoring, two types of measurement systems from TNO were applied within this project:

- Smart Emissions Measurement System (SEMS) [8]
- Living Car Lab Dongle (LCL)

SEMS is a relatively easy-to-install and compact sensor-based system, which can measure and record actual NO_x-concentration and O_2 and derive the CO_2-concentration from the machine's tailpipe. Because SEMS is compact and requires no user interaction it allows normal machine operation during monitoring, enabling long-term data collection, for instance for several months. The system connects to the CANbus to obtain machine data, translating measured concentrations into mass (grams). SEMS includes an integrated GPS sensor and GSM 4G connectivity. The system sends the collected data to a TNO database several times a day.

The LCL dongle is a more compact version of SEMS, designed for long-term monitoring with shorter installation times and lower costs. It has similar functionalities but fewer options for connecting additional sensors. In this project, the LCL dongle was only connected to the machine's power supply and an external NO_x sensor, without a CANbus connection to facilitate quicker installation. Further documentation on SEMS and LCL used in construction machinery can be found in the TNO's report of 2023: TNO 2023 R10553.

2.2 Short-term NO_x measurements

For machines with less variable emissions, such as those frequently operating at the same engine load or older engines without emission control systems (like SCR or EGR), long-term emissions monitoring is not always necessary. Moreover, short term measurements are an option to check for the proper functioning of SCR systems, that is no defects or manipulations in an SCR catalyst. TNO report 2023 R10553 outlines experiences with short-term measurements.

[8] https://www.youtube.com/watch?v=0mSbkR2GCw4

The advantage of short-term measurements is that they require little to no installation time for measurement equipment. Measurements are taken directly in the machine's exhaust pipe, eliminating the need for modifications. The downside is that these measurements represent a snapshot in time, often without results over the complete engine load spectrum. Occurring defects in, or manipulation of, emission reduction systems of the machine after the moment of short-term measurement become undetectable.

For short-term NO_x measurements, TNO has developed a portable emissions measurement system known as the BOEMkit, see Figure 2.1. This system uses the same sensors as those employed in long-term monitoring, primarily based on a NO_x/O_2 sensor. In addition to the emission sensors, a temperature sensor is included. Moreover, a NH_3-sensor is installed. The system has its own power supply, and a connection to the machine for reading engine parameters is not required, although it can be beneficial.

The BOEMkit can be placed next to the machine or secured with suction cups, allowing the machine to remain operational in most cases. If this is not feasible, measurements are taken while the machine is stationary, ideally at various engine loads and with both warm and cold engine(s). Measurement durations can range from 10 minutes to a full working day.

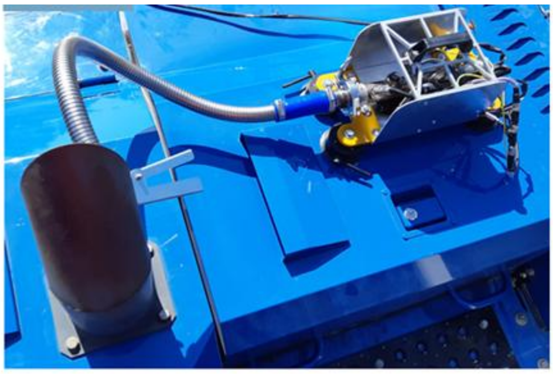


Figure 2.1: TNO's BOEMkit installed on a machine.

2.3 Measured objects

In this study 18 machines/engines/vehicles are measured, either by monitoring, or by short term measurements. The measured machines are construction machinery, rail equipment and road surface cleaners. The majority of the machines are non-road mobile machinery, while some are identified as road vehicles. Table 2.1 provides an overview of the measured machines in this study. All machinery is monitored or measured during their real-world operation.

Table 2.1: Overview of measured objects.

Sector	Type	Engine power	Emission class	Measurement	Monitoring-data [hour]
Construction machinery	Roller	55	Stage V	NO_x-monitoring	182
	Paver	140	Stage V	NO_x-monitoring	147
	Paver	157	Stage V	NO_x-monitoring	308
	Paver	129	Stage V	NO_x-monitoring	354
	Excavator	105	Stage IV	NO_x-monitoring	188
	Excavator	140	Stage IV	NO_x-monitoring	272
	Asphalt milling machine	470	Stage V	NO_x-monitoring	152
	Asphalt milling machine	283	Stage V	NO_x-monitoring	134
	Asphalt milling machine	563	Stage V	NO_x-monitoring	273
Rail equipment	Dieselloc	1500	non-certified	NO_x-monitoring	545
	Passenger train_engine 1	480	Stage IIIB	NO_x-monitoring	411
	Passenger train_engine 2	480	Stage IIIB	NO_x-monitoring	838
	Rail excavator	115	Stage IV	Short measurement	1
	Mineral conveyor and storage unit	148	Stage IIIA	Short measurement	<1
	Loading and unloading station	139	Stage IIIA	Short measurement	<1
Road surface cleaners	Road surface cleaner_highway	315	Euro VI	NO_x-monitoring	352
	Road surface cleaner _city 1	120	Euro VI	NO_x-monitoring	81
	Road surface cleaner _city 2	120	Euro VI	NO_x-monitoring	101

3 NO_x-emission monitoring results of construction machinery

This chapter describes the NO_x-emission results of machines which are deployed for construction activities. The machines are monitored in real-world conditions for several months. The chapter starts with an overview of the monitored machinery, followed by the emission results. The last part of this chapter zooms in on the impact of SCR-functioning.

3.1 Overview of monitored machines

This section provides an overview of the construction machines monitored during the project. It then describes the emissions monitoring results for machinery with a CANbus connection and then without this connection.

Table 3.1 lists the monitored machines equipped with NO_x sensors. The first column displays the machine ID, starting with an abbreviation of the brand and type, followed by the emission code used by TNO. Machines beginning with "NRE" are Stage V machines, with the number indicating the power category: 4, 5, 6, and 7 correspond to 37-56 kW, 56-130 kW, 130-560 kW, and >560 kW, respectively. Machines labelled "ST4" indicate Stage IV, followed by R or Q for power categories 56-130 kW and 130-560 kW. The NRE4 and NRE7 machines are the only ones without an SCR catalyst, and their limit values are significantly less stringent. The NO_x limit for NRE5 and NRE6 is 0.4 g NO_x/kWh, while for NRE4 and NRE7, it is 4.7 and 3.5 g/kWh, respectively. The next column indicates the machine type, maximum engine power, and Stage class, followed by the installed equipment and total monitoring time.

Table 3.1: Overview of monitored machines.

Machine ID	Type_engine power_stage	Equipment	Monitoring-data [hour]
DYN_CS1400_05_NWBDNRE4	Roller_55,4_V	NO_x-sensor with CANbus	182
BOM_BF700C_04_NWBDNRE6	Paver_140_V	NO_x-sensor with CANbus	147
DYN_SD2500_01_NWBDNRE6	Paver_157_V	NO_x-sensor with CANbus	308
VOG_18003i_08_NWBDNRE5	Paver_129_V	NO_x-sensor without CANbus	354
LIE_914LIT_02_NGMDST4R	Excavator_105_IV	NO_x-sensor without CANbus	188

LIE_R926WL_03_NGMDST4Q	Excavator _140_IV	NO_x-sensor with CANbus[9]	272
WIR_W250_1_02_NWBDNRE6	Asphalt milling machine_470_V	NO_x-sensor with CANbus	152
WIR_W250_2_02_NWBDNRE6	Asphalt milling machine_283_V	NO_x-sensor with CANbus	134
WIR_W210Fi_01_NWBDNRE7	Asphalt milling machine_563_V	NO_x-sensor with CANbus	273

3.2 Overview of NO_x emissions levels based on monitoring with NO_x-sensor and CANbus-connection

Table 3.2 shows the total NO_x- and CO_2-emissions per machine that occurred during the monitoring period. By accurately tracking the deployment of each machine on specific projects, emissions can be determined per project and compared with initial estimates to improve future predictions. Additionally, a summary of total emissions per machine can assist fleet owners in identifying which machines have the greatest impact on NO_x and CO_2 emissions, thus highlighting where effective measures can be implemented.

Table 3.2 underscores the varying emissions profiles across different machinery types and their operational impacts. The DYN_SD2500 paver was monitored for 308 hours, yet its NO_x emissions are relatively moderate at 3.4 kg. In contrast, the WIR_W210Fi asphalt milling machine stands out with significantly higher absolute NO_x emissions, approximately 40 times greater than the DYN_SD2500, while having less hours of monitoring. This can be attributed to the engine size, which falls under less stringent emission standards, and additionally the required power output, which is also reflected in the high CO_2 emissions.

Another example involves two asphalt milling machines: one with a single large Stage V engine (WIR_210F1) and the other with two smaller Stage V engines (WIR250). The machine with the single engine has an engine power rating above 560 kW, where emission limits are less stringent and SCR is not required. In contrast, the other machine's two smaller engines, each with a power rating below 560 kW, are equipped with SCR. Both machines were monitored for approximately the same number of hours. The NO_x emissions for the machine with the single large engine totaled 134 kg over the entire period, while the machine with two smaller engines emitted only 16 kg — a difference by a factor of eight. CO_2 emissions were similar, indicating comparable engine loads.

[9] Despite the connection with CANbus, no useful data for emission monitoring was available on the CANbus. Signals like fuel consumption, torque and engine speed were not available.

Table 3.2: Overview of emission totals per engine during the monitoring period

Machine ID	Type_engine power_stage	Deployment	NO_x	CO_2
		[hour]	[kg]	[kg]
DYN_CS1400_05_NWBDNRE4	Roller_55,4_V	182	7,9	1.378
BOM_BF700C_04_NWBDNRE6	Paver_140_V	147	2,4	4.764
DYN_SD2500_01_NWBDNRE6	Paver_157_V	308	3,4	10.669
VOG_18003i_08_NWBDNRE5	Paver_129_V	354	6,5	9.001
WIR_W250_1_02_NWBDNRE6	Asphalt milling machine_470_V	152	11,1	11.424
WIR_W250_2_02_NWBDNRE6	Asphalt milling machine_283_V	134	5,0	10.679
WIR_W210Fi_01_NWBDNRE7	Asphalt milling machine_563_V	273	134	24.759

Comparing machines is more effective when assessing emissions in grams per hour. The grams of NO_x per litre of fuel are also very useful, as they can help translate the emission performance of a measured machine to a comparable engine based on fuel consumption. Additionally, grams of NO_x per kWh can be useful for comparison with regulatory emission limits. However, the emission limit applies during type approval at specific engine load points, including a certain weighting, while this study's emissions monitoring considers all usage evenly. Consequently, a machine may have a higher average g/kWh emission than the limit during practical use but may still meet the emission limit during the type approval test.

Table 3.3 provides an overview of the units described above, including both average NO_x emissions and average emissions above 20% engine load. By assessing emissions above 20% engine load, it is possible to better determine whether emissions are low when an SCR is at operating temperature, thus nearing the emission limit.

The NRE6 machines in this study predominantly operate above 20% engine load, resulting in little difference between the average value and the value above 20% engine load for most machines. Most NRE6 machines have average emission levels below the limit of 0.4 g/kWh, with only the Paver_129_V (VOG_18003i) and the WIR_250_1 exceeding this when all operating conditions are considered. When the data with >20% engine load is considered, only the WIR_250_1 slightly exceeds the limit.

The WIR_W210Fi stands out with the highest emissions across all metrics, particularly in NO_x per hour and per litre. For example, the WIR_210Fi has with 490 grams of NO_x per hour 45 times higher emissions than the DYN_SD2500 with 11 grams of NO_x per hour.

Table 3.3: This overview presents the specific average NO_x emissions and those above 20% engine load for each engine during the monitoring period in real-world use. The limit value (NO_x in grams per kWh) according to European legislation is also included. It is important to note that the emission test to which this limit value applies, differs from actual operational use.

Machine ID	Type_engine power_stage	NO_x [g/kWh]			NO_x [g/h]		NO_x [g/l]	
		Limit-value	Average	>20% engine load	Average	>20% engine load	Average	>20% engine load
DYN_CS1400_05_NWBDNRE4	Roller_55,4_V	4,7	3,8	3,2	43	58	13	11
BOM_BF700C_04_NWBDNRE6	Paver_140_V	0,4	0,33	0,28	16	15	1,3	1,1
DYN_SD2500_01_NWBDNRE6	Paver _157_V	0,4	0,2	0,16	11	8,8	0,8	0,7
VOG_18003i_08_NWBDNRE5	Paver _129_V	0,4	0,5	0,4	18	18	1,9	1,7
WIR_W250_1_02_NWBDNRE6	Asphalt milling machine_470_V	0,4	0,65	0,45	73	113	2,8	2,0
WIR_W250_2_02_NWBDNRE6	Asphalt milling machine _283_V	0,4	0,3	0,3	37	56	1,3	1,2
WIR_W210Fi_01_NWBDNRE7	Asphalt milling machine _563_V	3,5	3,6	2,8	490	844	14	11

3.3 NO_x emissions levels over the engine load range, based on monitoring with NO_x sensor and CANbus connection

By determining engine power based on CANbus signals, emissions can also be clustered by engine load. This allows for a better understanding of the ranges of engine load where emissions are low or high, as well as how frequently the machine operates at those loads.

The data, as shown in Figure 3.1, illustrates the varying operational profiles of these machines. At the lowest power bin, the WIR_210Fi shows a significant 48% timeshare, the same is true for the WIR_W250_1 at 43%. The other machines show minimal activity in this bin. The other machines mainly have engine loads between 20 and 60%. The WIR_250_2 has a remarkable spike at the highest power bin. This is an engine with a lower power than its counterparts. This engine supports the WIR_250_1 when more power is needed (both engines are in one machine).

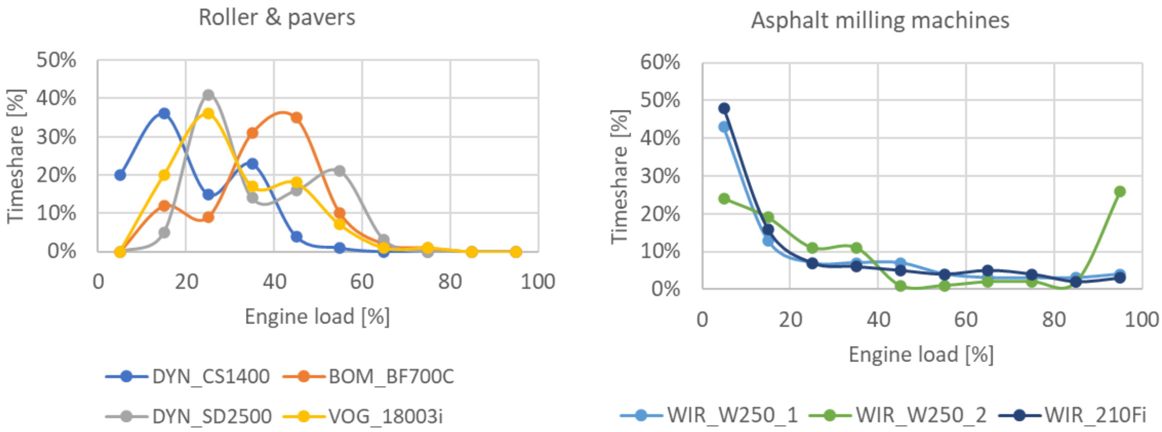


Figure 3.1: **Timeshares** as a function of engine load. The engine loads are bins, where the average of the load bin range is shown. For example, 0-10% is shown as 5%. The left graph shows the roller & pavers, the right graph shows the asphalt milling machines.

Figure 3.2, Figure 3.3 and Figure 3.4 show the emission results in grams per hour, grams per litre and share per load bin respectively. In the context of emissions monitoring, assessing emission performance across the power range can help determine whether high emissions are due to operational factors or issues with the engine or after-treatment system. Additionally, this analysis can provide valuable insights for machine owners to assess whether changes in operation could lead to lower emissions.

Figure 3.2 highlights the NO_x emissions in grams per hour across the machines. The WIR_210Fi consistently exhibits the highest emissions, peaking at 1300 g/h at 80-90% power. Moreover, the DYN_CS1400 shows relatively high emissions. This was to be expected as the WIR_210Fi and DYN_CS1400 are the only machines without SCR catalyst. For those machines the NO_x emission increase when the engine load increases. For the other machines, with SCR-catalyst, the NO_x emissions in grams per hour show only slight increases over the engine load bins, or no increase at all. Most of the machines with SCR, with the exception of the WIR_250_1, remain well below 50 grams of NO_x per hour for the majority of the time. The DYN_SD2500 even remains below 10 grams of NO_x per hour for the majority of the time.

Figure 3.3 shows the same trend for the machines with low or high emissions. However, in contrast to the graph in grams per hour, the grams NO_x per litre are typically lower at higher load bins.

Figure 3.4 shows in which load bin most of the NO_x is emitted. Basically, this is a combination of the grams per hour and timeshares per load bin. For the roller and pavers, the largest NO_x contribution is at the load bins between 20% and 50%. The WIR_250_1 and the WIR_210Fi show substantial emission shares at low loads, approximately 25%. This may be the result of extensive idling. The WIR_250_2 on the other hand shows a substantial fraction of NO_x in the highest load bin.

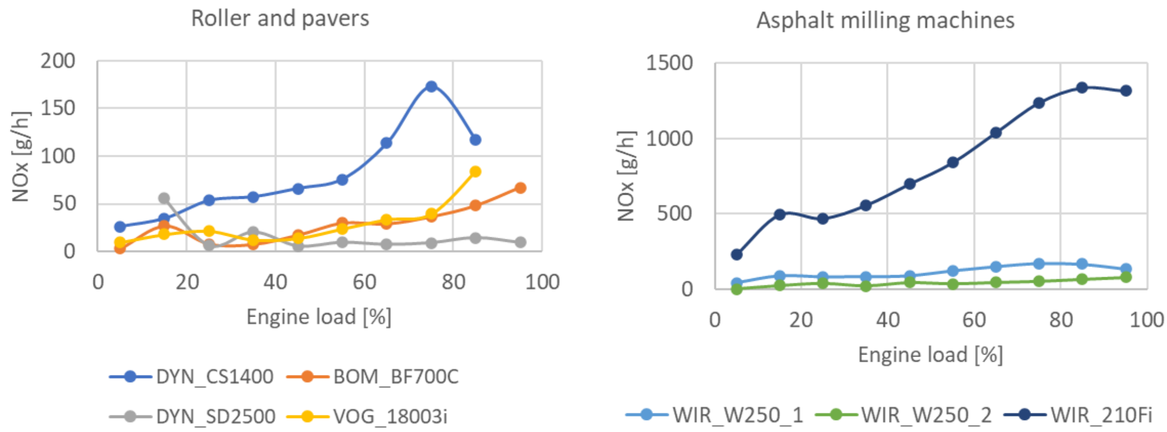


Figure 3.2: **NO$_x$ in grams per hour** as a function of engine load. The engine loads are bins, where the average of the load bin range is shown. For example, 0-10% is shown as 5%. The left graph shows the roller & pavers, the right graph shows the asphalt milling machines.

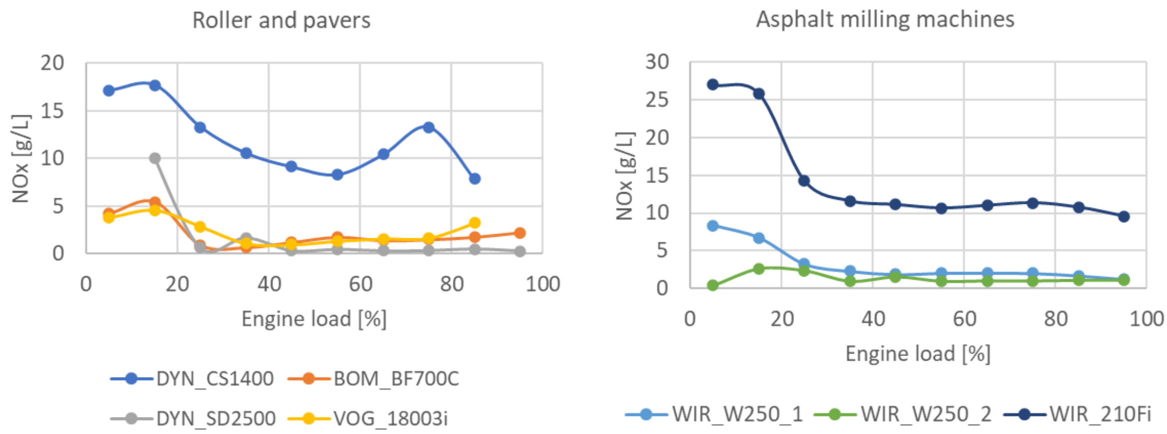


Figure 3.3: **NO$_x$ in grams per litre of fuel** as a function of engine load. The engine loads are bins, where the average of the load bin range is shown. For example, 0-10% is shown as 5%. The left graph shows the roller & pavers, the right graph shows the asphalt milling machines.

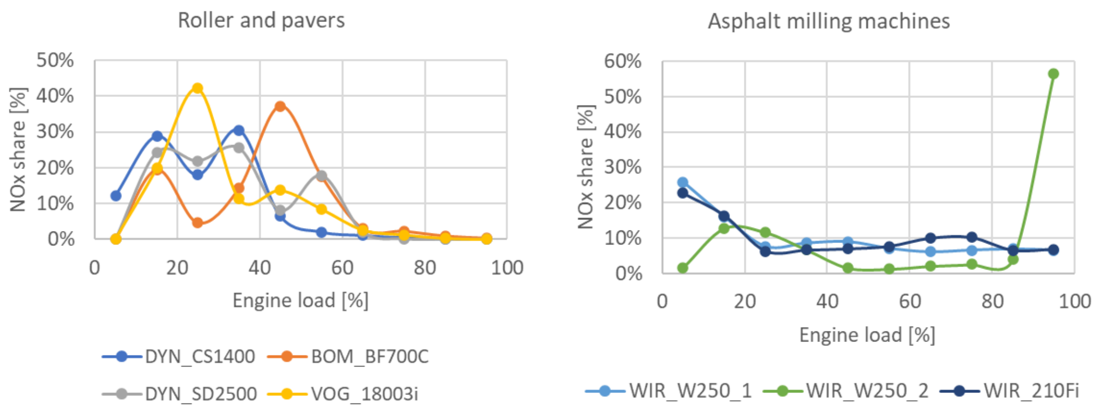


Figure 3.4: **NO$_x$ share** as a function of engine load. The engine loads are bins, where the average of the load bin range is shown. For example, 0-10% is shown as 5%. The left graph shows the roller & pavers, the right graph shows the asphalt milling machines.

3.4 Monitoring with NO_x sensor without CANbus connection

A total of nine engines from mobile machinery were monitored using an external NO_x-sensor. For seven of these machines, a connection to the CANbus was also established, those results are described in the previous paragraphs. This section focuses solely on the results based on the NO_x sensor data. As previously described, the NO_x sensor measures both NO_x and O_2 concentrations in the exhaust gas. The CO_2 concentration is calculated based on the measured O_2 concentration.

3.4.1 NO_x/CO_2 ratio

Generally, higher engine loads result in a higher CO_2 percentage in the exhaust gas. By using the NO_x (ppm)/CO_2 (%) ratio, the NO_x emissions performance can be better assessed across the power range. The analysis based on the NO_x/CO_2 ratio focuses on NO_x emissions, considering the power delivered (in terms of CO_2). In other words, if CO_2 emissions are high, NO_x emissions may also be higher. This ratio also aids in evaluating the effectiveness of the SCR catalyst and provides a rough indication of absolute emission levels.

Table 3.4 presents the NO_x/CO_2 ratios (in ppm/%), highlighting the emissions performance of various machines. Overall, the data highlights significant differences in emissions performance, with the DYN_CS1400 and WIR_W210Fi machines exhibiting the highest NO_x/CO_2 ratios. Those machines are the only machines monitored without an SCR-catalyst.

On the lower end, the BOM_BF700C paver has a ratio of 5.9, and the DYN_SD2500 paver 4.5, also the WIR_W250_2 shows low values of 4.9. The Stage IV excavators display relatively high emissions, with the LIE_914LIT at 13.4 and the LIE_R926WL at 11.9. The same goes for the WIR_W250_1 asphalt milling machine. These emission levels follow the same trend as the NO_x in grams per kWh and per litre fuel, as shown in Table 3.3.

It is clear from Table 3.4 that all monitored machines with SCR catalysts (Stage IV and Stage V machines with engine power between 56 and 560 kW) have significantly lower average emissions than machines without SCR. The worst performing machine with SCR has an average emission that is six times lower than that of machines without SCR. For the best performing machine with SCR, this difference increases to a factor of 17.

Table 3.4: Average NO_x/CO_2 ratio of the monitored machines

Machine ID	Type_engine power_stage	NO_x/CO_2 [ppm/%]
DYN_CS1400_05_NWBDNRE4	Roller_55,4_V	67,5
BOM_BF700C_04_NWBDNRE6	Paver_140_V	5,9
DYN_SD2500_01_NWBDNRE6	Paver_157_V	4,5
VOG_18003i_08_NWBDNRE5	Paver_129_V	9,2
LIE_914LIT_02_NGMDST4R	Excavator_105_IV	13,4
LIE_R926WL_03_NGMDST4Q	Excavator_140_IV	11,9
WIR_W250_1_02_NWBDNRE6	Asphalt milling machine_470_V	11,4

WIR_W250_2_02_NWBDNRE6	Asphalt milling machine _283_V	4,9
WIR_W210Fi_01_NWBDNRE7	Asphalt milling machine _563_V	76,8

A rough estimate of the grams of NO_x per kWh—based on the NO_x/CO_2 ratio—can be made by theoretically approximating the engine efficiency. For example, if the engine efficiency is 740 gCO_2/kWh at an average load of 30%, and the NO_x/CO_2 ratio is 6 ppm/%, the average gNO_x/kWh can be estimated as follows: 46/44*6/10*740/1000 = 0.46 g/kWh. If the engine efficiency is higher, e.g. 670 gCO_2/kWh, the estimated gNO_x/kWh would be 0.42. Depending on the engine efficiency, the theoretical approach to the emission limit (0.4 g/kWh) would correspond to a NO_x/CO_2 ratio between 5 and 6 ppm/%. However, this is dependent of the engine efficiency, which varies from engine to engine as well as at different engine loads.

Based on this approach, the VOG_18003i and the WIR_W250_1 would exceed the emission limit, and the other NRE6 machines stay below the emission limit. This is in line with the results in Table 3.3. However, following this formula, the values are not exactly the same as the calculated g/kWh from Table 3.3. Therefore, this theoretical approach must be considered as an indication. Nevertheless, it is likely that the monitored Stage IV machines will exceed the emission limit. This limit applies for the formal EU type approval test and not for real world use, however. Those machines were measured without CANbus-connection, with the NO_x/CO_2 ratio, the emission performance can be indicated.

3.4.1.1 Emission performance across the power range

For machines equipped with SCR catalysts, NO_x emission levels are often relatively high at low engine loads, typically below 20%—because the SCR catalyst may not reach operating temperature at this low load. Prolonged idling is an example of low engine load. The CO_2 concentration can serve as an indicator of engine load. By displaying the NO_x/CO_2 ratio as a function of CO_2 concentration, insights into emissions performance at various engine loads can be obtained. Additionally, showing the timeshare as a function of CO_2 concentration helps estimate the extent to which a machine operates at high or low engine loads.

Figure 3.5 illustrates the NO_x/CO_2 ratio as a function of CO_2 concentration for an NRE6 machine (with SCR) and an NRE7 machine (without SCR). The results are aggregated into 1% CO_2 bins, with the timeshare per bin represented as a blue line. Both machines exhibit lower NO_x/CO_2 ratios at higher CO_2 bins. The NO_x/CO_2 ratios for the NRE6 machine are significantly lower than those for the NRE7 machine, with differences reaching up to a factor of 20 at higher CO_2 bins. Furthermore, the NRE6 machine is often operated at higher engine loads, unlike the NRE7 machine, which typically operates at very low loads. The NRE7 machine has a maximum power output of 563 kW, and low engine loads are frequently observed in high-power machines, as noted in TNO report 2023 R10553.

When comparing different engines, EGR (exhaust gas recirculation) may influence CO_2 percentages in the exhaust gas (x-axis in the graph) at the same engine load and engine speed.

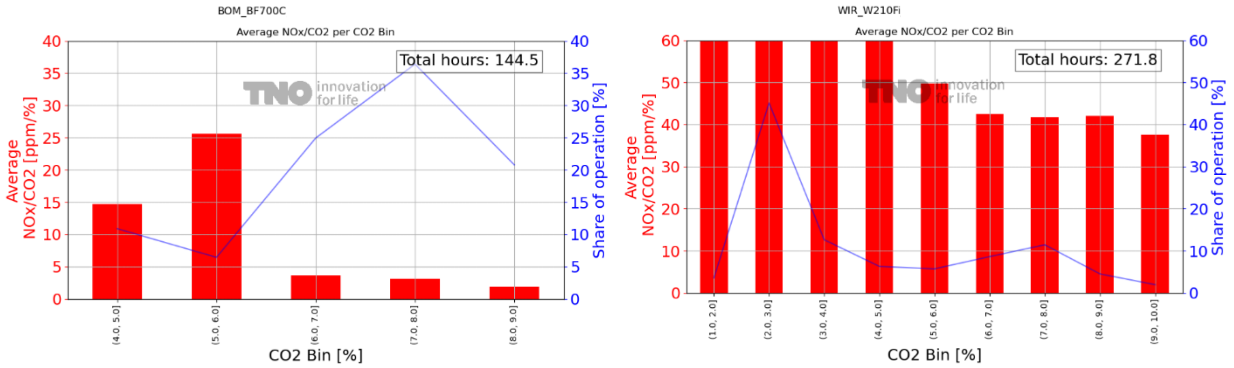


Figure 3.5: NO_x/CO_2 ratio (red bars) as a function of CO_2-concentration of a NRE6 machine with SCR (left) and a NRE7 machine without SCR (right). The blue line indicates the timeshare per CO_2-bin.

Figure 3.6 presents the NO_x/CO_2 ratio per CO_2 bin for two NRE6 engines (with SCR), both installed in one machine (asphalt milling machine). Engine W250_1 has a maximum power output of 470 kW, while W250_2 has 283 kW. The engine with the lower maximum power output (W250_2) clearly has a higher engine load and exhibits lower NO_x emissions. At higher CO_2-concentrations (i.e. engine loads) the W250_1 (left graph) also shows low NO_x/CO_2 ratio's, comparable to the smaller engine. However, the majority of the operation is at low engine loads (low CO_2-bins). The previously mentioned NRE7 machine is also an asphalt milling machine but features one large engine, instead of two smaller ones. The machine with two NRE6 engines has significantly lower total NO_x emissions.

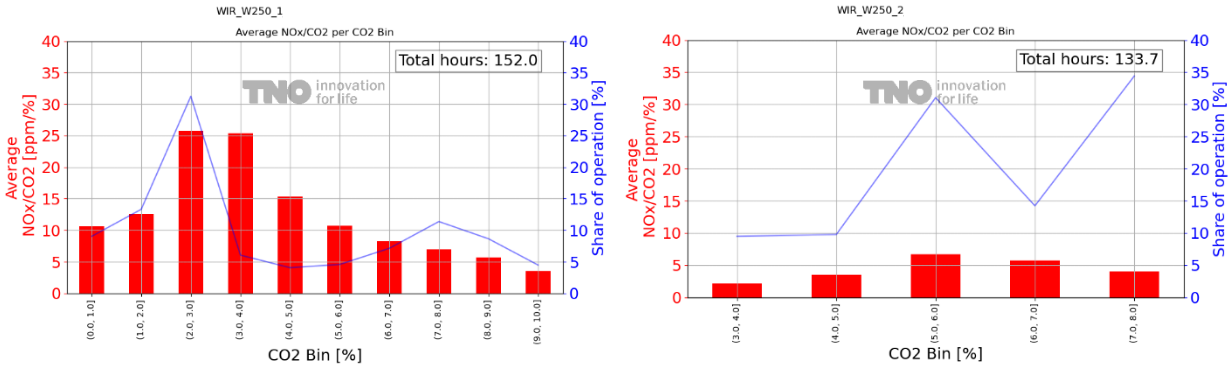


Figure 3.6: NO_x/CO_2 ratio (red bars) as a function of CO_2-concentration of two NRE6 engines with SCR. Both engines are installed in the same asphalt milling machine, the W250_1 has an engine power of 470 kW and the W250_2 has an engine power of 283 kW. The blue line indicates the timeshare per CO_2-bin.

Figure 3.7 shows the NO_x/CO_2 ratios for the two Liebherr Stage IV machines with SCR. Both machines showed relatively high average NO_x/CO_2 ratio's in Table 3.4. From Figure 3.7 it can be concluded that the NO_x/CO_2 ratios are around 5 ppm/% at the higher CO_2-bins. In contrast, the NO_x/CO_2 ratios at the lower CO_2 bins are between 10 and 35 ppm/%. A substantial part of the engine operation is at these lower CO_2-bins, which explains the relatively high averages.

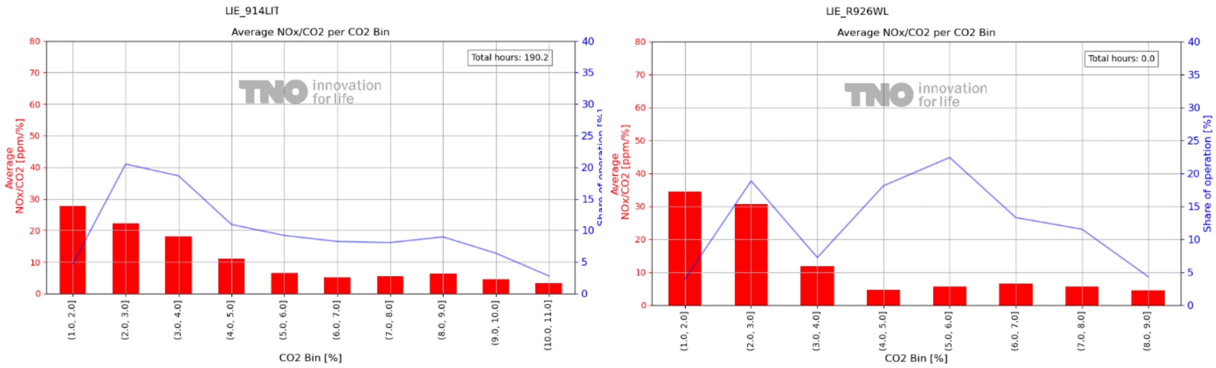


Figure 3.7: NO_x/CO_2 ratio (red bars) as a function of CO_2-concentration of two Stage IV machine with SCR. The blue line indicates the timeshare per CO_2-bin.

3.5 Emissions and deployment vary day to day

Daily usage and NO_x emissions levels can be accurately determined through emissions monitoring. Figure 3.8 presents an overview of the usage and emissions levels of the VOG_18003i_08_NWBDNRE5 per calendar day during the monitoring period, where the machine operated for at least half an hour. Daily deployment varied from 1.5 to nearly 13 hours. The daily average NO_x/CO_2 ratio also fluctuated significantly, ranging from 2.3 to 29 ppm/%. The highest value on 5 March 2024 resulted from dynamic machine operation, where the SCR catalyst did not reach operating temperature for most of the day. These variations also led to significant fluctuations in absolute NO_x emissions per day, roughly between 40 and 525 grams of NO_x daily. Thus, average emission performance provides only a limited perspective, as the variation can be substantial depending on operational conditions.

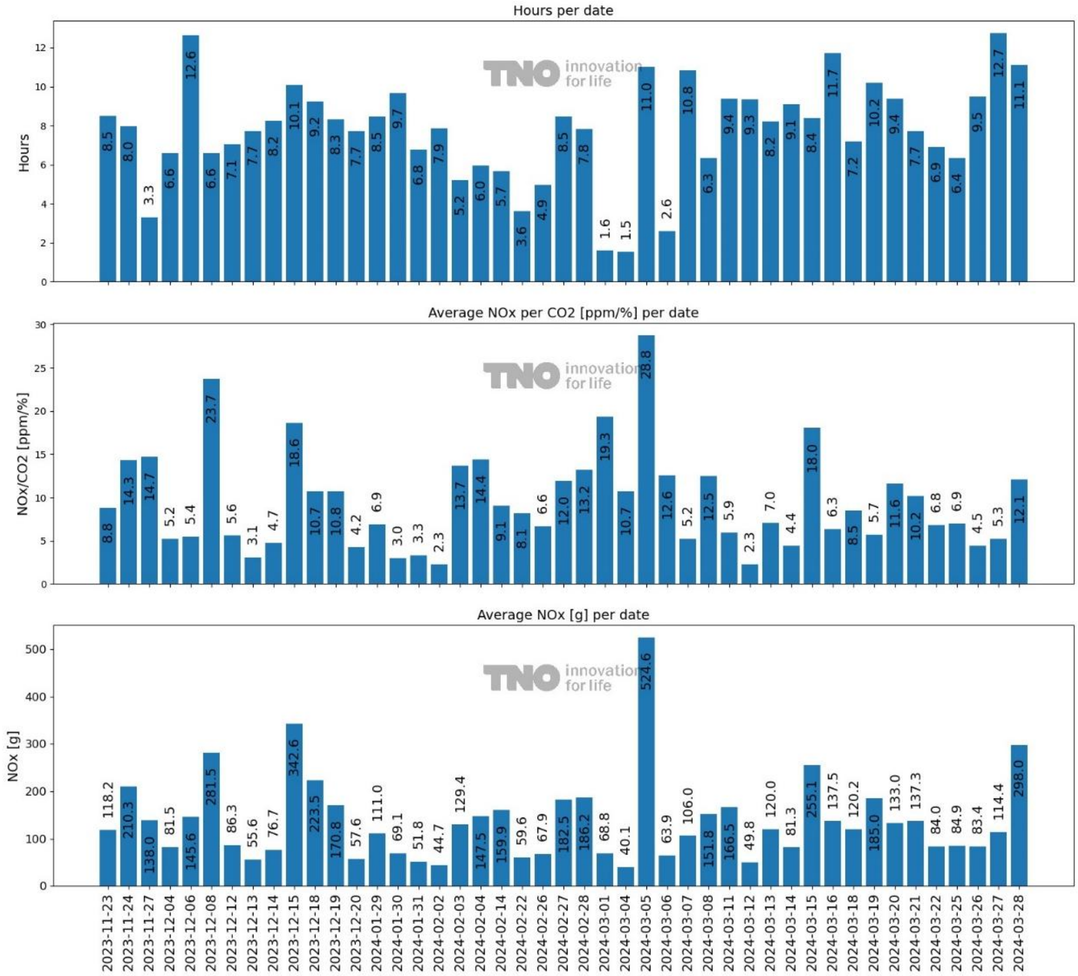


Figure 3.8: Usage (operating hours), NO_x/CO_2 ratios, and grams of NO_x per calendar day during the monitoring period, with a minimum usage of half an hour for the machine “VOG_18003i_08_NWBDNRE5.”

3.6 Impact of SCR-catalyst functioning

For machines with an SCR catalyst, the functionality of the SCR can also be determined based on the measured NO_x concentration (ppm) at the tail pipe. During the emission monitoring, a temperature sensor was installed in the exhaust of most machines. Temperature data helps to better understand the emission results. A sidenote to this is that the measured temperature cannot be compared across machines, because the temperature sensor is not always mounted in the same location. The further downstream from the engine, the lower the temperature. Nevertheless, it remains a good indication of the exhaust gas temperature level.

Figure 3.9 shows the NO_x concentration (blue line) and time share (red line) as a function of exhaust gas temperature for five Stage V machines, and one Stage IV machine, all with an SCR catalyst. A strong downward trend in NO_x concentration is generally observed from 180 degrees Celsius. Around 250 degrees Celsius, the NO_x concentration has dropped to values below 10 ppm for most of the monitored machines, indicating optimal SCR performance. Most of the machines are frequently used in the temperature range with low NO_x concentrations.

Above 350 degrees Celsius, the NO_x concentration rises again, likely due to occasional diesel particulate filter (DPF) regenerations or due to reduced catalyst efficiency at these higher temperatures. DPF regenerations occur at high exhaust gas temperatures, during which the SCR also emits NO_x and NH_3.

Figure 3.9 illustrates why the BOM_BF700C, DYN_SD2500, and WIR_W250_2 exhibit very low NO_x emissions. Their operational profiles align perfectly with the temperature range where the SCR catalyst functions optimally. In contrast, the WIR_W250_1, VOG_1800i, and LIE_R926WL demonstrate a greater timeshare at exhaust temperatures that fall outside this optimal range. Additionally, the Stage IV machine (LIE_R926WL) shows a relatively narrow range for effective SCR operation.

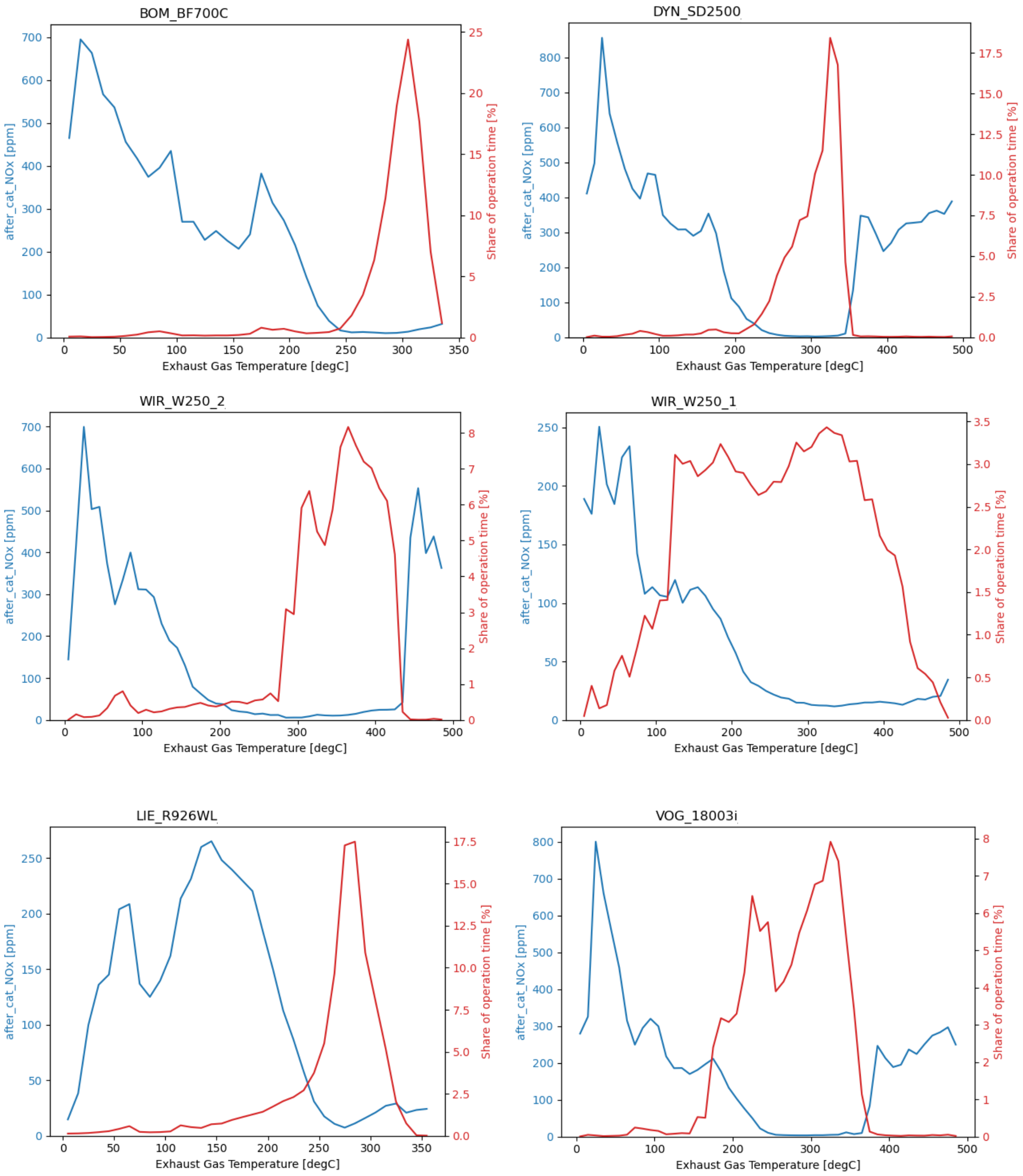


Figure 3.9: NO_x concentration (blue line) and time share (red line) as a function of exhaust gas temperature for five Stage V machines and one Stage IV machine, all with an SCR catalyst.

Both the optimization of usage, minimising low engine load of the machine and the selection of an appropriate engine power (not higher than necessary), can significantly reduce total NO_x emissions of a machine.

By means of emissions monitoring using a NO_x sensor it is possible to assess NO_x emission performance, and it is possible to optimise the operation of the machines.

3.6.1 Operation outside the SCR-operation window is dominant in total NO_x emissions

Figure 3.10 shows, in the left graph, the NO_x concentration (blue line) and time share (red line) as a function of exhaust gas temperature for a Stage V machine with an SCR catalyst (BOM_BF700C). The graph on the right in the same figure represents the cumulative NO_x emissions for this machine. The graph clearly indicates that, although the period during which the SCR is not functioning or is functioning sub optimally (red line up to 240 degrees Celsius), this period still dominates the contribution to the total NO_x emissions of this machine. Conversely, during the period when the SCR operates effectively, its contribution to the total NO_x emissions is limited.

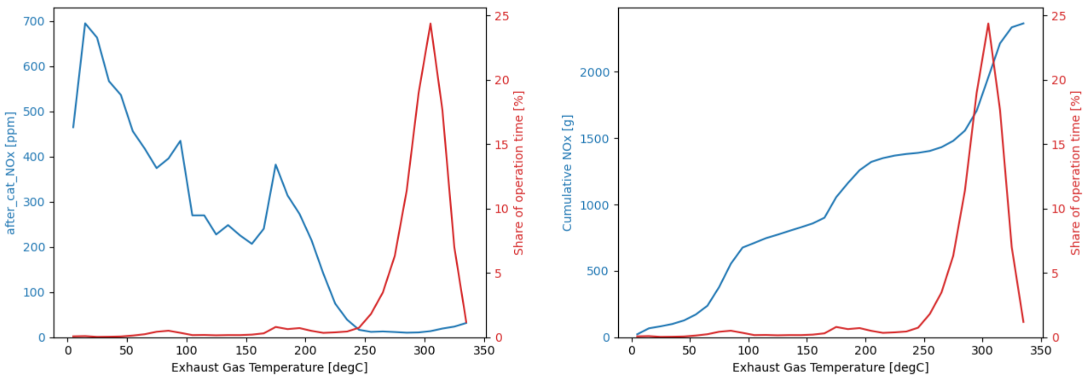


Figure 3.10: Left: NO_x concentration (blue line) and time share (red line) as a function of exhaust gas temperature for Stage V machines with an SCR catalyst (BOM_BF700C).

Based on the NO_x/CO_2 ratio, the proportion of time during which the SCR catalyst functions effectively can be estimated. This study assumes that the SCR catalyst operates well when emissions remain below the legal limit of 0.4 gNO_x/kWh. A rough estimate of the grams of NO_x per kWh—based on the NO_x/CO_2 ratio—can be theoretically approached as described in section 3.4.1. Depending on engine efficiency, the theoretical estimate of the emission limit (0.4 g/kWh) corresponds to a NO_x/CO_2 ratio between 5 and 6 ppm/%. In this study, all values below 6 ppm/% are considered as ‘SCR on’, while values above 6 ppm/% are classified as ‘SCR off’. In real-world, the distinction is not so clear-cut, as the SCR may still function (at least partially) at values above a NO_x/CO_2 ratio of 6 ppm/%, although these values will generally exceed the emission limit.

Table 3.5 shows the percentage of time that the SCRs of the monitored machines were ‘on’ or ‘off’. It indicates that the SCRs were ‘on’ for a relatively large portion of the time and were functioning effectively. However, for 7-29% of the total time, the SCRs were off, resulting in emissions that were 15 to 140 times higher than when the SCR was ‘on’.

Consequently, for each monitored machine, the period during which the SCR was 'off' accounted for 66 to 92% of the total NO_x emissions produced by that machine. The highest percentages for total NO_x emissions with SCR off are typically found in machines with a high proportion of 'SCR off'. The Dynapac 2500 is an exception; although its 'SCR off' time share is low, the NO_x contribution during this period is still very high. This can be explained by the very low NO_x/CO_2 ratio when the SCR is 'on'. Therefore, the shares of SCR 'on' and 'off' cannot be viewed independently of the NO_x/CO_2 ratios. Table 3.4 shows that the machines with the highest shares of "SCR off" (VOG_1800i and WIR_250_1) have the highest average NO_x/CO_2 ratios, and vice versa.

Table 3.5: Estimation of the time share for SCR off (>6 ppm/%) and SCR on (<6 ppm/%), including the corresponding average NO_x/CO_2 ratios and the estimation of the share of NO_x emissions.

	BOM BF700		Dynapac 2500		VOG_1800i		WIR_250_1		WIR_250_2		LIE_R926W	
	SCR off	SCR on	SCR off	SCR on	SCR off	SCR on	SCR off	SCR on	SCR off	SCR on	SCR off	SCR on
Time [%]	9	91	7	93	25	75	29	71	11	89	19	81
Average NO_x/CO_2 [ppm/%]	46	1,9	57	0,4	34	0,8	36	1,3	30	1,9	56	1,5
Total NO_x [%]	71%	29%	92%	8%	94%	6%	92%	8%	66%	34%	90%	10%

4 Emission performance of rail machinery & trains

In this chapter, the emission performance of rail machinery and diesel trains is described. A total of five machines and trains were measured, including one passenger train with two separately reported engines. Table 4.1 below presents an overview of the measured and monitored trains and rail equipment, detailing their specifications and environmental classifications. The engine power varies significantly among the different machines, and the emission classes range from non-certified[10] to Stage IV. The diesel locomotive (dieselloc) and the passenger train were monitored over several months, using SEMS. The other rail equipment was measured for a short duration using the BOEMkit. The diesel locomotive (dieselloc) is partly utilized in rail construction activities, alongside the rail excavator, the mineral conveyor and storage unit, and the loading and unloading station, but is mainly used for logistic purposes. The passenger train, on the other hand, is employed for public transport on routes where overhead lines for electric trains are unavailable. The diesel engines of the passenger train also used Hydrotreated Vegetable Oil (HVO) as fuel for a certain period. This report does not differentiate between regular diesel fuel and HVO. The use of HVO in these engines resulted in a NO_x reduction of 11% to 17%. A detailed analysis on the effects of HVO can be found in report “TNO 2023 R12287”.

Table 4.1: Overview of measured and monitored rail equipment: Specifications and environmental classification.

Specifica-tions	Dieselloc	Passenger train - engine 1	Passenger train - engine 2	Rail excavator	Mineral conveyor and storage unit	Loading and unloading station
Make	MaK	Stadler Rail	Stadler Rail	Atlas	Plasser & Theurer	Plasser & Theurer
ID	MAK_G1206_04	STA_D_01	STA_D_02	ATL_180WSR_01	PLA_MFS100_02	PLA_ULS300_03
Engine power [kW]	1500	480	480	115	148	139
Emission class [Stage]	Non-certified [1]	IIIB	IIIB	IV	IIIA	IIIA
Fuel	Diesel	Diesel/HVO	Diesel/HVO	Diesel	Diesel	Diesel
Monitoring method	SEMS	SEMS	SEMS	BOEMkit	BOEMkit	BOEMkit

[10] Diesel engines for locomotives have been subject to non-road mobile machinery emission regulations since Stage IIIA (2004/26/EC). The regulation for locomotives (RH A) with engines >560 kW came into effect in 2008 for “Type-approval” and 2009 for "placing on the market," with provisions for delays. The monitored diesel locomotive was produced in 2008, but its engine plate did not indicate an emission class. As a result, it is assumed that the engine is non-certified. At best, the engine may comply with Stage IIIA standards, which impose a NO_x limit of 6 grams per kWh.

This chapter begins with the results of the monitored machines, i.e., the diesel locomotive and passenger train. Then, the short measurements are discussed.

4.1 Monitoring results of the diesel locomotive and passenger train

In this paragraph an overview of the monitoring emission results of the diesel locomotive and passenger train engines are described. Table 4.2 provides data on operational hours and emissions of the monitored diesel locomotive and the two passenger train engines. The diesel locomotive was monitored for 545 hours with the diesel engine running. Engine 1 of the passenger train was monitored for 411 hours while engine 2 was monitored for 838 hours. The difference in running hours between engine 1 and engine 2 is mainly related to a longer monitoring period for engine 2. For each measured machine, the cumulative emissions and the average emissions per hour for NO_x and CO_2 are shown in the table. Cumulative emissions deviate significantly from each other since one machine is monitored for more hours than the other and because the grams per hour differ. Moreover, some machines demand a higher engine load, which increases the fuel consumption and absolute NO_x and CO_2 emissions. The emission levels vary significantly, with the diesel locomotive emitting 1,453 grams of NO_x per hour on average, while the passenger train showed NO_x-emissions between 700 and 850 grams per hour. The higher NO_x emissions in grams per hour from the diesel locomotive can be attributed to its greater engine power, which also leads to higher CO_2 emissions per hour. In comparison, various monitored Euro VI trucks showed average NO_x-emissions of around 50 grams per hour (TNO 2021 R10121: *Dutch In-service emissions testing programme for heavy-duty vehicles 2019-2020*).

To incorporate engine load into the analysis, the NO_x emissions per litre of fuel and the NO_x/CO_2 ratio are shown. Fuel consumption serves as a relatively reliable indicator of engine load, as does the CO_2 concentration. The fuel rate is retrieved from the machine signals, though it is not directly available for every machine (it is available for the three monitored engines). Using the SEMS data from the installed NO_x sensor, the NO_x/CO_2 ratio can be calculated. This calculation is straightforward, requiring only the division of NO_x concentrations by CO_2 concentrations. For example, with a NO_x concentration of 300 ppm and a CO_2 concentration of 5%, the NO_x/CO_2 ratio is 60 ppm/%.

The NO_x emissions per litre of fuel show minimal difference between the non-certified diesel locomotive and the Stage IIIB engines, while the regulated NO_x-emission limit for Stage IIIB is relatively low with 2 grams per kWh. As the fuel used serves as an indicator of energy usage (although it depends on the engine's efficiency, which depends on the engine load), lower NO_x emissions per litre were expected from the Stage IIIB engines. Additionally, there is a notable difference in NO_x emissions per litre fuel between the two passenger train engines. The NO_x/CO_2 ratio does clearly show the distinction in emission levels between the dieselloc and passenger trains, with substantial lower values for the passenger train engines.

However, with a Stage IIIB emission limit of 2 g/kWh, values in the range of 25-30 ppm/% would be expected. An estimation of the NO_x emission levels for these engines, based on engine signals in combination with the NO_x sensor and/or based on the NO_x/CO_2 ratio, would be around 6.5 grams per kWh for engine 1 and around 8 grams per kWh for engine 2.

In the next paragraph the results are shown in more detail per machine/engine.

Table 4.2: Monitoring results of the diesel locomotive and passenger train engines.

		Diesel locomotive	Passanger train - engine 1	Passanger train - engine 2
Monitored hours	[h]	545	411	838
NO_x	[kg]	792	290	719
CO_2	[kg]	61.840	26.751	51.885
NO_x	[g/h]	1,453	706	858
NO_x	[g/L_fuel]	34	29	37
NO_x/CO_2	[ppm/%]	173	80	104
CO_2	[kg/u]	113	65	62

4.1.1 Detailed monitoring results of the diesel locomotive

This paragraph provides a detailed analysis of the monitoring results for the diesel locomotive (dieselloc). It begins by outlining the operational characteristics, including vehicle speed distribution, engine load, and fuel consumption. Following this, the emission results are presented.

4.1.1.1 Operational characteristics of the dieselloc

As previously mentioned, the diesel locomotive (dieselloc) is utilized in rail construction activities and logistics. Figure 4.1 illustrates the speed profile of the dieselloc, with speed data recorded only when the diesel engine is running. The figure clearly indicates that the dieselloc remains stationary for the majority of the total monitoring time, this is approximately 60% of the time. About 10% of the time, the speed ranges between 90 and 100 km/h, while the remaining 30% is distributed between standstill and 90 km/h.

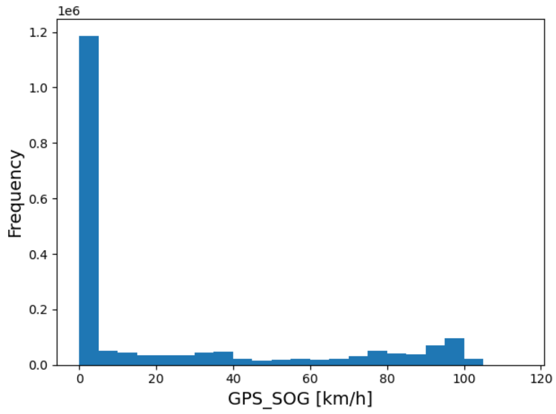


Figure 4.1: Speed distribution of the dieselloc, with diesel engine on.

To gain an overview of the engine load, the fuel rate signal from the machine was used, as there were no available signals for engine torque or engine load. The fuel rate is a good indicator of engine load. For the analysis, the fuel rate (litres per hour) was divided into 10 bins. Figure 4.2 displays the time distribution per fuel bin (left graph) and fuel consumption per fuel bin (right graph). The graphs only show data when the diesel engine is running. The time distribution per fuel bin (left graph) is comparable to the speed profile, with a significant portion of the time in the low fuel bin (up to 38 litres per hour), indicating that the dieselloc spends a large part of the time idling and operating under low load. On average, the estimated engine load is 10%. This low engine load was also observed in earlier research (TNO 2017 R11414: "*Inzicht in het energieverbruik, de CO_2-uitstoot en de NO_x-uitstoot van het spoorgoederenvervoer*"). Additionally, for fuel consumption (right graph), the lowest fuel bin is dominant, with approximately 30% of the fuel consumption occurring during idling and low engine load.

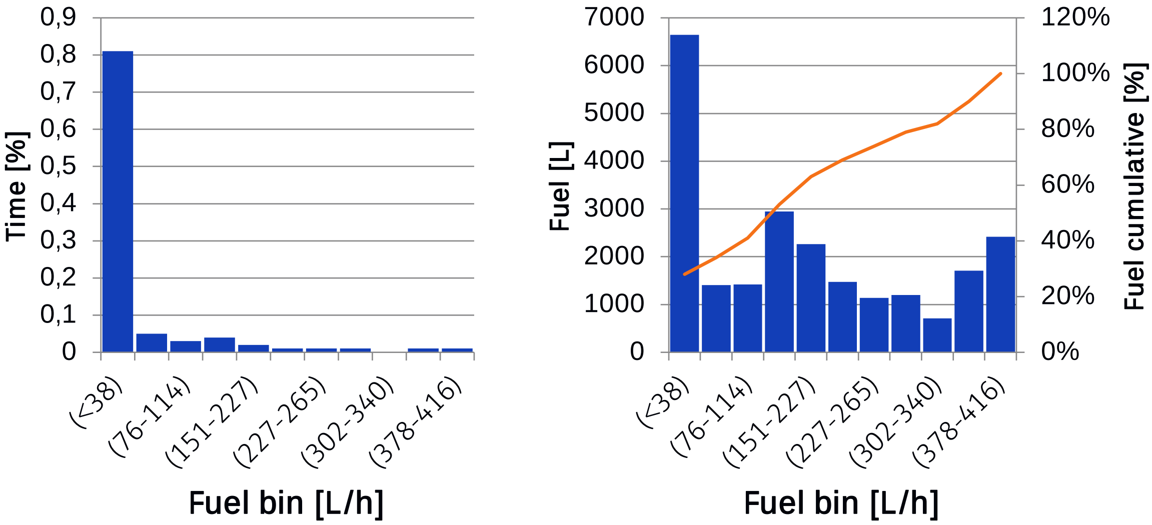


Figure 4.2: Dieselloc: time distribution per fuel bin (left), fuel consumption per fuel bin (right).

4.1.1.2 NO_x emission performance of the dieselloc

In Figure 4.3 the NO_x emission level per fuel bin of the dieselloc is presented as follows, from left to right: NO_x/CO_2 [ppm/%], NO_x [grams per hour], and NO_x [kg].

The left graph presents the average NO_x/CO_2 ratio (in ppm/%) across different ranges of fuel rate, expressed as fuel bins in litres per hour. The NO_x/CO_2 ratio decreases as the fuel rate increases, with a few minor fluctuations. At the lowest load range (<38 L/h), where most of the operation occurs, the NO_x/CO_2 ratio is highest at 187 ppm/%. As the fuel rate increases, the ratio generally decreases, reaching its lowest value of 91 ppm/% in the 227-265 fuel bin.

The graph in the middle highlights the relationship between fuel rate and NO_x emissions in grams per hour. Overall, the data shows a clear trend of increasing NO_x emissions in grams per hour with higher fuel consumption. At the lowest fuel consumption bin (<38 L/h), NO_x emissions are 750 g/h. This value increases significantly in the 38-76 L/h bin to 2,300 g/h and continues to rise across higher fuel bins. The highest NO_x emissions are observed in the 340-378 L/h bin at 10,436 g/h.

The graph on the right highlights total NO_x emissions in kilograms across different fuel consumption bins, in addition the cumulative NO_x emissions are provided. At the lowest fuel rate bin (<38 L/h), the total NO_x emissions are 330 kg, which is 41% of the total NO_x-emissions, despite the low NO_x emissions in grams per hour. This is the result of the large amount of time spent at low engine load.

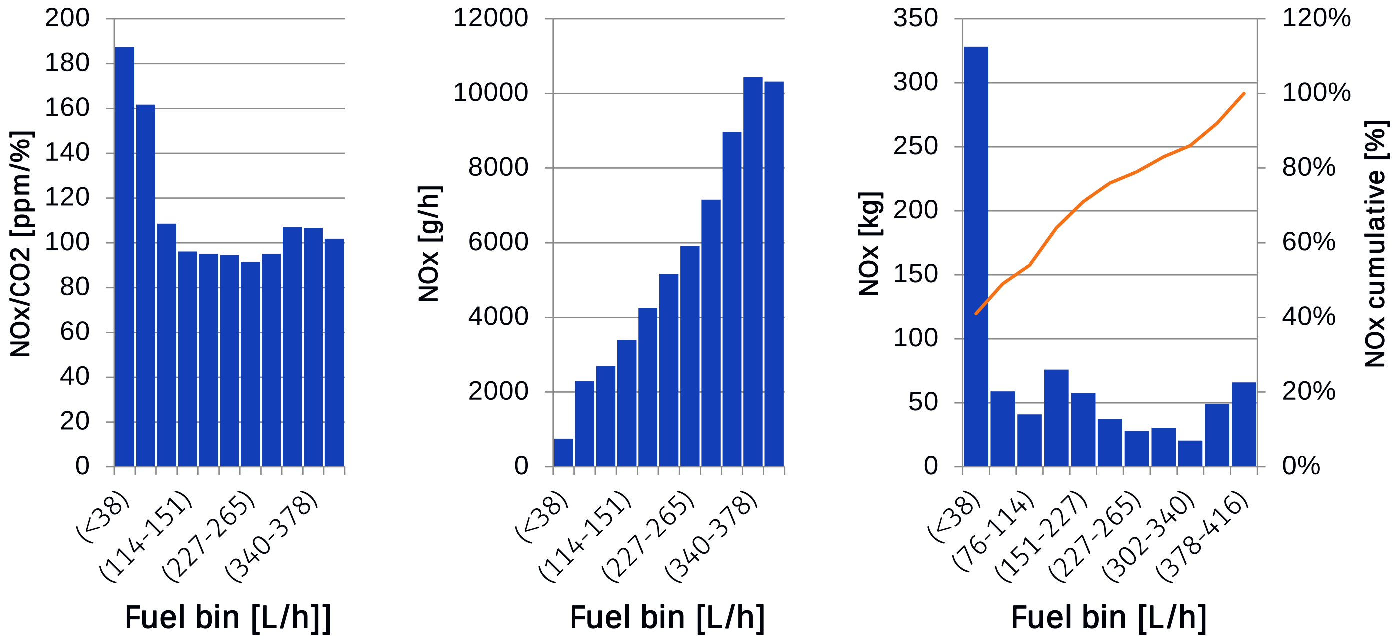


Figure 4.3: NO_x-emission levels per fuel bin of the dieselloc, from left to right; NO_x/CO_2 [ppm/%], NO_x [grams per hour], NO_x [kg].

4.1.1.3 Day to day variations at the dieselloc

Figure 4.4 illustrates the operational characteristics and emission performance for each monitored calendar day, including only data when the engine is on. Days with less than one hour of data are excluded. The graph reveals significant day-to-day variations in operational characteristics. On some days, the diesel locomotive (dieselloc) is used for just over an hour, while on others, it operates for nearly 24 hours. Similarly, the distance covered ranges from as little as 10 km to as much as 800 km. The average fuel rate also varies widely, from 15 litres per hour to 96 litres per hour. As the maximum observed fuel rate (for a short period) is 416 litres per hour, the daily averages are relatively low, indicating low engine loads. Generally, days with longer distances correspond to higher fuel consumption.
In contrast to the operational characteristics, the average NO_x/CO_2 ratio remains relatively constant, with lower values observed when the average fuel rate is high. The absolute NO_x emissions per day vary significantly, ranging from 3 kg to 37 kg. Higher total emissions are associated with days of extended operation and relatively high fuel rates.

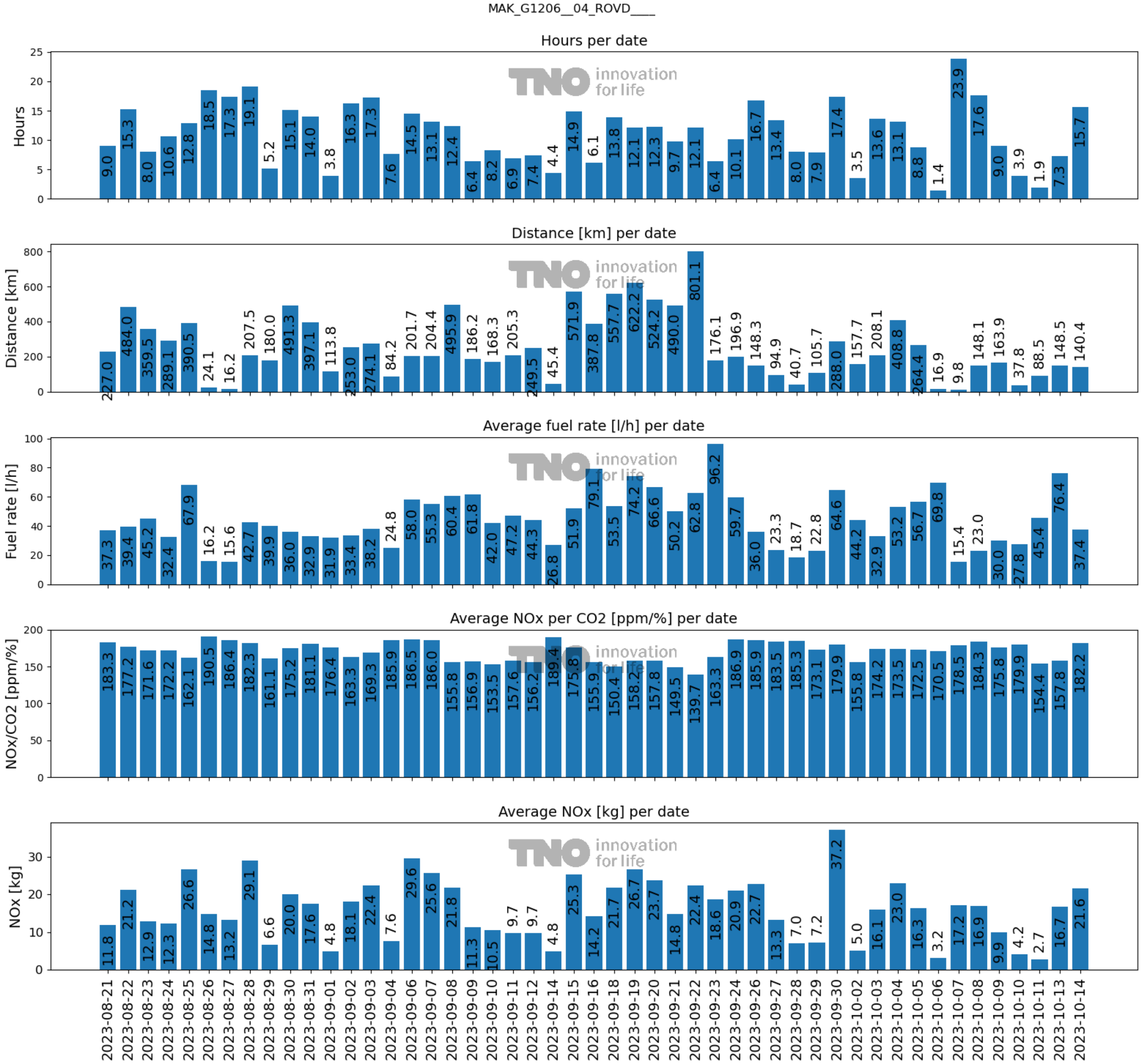


Figure 4.4: Operational characteristics and emission performance per monitored calendar day of the dieselloc.

4.1.2 Detailed monitoring results of the passenger train

This paragraph provides a detailed analysis of the monitoring results for both engines of the diesel passenger train. It begins by outlining the operational characteristics, including the train's speed distribution, engine load, and fuel consumption. Following this, the emission results are presented.

4.1.2.1 Operational characteristics of the passenger train

As previously mentioned, the passenger train is utilized for public transport. Figure 4.1 illustrates the speed profile of the passenger train, with speed data recorded only when the diesel engine is running. The figure clearly indicates that the passenger train remains stationary for a substantial part of the total monitoring time, this is approximately 30% of the time. About 20% of the time, the train is operated around 100 km/h. The remaining 50% is mainly distributed between standstill and 90 km/h, with some small peaks between 50 and 60 km/h.

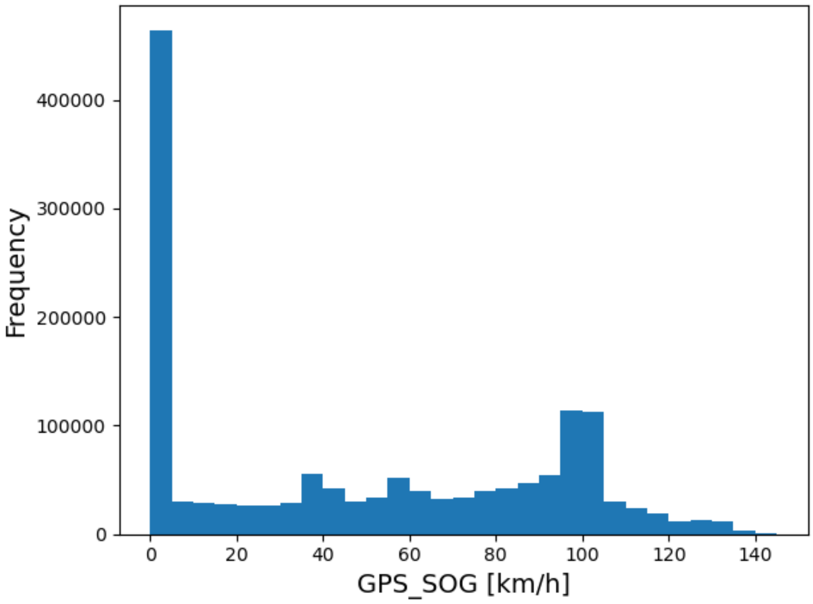


Figure 4.5: Speed distribution of the passenger train, with diesel engine on.

To calculate the engine load, the engine torque signal and the engine speed from the machine were used. For the analysis, the engine load is divided into 10 bins, i.e. power ranges as a percentage of their rated power. Figure 4.6 displays the time distribution per engine load bin (left graph) and fuel consumption per engine load bin (right graph). The upper graphs show data from engine 1, the lower graphs show data from engine 2.

Both engines spend the majority, approximately 60%, of their time operating at low power levels, specifically within the 0-10% range of their rated power. As the power range increases, the timeshare percentages decrease significantly. The timeshare increases to approximately 20% for engine loads between 60% and 90%, with some variations between the two engines.

The graphs on the right highlights the fuel consumption (in litres) for Engine 1 and Engine 2 across different power ranges, including the cumulative share. Both engines show the highest fuel share, approximately 60%, in the 70-90% power range, with Engine 1 having a peak in the 80-90% bin and Engine 2 having two peaks between 70-90%. In the lowest power range (0-10%), the share of fuel consumption is 10% for both engines. The total litres for engine 1 are lower than for engine 2, as engine 2 is monitored for a longer period.

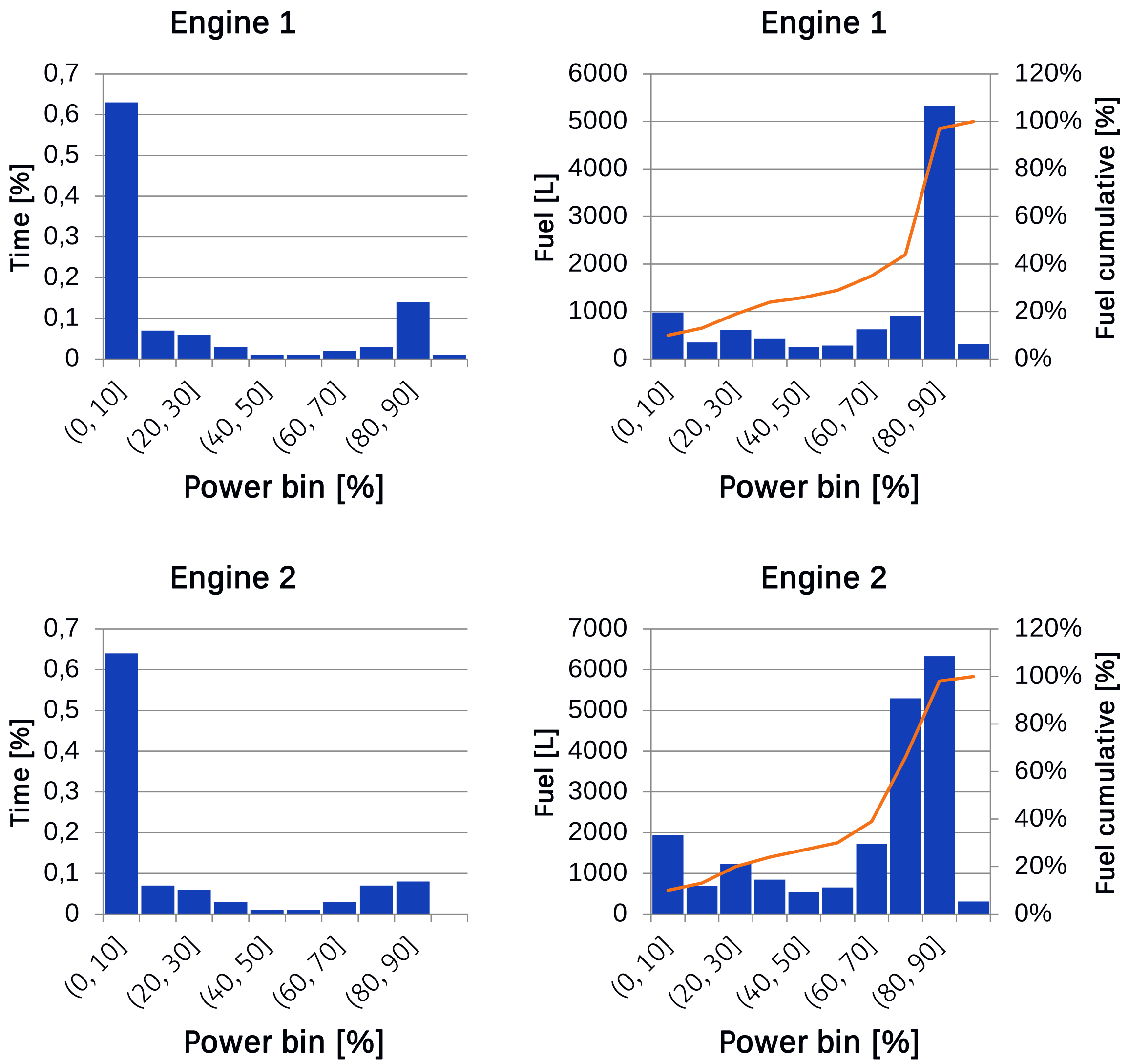


Figure 4.6: Passenger train: time distribution per fuel bin (left), fuel consumption per fuel bin (right). The upper graphs show data from engine 1, the lower graphs show data from engine 2.

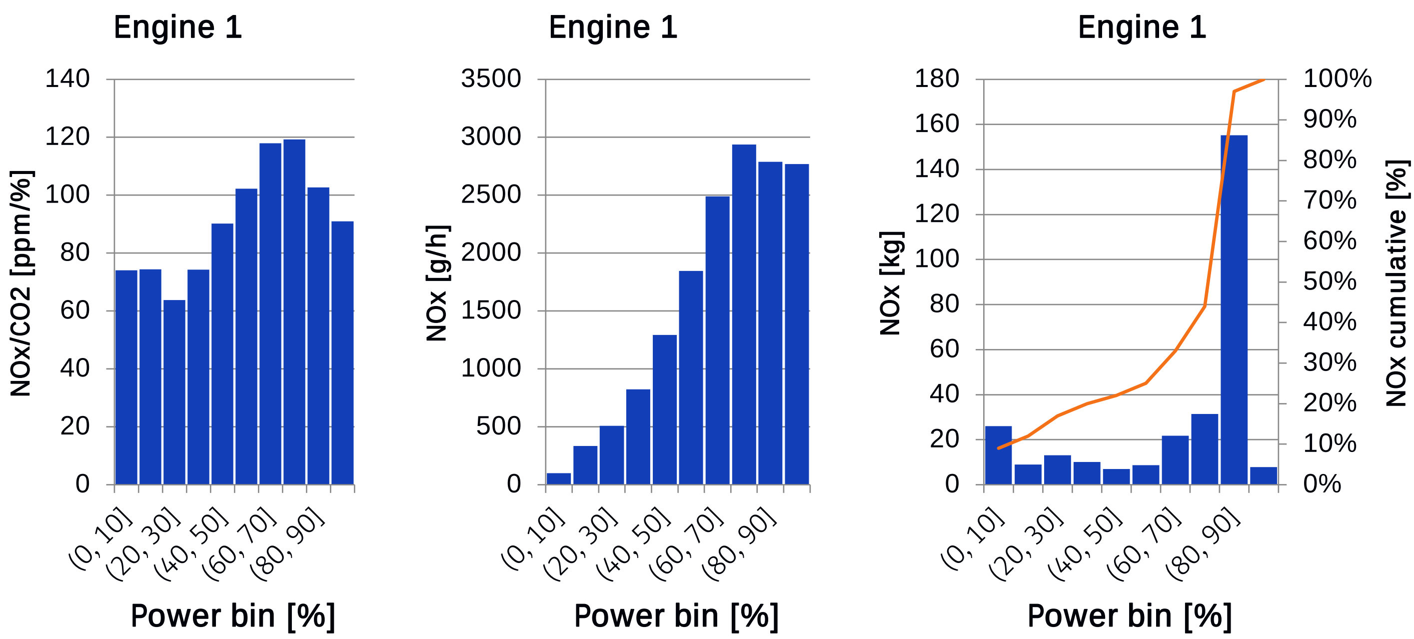
4.1.2.2 NO_x-emission level of the passenger train

In Figure 4.7 the NO_x emission level per engine load bin of the passenger train is presented as follows, from left to right: NO_x/CO_2 [ppm/%], NO_x [grams per hour], and NO_x [kg]. The upper graphs show data from engine 1, the lower graphs show data from engine 2.

The left graph presents the NO_x/CO_2 ratios for Engine 1 and Engine 2 across various power ranges, expressed as a percentage of their rated power. Both engines show an increase in the NO_x/CO_2 ratio as the power range increases, with some fluctuations. In the lowest power range (0-10%), Engine 1 has a NO_x/CO_2 ratio of 74 while Engine 2 has a higher ratio of 94. As the power range increases, the ratios increase as well. The ratios are peaking in the 70-80% power range, where Engine 1 has a ratio of 119 and Engine 2 has the highest ratio of 144. In the highest power range (90-100%), the ratios decrease again. Overall, the NO_x/CO_2 ratios are generally higher for Engine 2 than Engine 1 across most power ranges, indicating higher NO_x emissions relative to CO_2 as the engine load increases.

The graph in the middle highlights the relationship between engine load and NO_x emissions in grams per hour. Both engines show an increase in NO_x emissions as the power range increases, with some fluctuations. In the lowest power range (0-10%), Engine 1 emits 100 g/h of NO_x, while Engine 2 emits 115 g/h. As the power range increases, NO_x emissions rise as well, peaking in the 70-80% range, where Engine 1 emits 2940 g/h and Engine 2 emits 3615 g/h. Emissions slightly decrease in the 80-100% range. Overall, NO_x emissions are highest at mid to high power levels, and Engine 2 has higher overall emissions than Engine 1.

The right graphs highlight the total NO_x emissions (in kilograms) for Engine 1 and Engine 2 across different power ranges, including the cumulative share. As mentioned earlier, the monitored hours for engine 2 are higher than for engine 1, therefore engine 2 emits more kilograms of NO_x. Engine 1 and engine 2 can be compared by using the cumulative NO_x emissions. Both engines exhibit the highest NO_x emission contribution in the 70-90% power range, with 60 to 65% of the NO_x emitted. In the lowest power range (0-10%), approximately 10% of the NO_x is emitted for both engines.



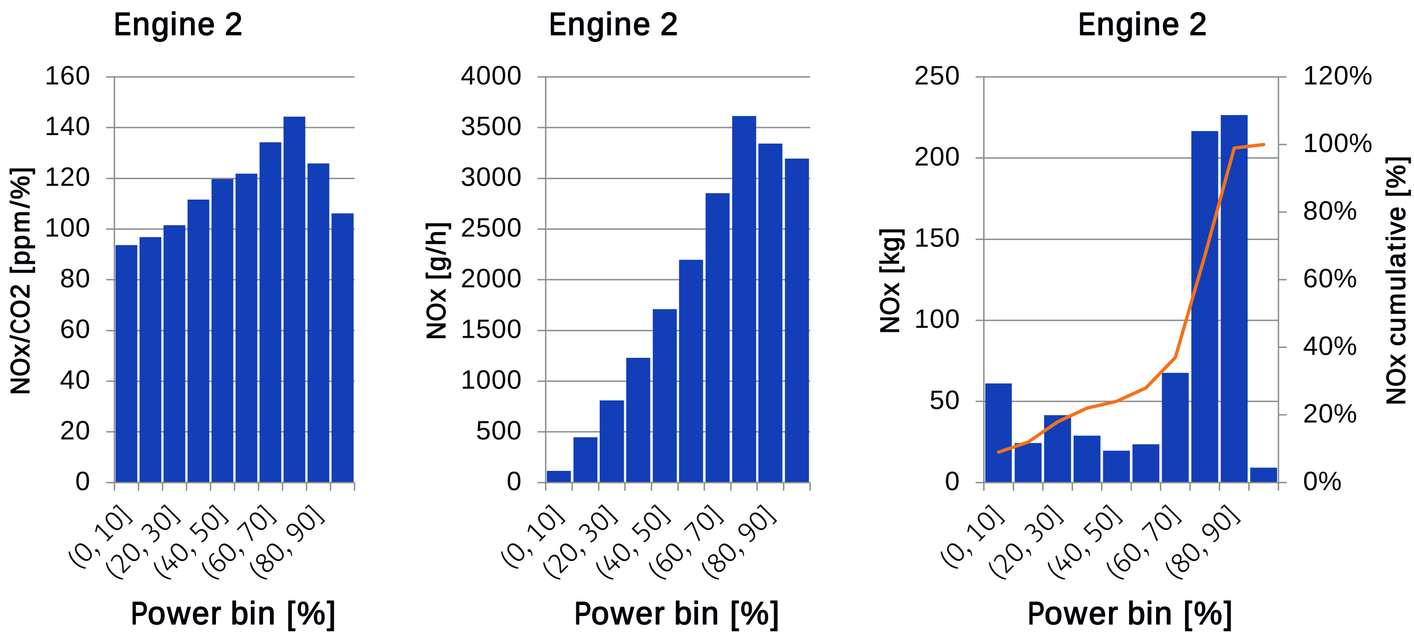


Figure 4.7: NO_x-emission performance per fuel bin of the passenger train, from left to right; NO_x/CO_2 [ppm/%], NO_x [grams per hour], NO_x [kg]. The upper graphs show data from engine 1, the lower graphs show data from engine 2.

As mentioned in paragraph 4.1, the emissions of the passenger train with Stage IIIB engines are higher than expected based on the emission limits. To reduce NO_x emissions, these engines are equipped with an SCR catalyst, which should operate effectively between approximately 200 and 300 degrees Celsius. To check the functioning of the SCR catalyst, NO_x concentrations are compared to the exhaust temperature.

Figure 4.8 shows NO_x concentrations as a function of exhaust temperature, including the share of operation time per exhaust gas temperature bin. The left graph represents Engine 1, and the right graph represents Engine 2. With a well-functioning SCR catalyst, the NO_x concentrations should be well below 100 ppm. For well-performing Stage V engines, with a NO_x limit of 0.4 g/kWh, the ppm levels are often below 10 ppm. The graphs indicate that the engines are operated within the correct temperature range. However, the NO_x concentrations are not lower than 300 ppm, indicating poor SCR performance.

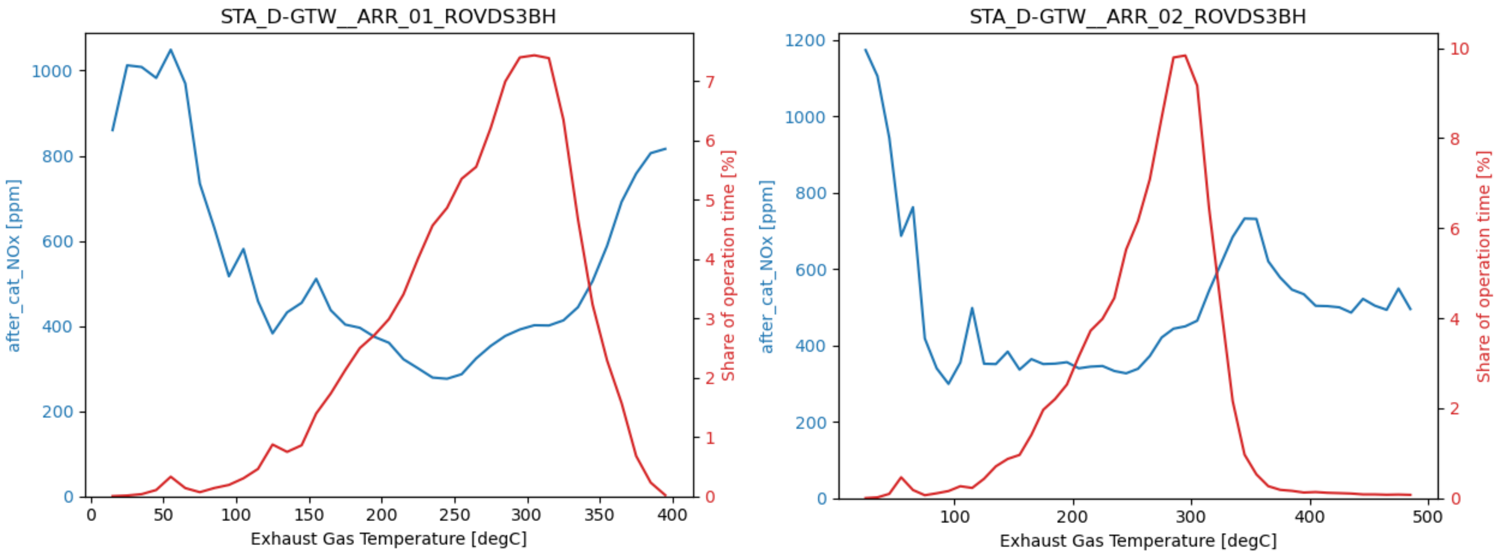


Figure 4.8: NO_x concentrations (blue line) as function of exhaust temperature, including the share of operation time (red line) per exhaust gas temperature bin. The left graph represents engine 1, and the right graph represents engine 2.

4.1.2.3 Day to day variations at the passenger train

Figure 4.9 illustrates the operational characteristics and emission performance of Engine 1 for each monitored calendar day, including only data when the engine is on. Days with less than one hour of data are excluded.

The graph reveals some day-to-day variations in operational characteristics. On some days, the engine is used for a couple of hours. However, most of time it's operating between 13 and 17 hours per day. The days with a low number of hours can also indicate other events, such as maintenance. The distance covered are mostly between 600 and 900 km.

The average fuel rate is relatively constant, around 25 litres per hour. As the maximum observed fuel rate (for a short period) is 120 litres per hour, the daily averages are relatively low, indicating low engine loads.

The average NO_x/CO_2 ratio remains relatively constant, with higher values observed when the average fuel rate is high. The absolute NO_x emissions mirror the variations as observed in the hours active per day.

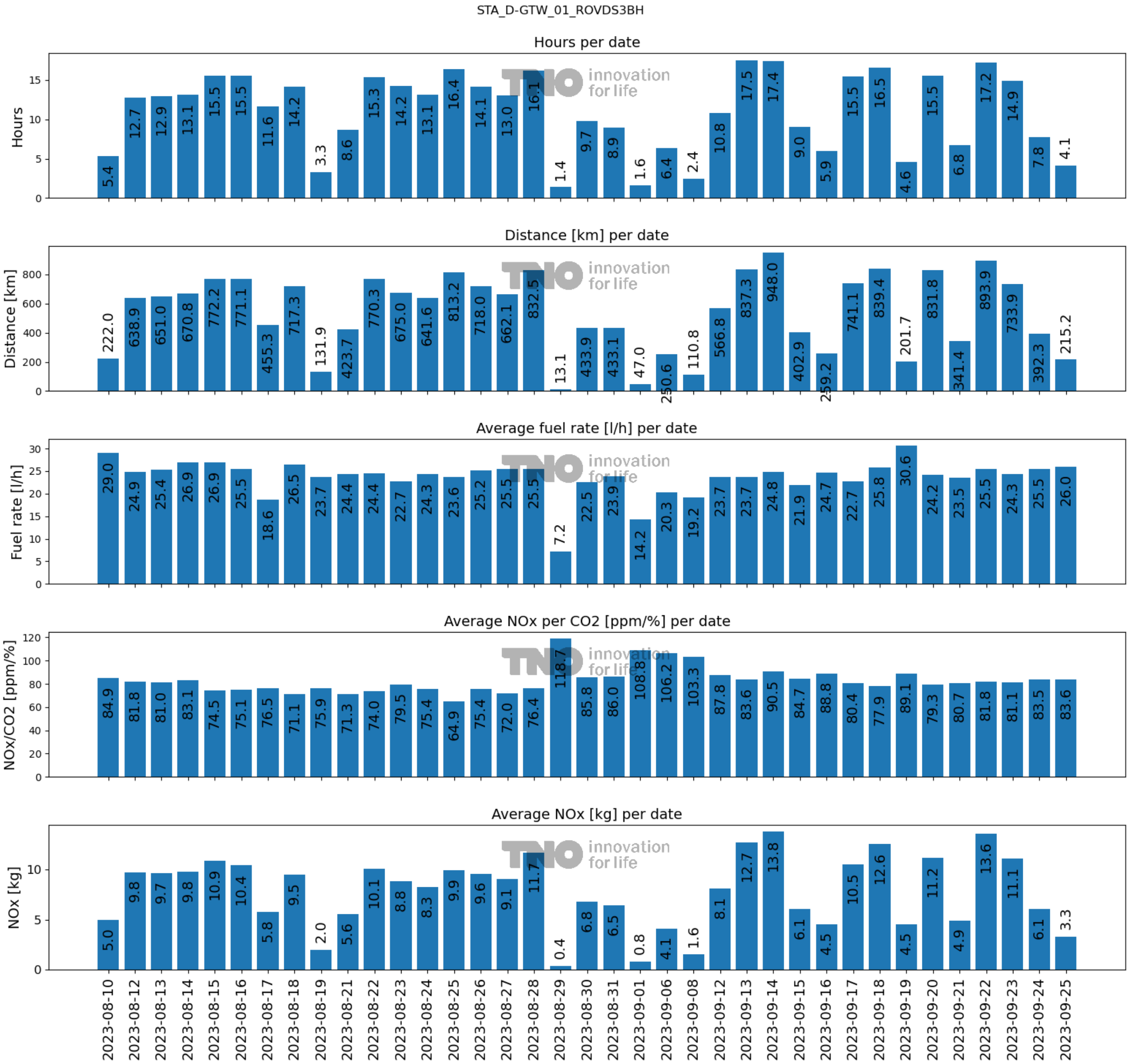


Figure 4.9: Operational characteristics and emission performance per monitored calendar day of the passenger train, engine 1.

4.2 Results of the short measurements on rail equipment

As mentioned in the introduction of this chapter, the Rail excavator (Stage IV), the mineral conveyor and storage unit (Stage IIIA), and the loading and unloading station (Stage IIIA) were measured for a short duration using the BOEMkit. These machines are utilized in rail construction activities, alongside the monitored diesel loc. The Rail excavator is the only machine with an SCR-catalyst, as it is a diesel-powered Stage IV machine with 115 kW. Measurements took place during real-world operating conditions, without specific load points being measured. However, as the measurement period was relatively short (between 10 and 60 minutes), it is not necessarily representative for average operating conditions.

During the short measurements with the BOEMkit, NO_x and CO_2 are determined as concentrations. No connection was made with the machine to retrieve engine signals. Therefore, no results are provided as absolute mass emissions (i.e. grams of NO_x or grams or NO_x per kWh). To incorporate engine load into the analysis, the NO_x/CO_2 ratio is shown, as the CO_2 concentration indicates engine load. This ratio is explained in the previous paragraph and also shown for the machines with long-term monitoring.

4.2.1 Rail excavator measurement results

Figure 4.10 shows the NO_x/CO_2 ratio as function of exhaust temperature (left graph) and as function of CO_2 (right graph) for the Rail excavator. The exhaust temperature indicates whether the SCR-catalyst reaches its operational temperature, measured at the end of the exhaust pipe (the actual SCR temperature will be higher). The Rail excavator was measured for 58 minutes. During the measurements, no heavy rail work was required, which is evident in both graphs. They show that the machine operated at a very low engine load (low exhaust temperature and low CO_2 concentrations) for the majority of the time (>80%). The Rail excavator briefly performed more demanding work, as indicated by the higher CO_2 concentrations and exhaust temperatures reaching 225 degrees Celsius. The NO_x/CO_2 ratio decreases substantially at higher engine loads. During low engine loads, the NO_x/CO_2 ratio lies between 80 and 100 ppm/%, whereas, at high engine loads, it is reduced to an average of 20 ppm/%. This shows that the SCR-catalyst is active at higher engine loads. Based on the Stage IV NO_x emission limit of 0.4 g/kWh, values below 6 ppm/% (see paragraph 3.4.1) were expected. However, second-by-second data show that such low values are briefly reached, but the high-load conditions are too short to maintain these low emission levels.

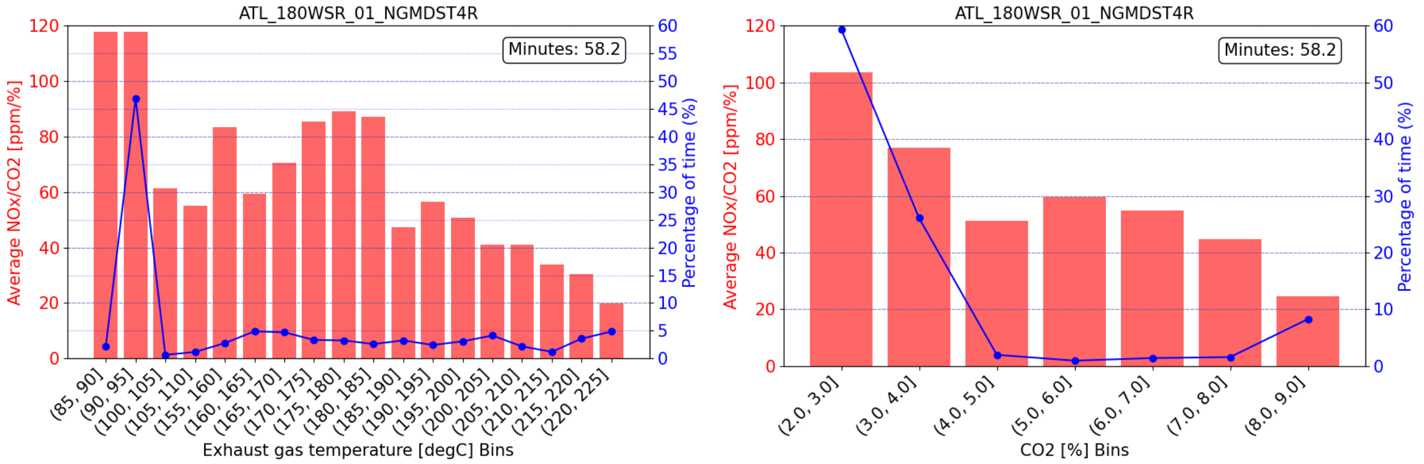


Figure 4.10: Rail excavator: NO_x/CO_2 ratio as function of exhaust temperature (left graph) and as function of CO_2 (right graph).

4.2.2 Mineral conveyor and storage unit, and the loading and unloading station measurement results

The mineral conveyor and storage unit (PLA_MFS100) and the loading and unloading station (PLA_ULS300) were measured for 21 and 11 minutes, respectively. Both machines have the emission class "Stage IIIA," with comparable rated engine power, and therefore share the same emission limit value. Neither engine has an SCR-catalyst for NO_x reduction.

Figure 4.11 and Figure 4.12 show the results for the MFS100 and ULS300, respectively. Based on the temperature levels and CO_2 concentrations, it is clear that the ULS300 operated at a higher engine load. The MFS100 shows very low exhaust temperatures and relatively low CO_2 concentrations, indicating low engine loads. The emission performance of the ULS300 is substantially better than the MFS100, with average NO_x/CO_2 ratios of 35 ppm/% and 70 ppm/%, respectively. The NO_x concentrations are, on average, about 30% lower for the ULS300, while the CO_2 concentrations are more than 1.5 times higher, leading to the lower NO_x/CO_2 ratio. With an emission limit of 4 g/kWh (NO_x + HC), NOx/CO_2 values below 50 were expected. However, since the official emission test is conducted at various engine loads, with a focus on medium and high engine loads, it is possible that the MFS100 performs better at somewhat higher engine loads.

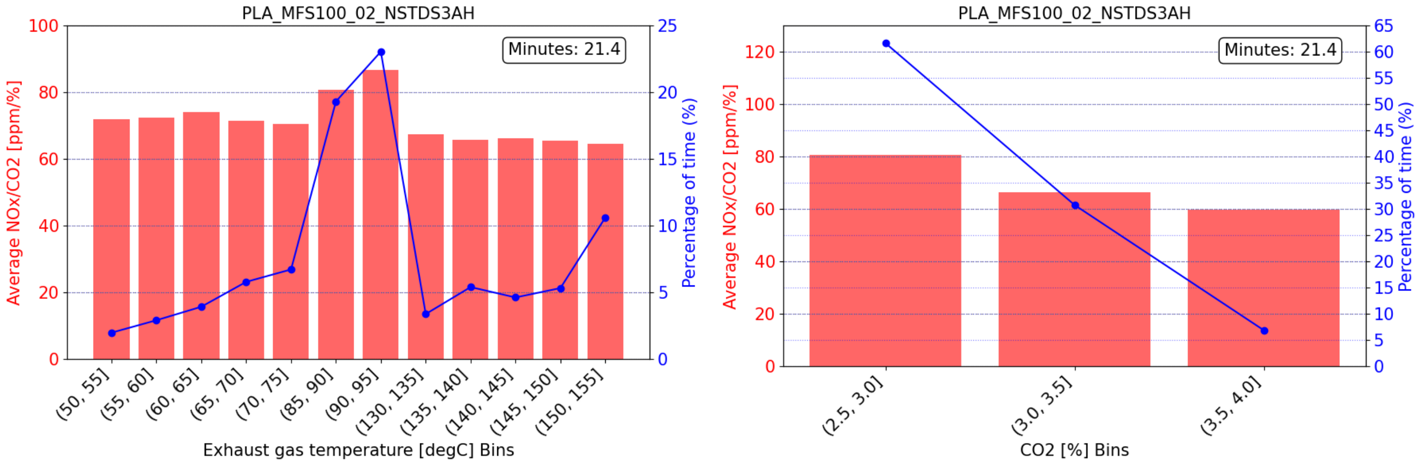


Figure 4.11: Mineral conveyor and storage unit: NO_x/CO_2 ratio as function of exhaust temperature (left graph) and as function of CO_2 (right graph).

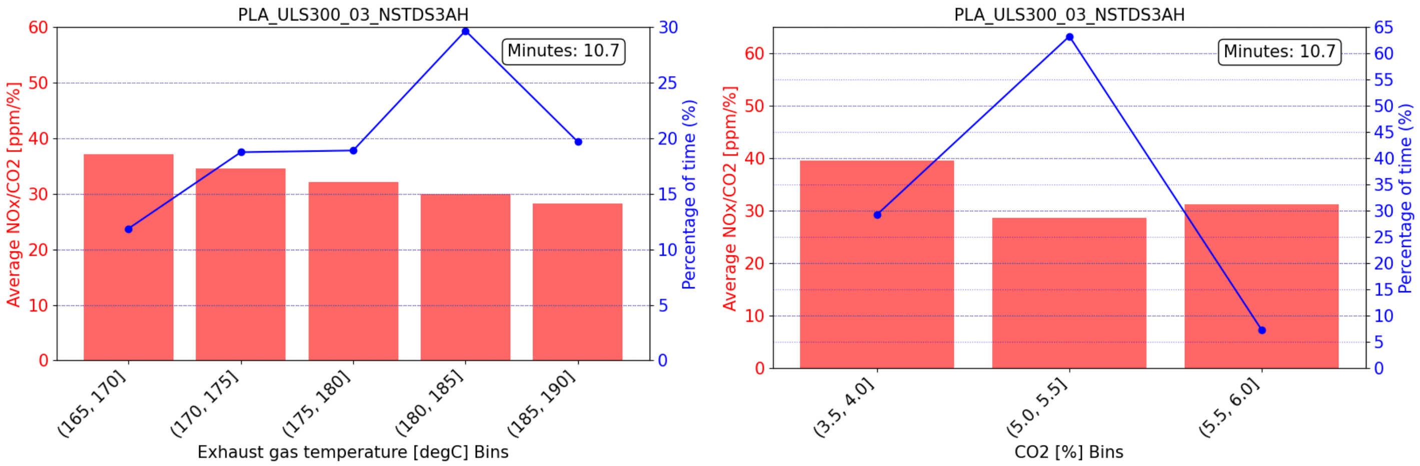


Figure 4.12: Loading and unloading station: NO_x/CO_2 ratio as function of exhaust temperature (left graph) and as function of CO_2 (right graph).

5 Monitoring results of road surface cleaners

During the project, three road surface cleaners were monitored for several months. In this chapter, the emission performance of those vehicles is described.

Two of those cleaners are relatively small vehicles, deployed for road cleaning in urban areas. These vehicles are not classified as standard road vehicles but are specifically labelled as 'Motorrijtuig met beperkte snelheid' (motor vehicle with limited speed). The maximum allowed speed for this category is 40 km/h, though these cleaners are restricted to a maximum of 25 km/h. Vehicles in this category may not always be equipped with engines that meet the emission standards for road vehicles (Euro-class), some feature non-road engines (Stage engines). For the monitored vehicles, the engines are Euro-class certified, i.e., Euro VI.

The other cleaner is a larger vehicle, deployed for road cleaning after road construction activities on the highway. This vehicle also falls under the emission legislation for road traffic (Euro-class). All vehicles are be equipped with an SCR.

Table 5.1 provides an overview of the specifications and environmental classification of the measured and monitored vehicles.

Table 5.1: Overview of measured and monitored road surface cleaners: Specifications and environmental classification.

Specifica-tions	Road surface cleaner_highway	Road surface cleaner _city 1	Road surface cleaner _city 2
Make	DAF	Schmidt	Schmidt
Type	CF430 FA	Cleango 500	Cleango 500
ID	DAF_CF430F		
Engine power [kW]	315	120	120
Construction year	2022	2017	2017
Emission class	Euro VI	Euro VI	Euro VI
Fuel	Diesel	Diesel	Diesel
Monitoring method	SEMS	SEMS	SEMS

5.1 Overall monitoring results of the road surface cleaners

In this paragraph an overview of the monitoring emission results of the road surface cleaners are described. Table 5.2 provides data on the operational performance and emissions of the monitored road surface cleaners. The cleaner for the highway was monitored for 352 hours with the diesel engine on. The cleaner _city 1 was monitored for 81 hours and the cleaner_city 2 was monitored for 101 hours. For each measured vehicle, the cumulative emissions and the average emissions per hour for NO_x and CO_2 are shown in the table.

Cumulative emissions deviate significantly from each other since the machines are monitored for different periods, and because the grams per hour differ. Moreover, the engine load differs (as indicated by the CO_2-emissions in kg/u), which increases the fuel consumption and absolute NO_x and CO_2 emissions. The emission levels vary significantly, with the highway cleaner emitting 17 grams of NO_x per hour on average, while the city cleaners showed NO_x-emissions between 41 and 83 grams per hour. The lower NO_x emissions from the highway cleaners compared to the city cleaners seem to be the result of a better SCR-functioning. The same goes for the difference between city cleaner 1 and 2. The NO_x-emission limit for Euro VI over an engine test is 0.46 grams per kWh and is 0.69 g/kWh for an in-service conformity test. A NO_x/CO_2 ratio between 6 and 10 ppm/% would be expected for the highway cleaner, which is in line with the measured average value. Although the same emission limit applies to city cleaners, their emission levels are significantly higher.

The results per vehicle are elaborated in more detail in next paragraph.

Table 5.2: Monitoring results of the road surface cleaners.

		Road surface cleaner_highway	Road surface cleaner _city 1	Road surface cleaner _city 2
Monitored hours	[h]	352	81	101
NO_x	[kg]	5.9	3.4	8.4
CO_2	[kg]	11 648	1 593	2 398
NO_x	[g/h]	17	41	83
NO_x	[g/L_fuel]	1.3	5.6	9.3
NO_x/CO_2	[ppm/%]	5.7	26	33
CO_2	[kg/u]	33	19.6	23.8

5.2 Detailed monitoring results of the highway road surface cleaner

This paragraph provides a detailed analysis of the monitoring results for the highway road surface cleaner. It begins by outlining the operational characteristics, including vehicle speed distribution, engine load, and fuel consumption. Following this, the emission results are presented.

5.2.1 Operational characteristics of the highway surface cleaner

As previously mentioned, the monitored highway surface cleaner is utilized in road construction activities. Figure 5.1 illustrates the speed profile, with speed data recorded only when the diesel engine is running. The figure clearly indicates that the cleaner remains below 5 km/h for the majority of the total monitoring time, this is approximately 60% of the time. About 15% of the time, the speed ranges between 60 and 95 km/h, while the remaining 25% is distributed between 5 and 60 km/h.

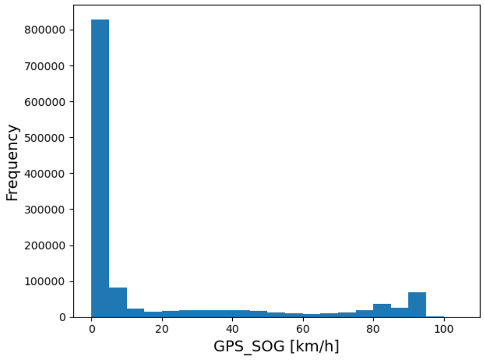


Figure 5.1: Speed distribution of the highway surface cleaner, with diesel engine on.

To calculate the engine load, the engine torque signal and the engine speed from the vehicle were used. For the analysis, the engine load is divided into 10 bins, i.e. power ranges as a percentage of their rated power. Figure 5.2 displays the average speed (blue bars) and time distribution (line) per power bin (left graph) and fuel consumption per power bin (right graph).

The vehicle spent the majority, approximately 50%, of the time operating at low power levels, specifically within the 0-10% range of their rated power. The average speed in this low power bin is less than 5 km/h. This aligns with the speed profile as shown in Figure 5.1.
As the power range increases, the timeshare percentages decrease significantly. However, there is a peak of 20% and 15% between 20 and 40% power. In those power bins the average speed is with 10 and 20 km/h still relatively low. Most likely the vehicle is cleaning on those engine loads. Above the 40% engine load, the average vehicle speeds are above 50 km/h, indicating driving (including accelerations).

The graph on the right highlights the fuel consumption (in litres) across different power ranges, including the cumulative share. The highest fuel share, approximately 55%, is shown in the 20-40% power range. In the lowest power range (0-10%), the share of fuel consumption is 15%.

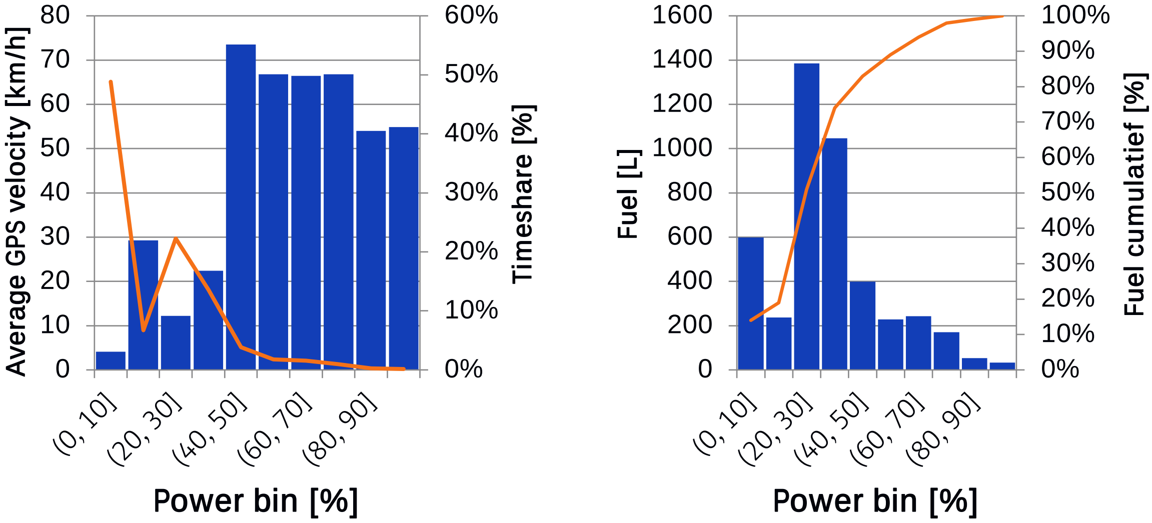


Figure 5.2: Highway road surface cleaner: Average speed (blue bars) and time distribution (line) per power bin (left graph), fuel consumption per power bin (right).

5.2.2 NO_x emission performance of the highway surface cleaner

In Figure 5.3 the NO_x emission levels per engine load bin of the highway cleaner are presented as follows, from left to right: NO_x/CO_2 [ppm/%], NO_x [grams per hour], and NO_x [kg]. The left graph presents the NO_x/CO_2 ratios across various power ranges, expressed as a percentage of their rated power. The NO_x/CO_2 ratio are relatively low over the majority of the power range. The only outliers are observed between 80 and 100% engine load. However, the vehicle is hardly operating at those engine loads. In addition, the ratio is somewhat higher in the lower power bins, which can be expected with machines with an SCR. At the engine load where the vehicle is operating most of the time, between 20 and 40% engine load, the NO_x/CO_2 ratio is below 4 ppm/%, which is very low.

The graph in the middle highlights the relationship between engine load and NO_x emissions in grams per hour. In general, there is an increase in NO_x emissions as the power range increases. In the power range up to 40%, where the vehicle is operated the most, the NO_x levels are 20 grams per hour or lower.

The right graphs highlight the total NO_x emissions (in grams) across different power ranges, including the cumulative share. The vehicle exhibits the highest NO_x emission contribution in the 20-40% power range, with 40% of the NO_x emitted. In the lowest power range (0-10%), 20% of the NO_x is emitted.

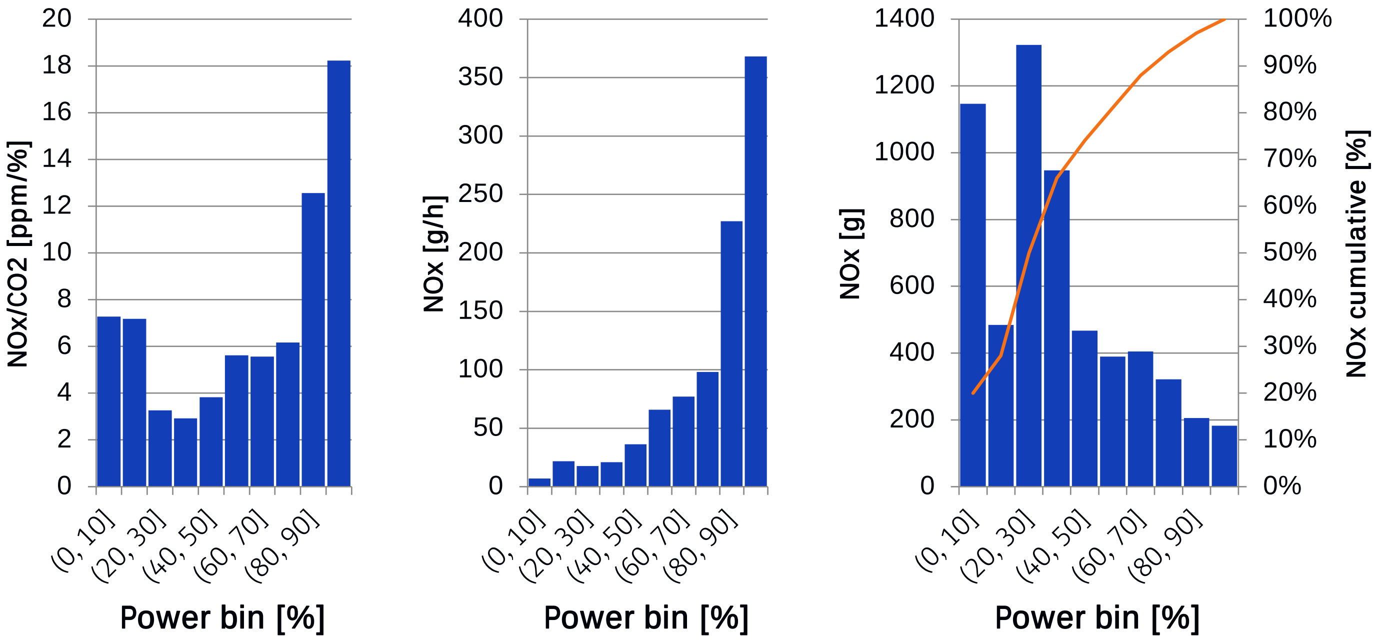


Figure 5.3: NO_x-emission performance per fuel bin of the highway cleaner, from left to right; NO_x/CO_2 [ppm/%], NO_x [grams per hour], NO_x [kg].

To check the functioning of the SCR catalyst, NO_x concentrations are compared to the exhaust temperature. Figure 5.4 shows NO_x concentrations as a function of exhaust temperature, including the share of operation time per exhaust gas temperature bin in the left graph. The right graph shows the cumulative NO_x instead of NO_x concentrations. The left graph shows that the SCR is effectively working from 200 degrees onwards, up to slightly above 300 degrees Celsius. At higher temperatures, there are probably DPF regenerations, which also cause elevated NO_x emissions and reduced SCR efficiency. The left graph displays that the vehicle operates most of time in the effective working area of the SCR. However, also a substantial time below 200 degrees Celsius exhaust temperature occurs. The right graph shows that approximately 50% of the NO_x emissions occur at exhaust temperatures below 200 degrees Celsius. Moreover, 25% of NO_x emissions occur at exhaust temperatures above 300 degrees Celsius. Hence, approximately 75% of the NO_x is emitted outside the effective SCR working area.

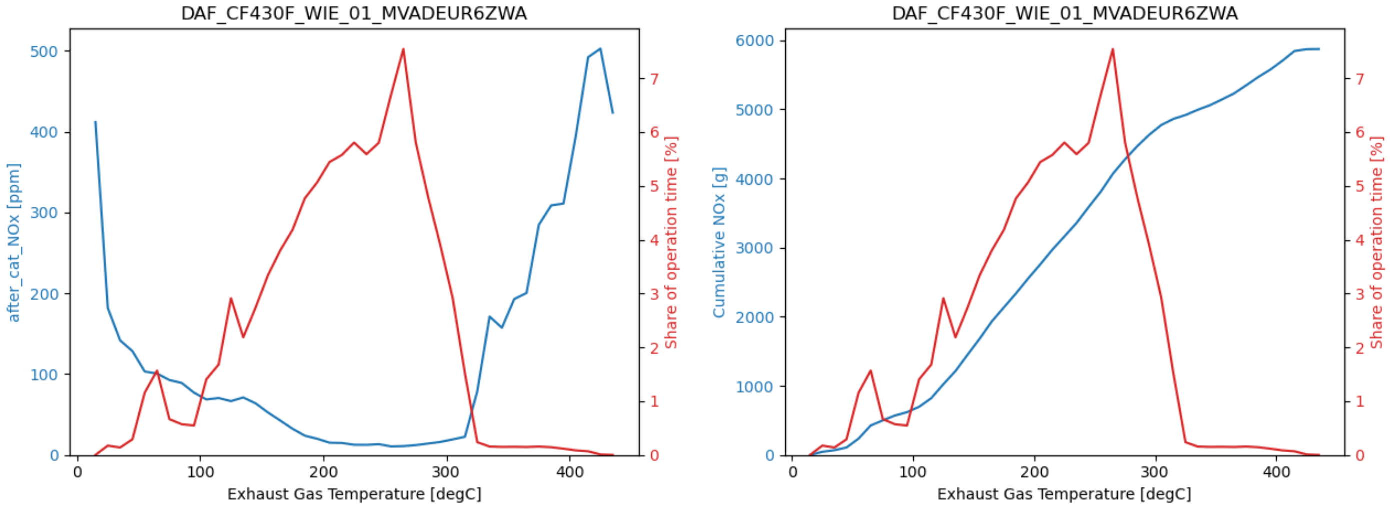


Figure 5.4: Left graph: NO_x concentrations (blue line) as function of exhaust temperature, including the share of operation time (red line) per exhaust gas temperature bin. Right graph: Cumulative NO_x in grams (blue line) as function of exhaust temperature, including the share of operation time (red line) per exhaust gas temperature bin.

5.2.2.1 Day to day variations at the highway road cleaner

Figure 5.5 illustrates the operational characteristics and emission performance for each monitored calendar day, including only data when the engine is on. Days with less than one hour of data are excluded. The graph reveals significant day-to-day variations in operational characteristics. On some days, the vehicle is used for just over an hour, while on others, it operates for nearly 20 hours. Similarly, the distance covered ranges from as little as 12 km to as much as 554 km.

The average fuel rate also varies widely, from 9 litres per hour to 22 litres per hour. As the maximum observed fuel rate (for a short period) is 73 litres per hour, the daily averages are relatively low, indicating low engine loads, around 12 to 30% engine load.

The average NO_x/CO_2 ratio are most of the days between 3 and 5 ppm/%. Nevertheless, there are some days with elevated values, up to 19 ppm/%. The absolute NO_x emissions per day vary significantly, ranging from 24 grams to 859 grams.

Figure 5.5: Operational characteristics and emission performance per monitored calendar day of the highway road cleaner.

5.3 Detailed monitoring results of the city road surface cleaners

This paragraph provides a detailed analysis of the monitoring results for the city road surface cleaners. It begins by outlining the operational characteristics, including vehicle speed distribution, engine load, and fuel consumption. Following this, the emission results are presented.

5.3.1 Operational characteristics of the city road cleaners

The monitored city road cleaners are utilized for regular cleaning of the roads in urban areas. Figure 5.6 illustrates the speed profile, with speed data recorded only when the diesel engine is running. The figure clearly indicates that the cleaner remains below 10 km/h for the majority of the total monitoring time, this is approximately 75% of the time. About 12% of the time, the speed ranges between 10 and 20 km/h, while the remaining 13% is above 20 km/h. The average speed over the total monitoring period is 7 km/h. The speed profile of the other city cleaner is very similar, with a comparable average speed.

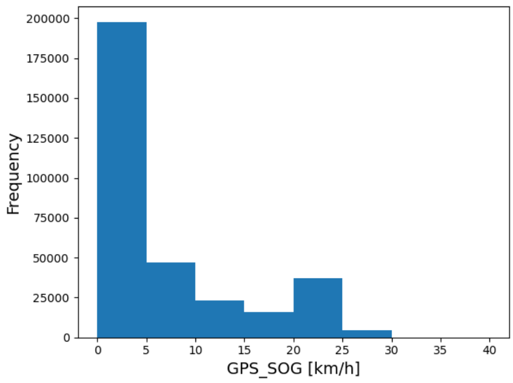


Figure 5.6: Speed distribution of the city cleaner_2, with diesel engine on. Cleaner 1 showed a similar trend.

To calculate the engine load, the engine torque signal and the engine speed from the vehicle were used. For the analysis, the engine load is divided into 10 bins, i.e. power ranges as a percentage of their rated power. Figure 5.7 displays the average speed (blue bars) and time distribution (line) per power bin (left graph) and fuel consumption per power bin (right graph). The upper graphs show city cleaner_1, and the lower graphs show city cleaner_2.

Both vehicles operate approximately 25% of the time at low power levels, specifically within the 0-10% range of their rated power. The average speed in this low power bin is less than 3 km/h, which indicate a large share of standing still. This aligns with the speed profile as shown in Figure 5.6. The timeshare percentages show a second peak between 30% and 50% power for both vehicles. In those power bins the average speeds are between 4 and 6 km/h.

Considering the higher engine power, this indicates active cleaning. Between 10% and 30% engine load, the average vehicle speeds are highest, indicating driving (including accelerations). A closer analysis of the data reveals that less power is required at higher speed ranges. The highest power demand occurs at speeds below 10 km/h.

The graphs on the right highlights the fuel consumption (in litres) across different power ranges, including the cumulative share. The highest fuel share, more than 60%, is shown in the 30-50% power range. In the lowest power range (0-10%), the share of fuel consumption is 6%.

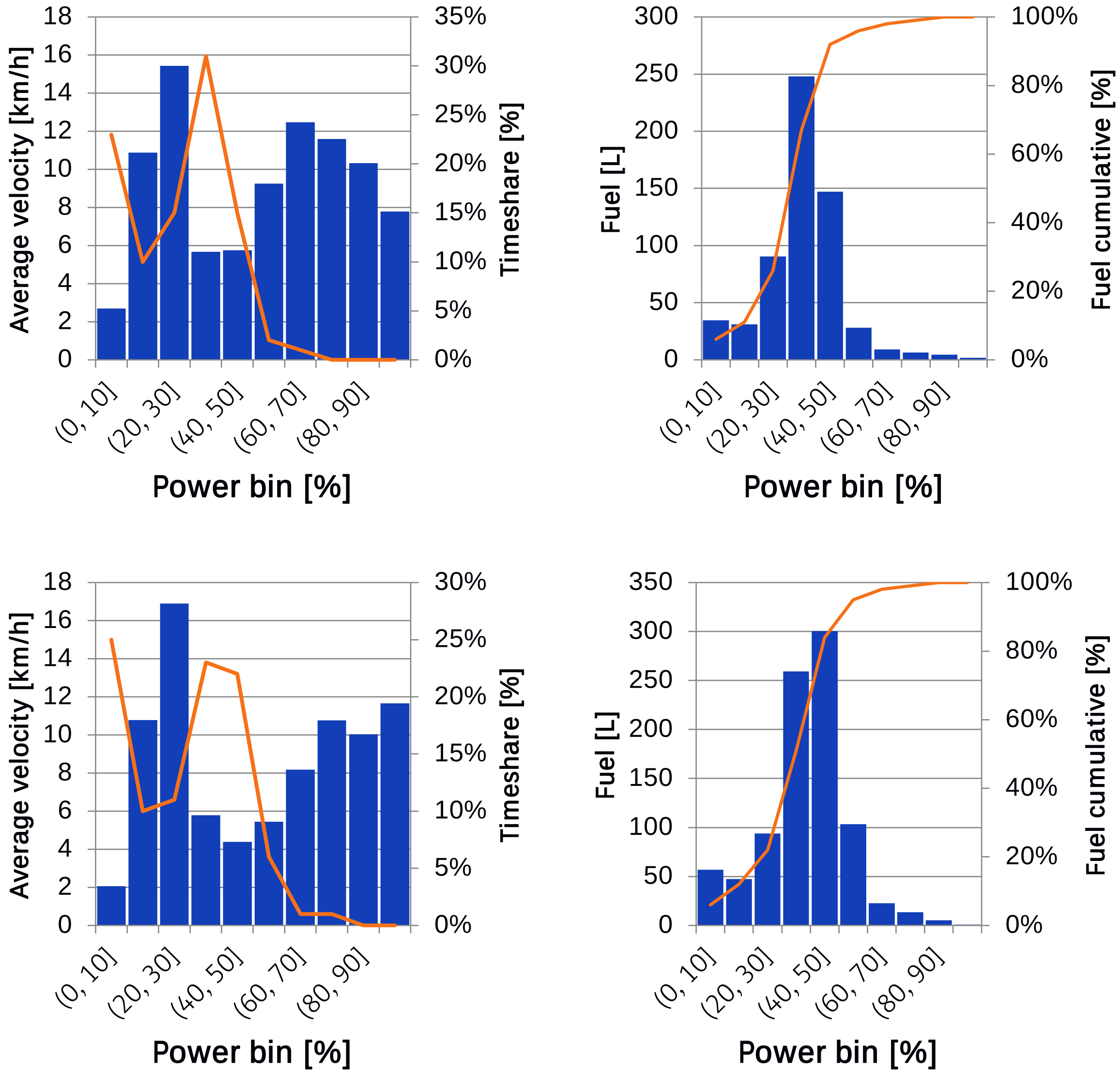


Figure 5.7: City road surface cleaners (cleaner 1: upper graphs, cleaner 2: lower graphs): Average speed (blue bars) and time distribution (line) per power bin (left graph), fuel consumption per power bin (right).

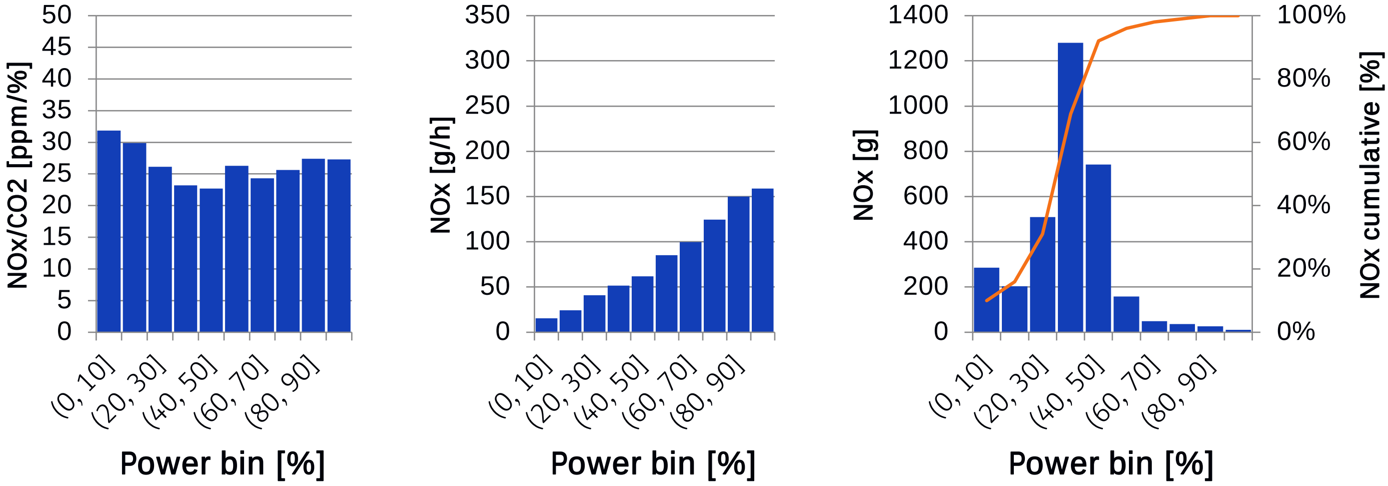
5.3.2 NO_x emission performance of the city surface cleaners

In Figure 5.8 the NO_x emission performance per engine load bin of the city cleaners are presented as follows, from left to right: NO_x/CO_2 [ppm/%], NO_x [grams per hour], and NO_x [kg]. The upper graphs show cleaner 1 while the lower graphs show cleaner 2.

The left graphs present the NO_x/CO_2 ratios across various power ranges, expressed as a percentage of their rated power. In Table 5.2, it is shown that cleaner 1 has a somewhat lower average NO_x/CO_2 ratio compared to cleaner 2, with values of 26 ppm/% and 33 ppm/% respectively. The graphs in Figure 5.8 illustrate that the higher values for cleaner 2 predominantly occur in the medium and higher power range. With a proper functioning SCR-catalyst, lower values are to be expected at the medium to high power range. This indicates the SCR-catalyst of cleaner 2 is not functioning properly. Although Cleaner 1 outperforms Cleaner 2, its emission levels are still significantly higher than those of the highway cleaner, which has an average of 5.7 ppm/%. Notably, both vehicles are equipped with Euro VI engines.

The graphs in the middle highlights the relationship between engine load and NO_x emissions in grams per hour. In general, there is an increase in NO_x emissions as the power range increases. In the power range between 30 and 50%, where the vehicle is operated the most, the NO_x levels of cleaner 1 are 50 to 60 grams per hour respectively. This is significantly higher than the highway cleaner, which emitted 20 to 25 grams of NO_x per hour in the same power range, despite having a larger engine. Again, cleaner 2's NO_x-emissions are higher than those of Cleaner 1, ranging from 95 to 150 grams per hour in the power range between 30 and 50%.

The graphs on the right highlight total NO_x-emissions (in grams) across different power ranges, along with their cumulative share. Cleaner 1 contributes the highest proportion of NO_x-emissions in the 30-50% power range, accounting for 60% of the total NO_x. In the lowest power range (0-10%), it emits 10% of the total NO_x. Cleaner 2 follows a similar trend, but with a notable difference: a larger share of its NO_x-emissions occurs between 40-50% engine load, rather than in the 30-40% range, as seen with Cleaner 1.



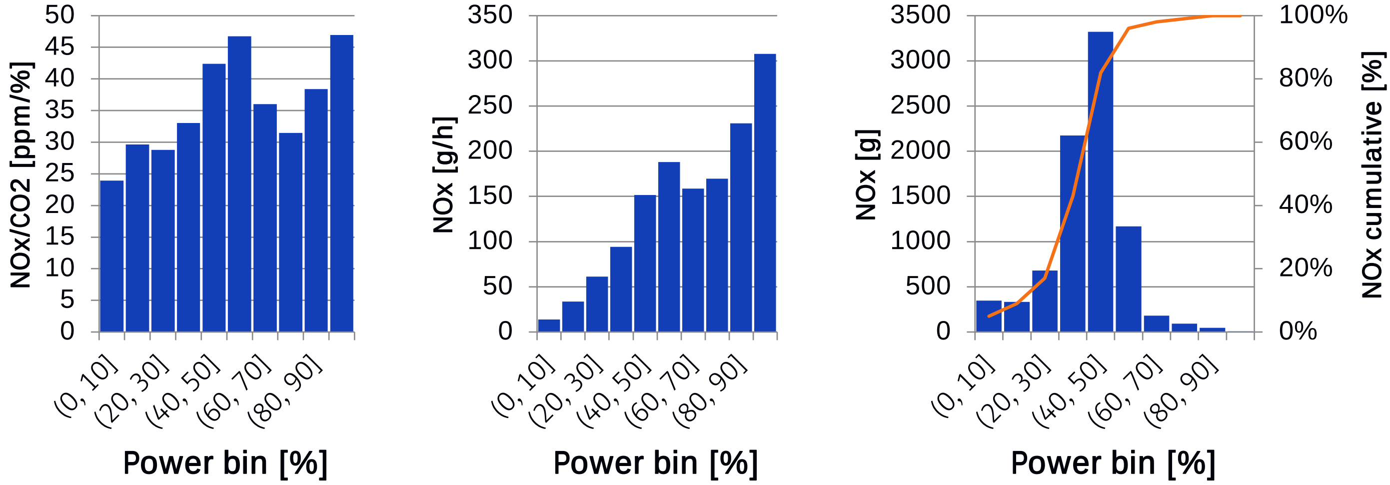


Figure 5.8: NO_x-emission performance per fuel bin of the city cleaners (cleaner 1: upper graphs, cleaner 2: lower graphs), from left to right; NO_x/CO_2 [ppm/%], NO_x [grams per hour], NO_x [kg].

To check the functioning of the SCR catalyst, NO_x concentrations are compared to the exhaust temperature. Figure 5.9 shows NO_x concentrations as a function of exhaust temperature, including the share of operation time per exhaust gas temperature bin. The left graph shows cleaner 1 and the right graph cleaner 2.

Both graphs show that the exhaust temperatures during operating conditions are high. However, in both graphs there is no evidence of SCR activity, as emission levels do not decrease above 200 degrees Celsius. For cleaner 2 the exhaust temperatures are remarkably high. Moreover, the NO_x-concentrations rise at these high temperatures. The cause of the elevated emissions and high exhaust temperatures has not yet been investigated thoroughly. However, the owner mentioned that underlying defects were addressed after the measurement period. It is currently being attempted to conduct further research on these vehicles in 2025.

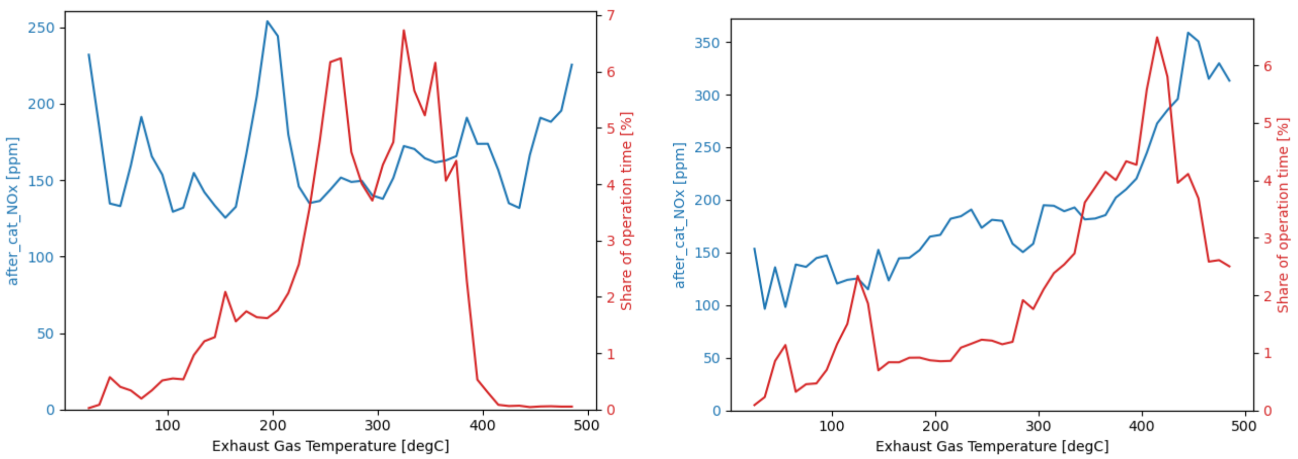


Figure 5.9: NO_x concentrations (blue line) as function of exhaust temperature, including the share of operation time (red line) per exhaust gas temperature bin. Left graph shows cleaner 1, right graph shows cleaner 2.

5.3.2.1 Day to day variations at the city road cleaners

Figure 5.10 and Figure 5.11 illustrate the operational characteristics and emission performance for each monitored calendar day for cleaner 1 and 2, including only data when the engine is on. Not all monitoring data is included in these graphs due to missing GPS-data. Moreover, days with less than one hour of data are excluded.

The graph shows significant day-to-day variations in operational characteristics. On some days, the vehicle is used for just over an hour, while on others, it operates for nearly 11 hours. The same trend is shown for the distance covered per day.

The average fuel rate is relatively constant for both vehicles, with cleaner 2 having a slightly higher consumption. The average NO_x/CO_2 ratios are most of the days between 24 and 32 ppm/% for cleaner 1, and between 28 and 36 ppm/% for cleaner 2. Nevertheless, there are some days with elevated values. The absolute NO_x emissions per day vary significantly, ranging from 30 grams to 400 grams for cleaner 1, and from 65 to 1045 for cleaner 2.

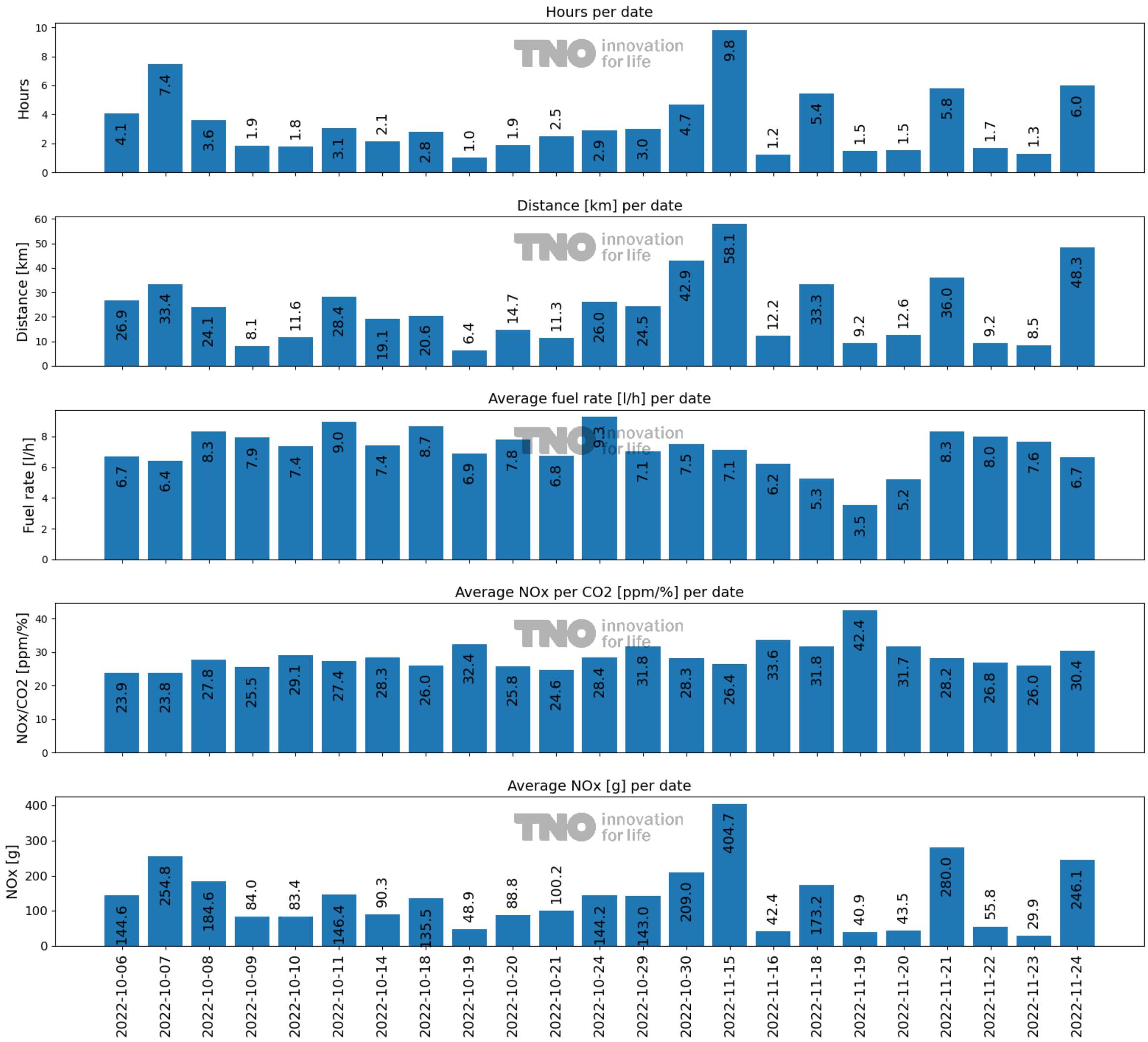


Figure 5.10: Operational characteristics and emission performance per monitored calendar day of the city roadcleaner_1.

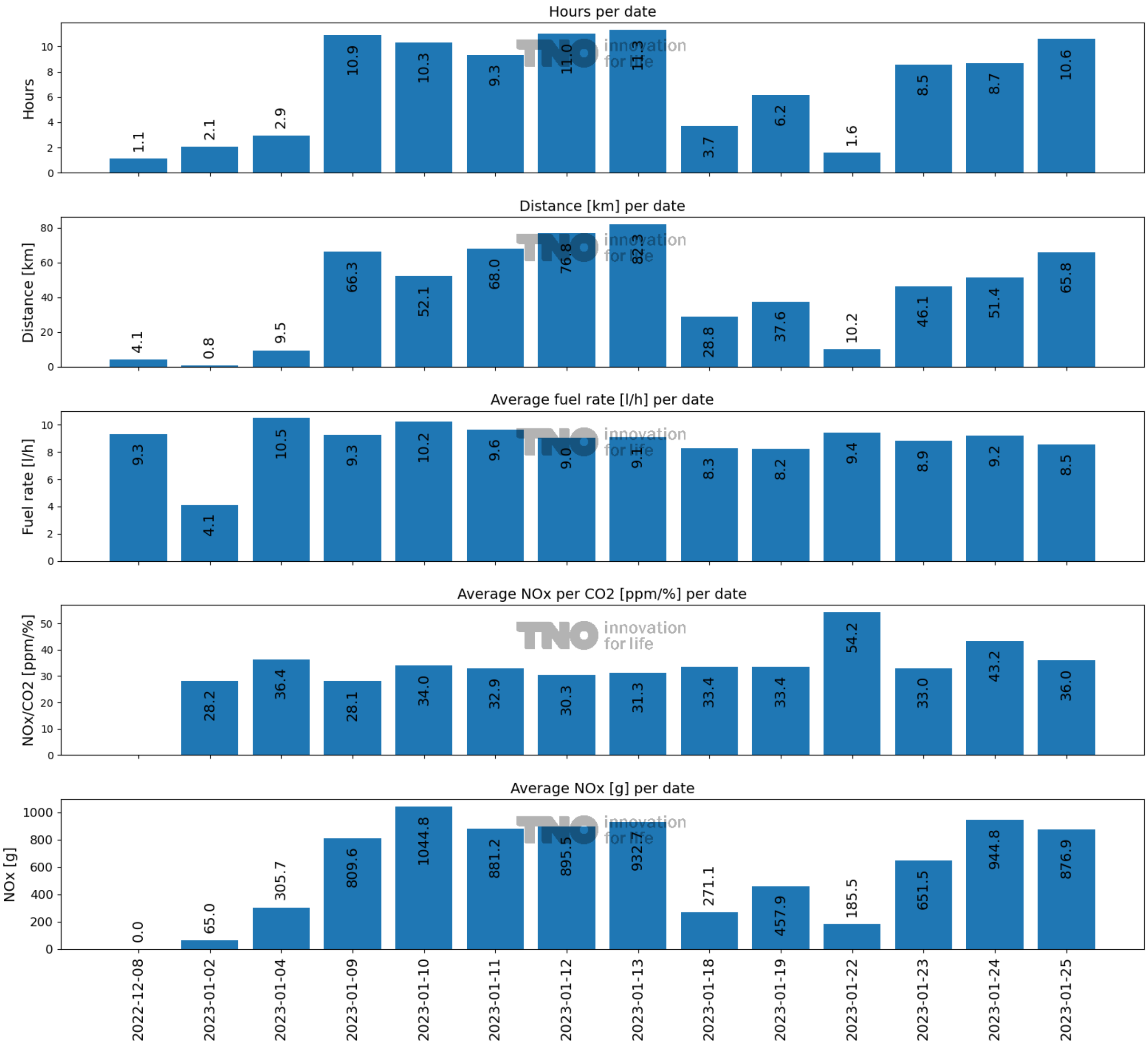


Figure 5.11: Operational characteristics and emission performance per monitored calendar day of the city road cleaner_2.

6 Discussion

Real-world NO_x-emission performance of NRMM using SCR

The study evaluates the effectiveness of SCR systems in reducing NO_x-emissions from various machines. SCR systems perform optimally at moderate to high engine loads but are less effective at low engine loads, resulting in increased emissions during idling and low-load operations.

Temperature sensors installed in the exhaust systems provided context for emission data, although temperature measurements varied due to sensor placement. Optimal SCR performance was observed around 250°C, where NO_x levels dropped below 10 ppm. Machines operating frequently within this temperature range exhibited low average NO_x emissions, while those operating outside this range had higher average emissions.

The study estimated the NO_x-emission contributions during periods when SCR systems were active and inactive. SCR systems were active most of the time for most of the machines. However, during the 7-29% of the time when they were inactive, emissions were significantly higher. This period accounted for 66 to 92% of total NO_x emissions. Machines with high inactive SCR time shares showed the highest average NO_x emissions.

Implications for policy and regulation

The results underscore the need for emissions regulations that better reflect the real-world operating conditions of NRMM, especially for machinery frequently used at low engine loads. Emission standards should more effectively account for low-load conditions, where SCR technology is less efficient. These conditions should also be included in In-Service Monitoring. Additionally, given the considerably less stringent emission limits for engines below 56 and 560 kW, introducing stricter NO_x emission limits for these categories would be beneficial. Moreover, by improving inspection and surveillance on emission performance and SCR-functioning, high emitters can be detected.

Options for emission monitoring

As mentioned in the introduction, the primary goal of the program was to gain experience with options for emission monitoring of mobile machines during real-world usage. Publications on this topic were released in 2023 and 2024[11] [12]. Although this report primarily focuses on the emission results, some considerations regarding the monitoring options are provided below.

Using a MAF sensor as an alternative for CANbus-connection

The primary reason for connecting to the CANbus is to register signals that allow the measured concentrations (of NO_x and CO_2 in this case) to be translated into absolute emissions, or emissions in grams. To make this translation into absolute emissions, the exhaust gas flow must be determined. In official emission measurements, the exhaust gas flow is directly measured.

[11] TNO 2024 R11077 - Opties voor monitoring van de NOx-emissies van mobiele werktuigen
[12] TNO 2023 R10553 - Pilot project Emissie Monitoring en Periodieke Keuring (EMPK) van bouwmachines

However, the equipment used for this is not suitable for long-term monitoring. Therefore, CANbus signals are used in combination with the measured oxygen concentration in the exhaust gas.
This includes signals such as fuel consumption, intake air flow, and engine speed. Additionally, (work-specific) mass emissions (g/kWh) can be calculated if information about engine speed and torque is available via the CANbus.

A problem with this methodology is that there is no standardization of the signals available on a CANbus; sometimes the required signals are not available. Furthermore, the quality and reliability of these signals are not always known. This leads to extra installation time and additional time in data processing, as custom solutions are needed for each machine that must be assessed. An alternative is desirable for determining absolute emission levels.

The most accurate alternative to become independent of CANbus signals is expected to be measuring the airflow through the intake. This is possible with a so-called Mass Air Flow (MAF) sensor. This airflow, combined with the measured oxygen percentage in the exhaust gas and the theoretical stoichiometric air/fuel ratio, can provide an accurate estimate of the exhaust gas flow. Further research is being conducted in an ongoing study. Some challenges include the installation of the sensor and the availability of a sensor for large diameter air intakes (which are often found in mobile machinery).

Emission monitoring with an external NOx-sensor, without using CANbus data

From the data provided by an external NO_x sensor (installed by TNO in the exhaust in this study), the NO_x/CO_2 ratio can be calculated. This allows useful conclusions to be drawn about the emission levels of a machine. The calculation method is very simple, as it only involves dividing the NO_x concentrations by the CO_2 concentrations, with no CANbus signals required. The NO_x/CO_2 ratio clearly shows the distinction in emission levels, the functioning of the SCR catalyst, and emissions under varying engine loads. Due to its simplicity and independence from CANbus signals, this ratio is an interesting option for emission monitoring.

Assessing SCR-catalyst functioning

The operation of an SCR catalyst can be effectively assessed through emission monitoring using only a NO_x sensor. Machines with a functioning SCR catalyst can be easily identified based on the NO_x concentrations from the NO_x sensor data. In the case of a non-functioning SCR catalyst, the NO_x concentrations often remain above 200 ppm, while a well-functioning SCR catalyst shows concentrations below 10 ppm, a factor of 20 difference.

7 Conclusions

On behalf of the Dutch Ministry of Infrastructure and Water Management, TNO conducted emission measurements to gain more insight into the real-world NO_x emissions of various mobile machines and vehicles. In terms of emission regulations, the machines largely fall under the European Non-Road Mobile Machinery (NRMM) legislation, whereas the measured vehicles fall under the Euro standards. In this study, a total of 18 diesel-powered machines, engines, and vehicles were measured and evaluated, covering construction equipment, rail machinery, and road surface cleaners. The overarching goal of the program was to gain experience with options for emission monitoring of mobile machines during real-world usage. Publications on this topic were released in 2023 and 2024[13] [14]. This report primarily focuses on the emission results.

The variation in measured NO_x emissions between machine categories is significant. This variation mainly depends on the engine power class, the emission class, the presence of an Selective Catalytic Reduction (SCR) system, the functioning of the SCR, and machine usage. The measurement data show that machines with engines without an SCR system, older engines, and those with simpler emission reduction systems have considerably higher emissions than newer machines equipped with SCR.

In general, the measurements indicate that the effectiveness of SCR systems for NO_x reduction strongly depends on machine operation and the corresponding engine load. The SCR functions optimally at moderate to high engine loads, where the exhaust gas temperature is sufficiently high. At low engine loads, such as idling, its effectiveness decreases significantly, leading to increased NO_x-emissions, contributing substantially to average NO_x-emissions. For most of the measured machines, the SCR system operated effectively most of the time. However, during 7-30% inactivity, the NO_x-emissions increased significantly, contributing to 66-94% of the total NO_x-emissions.

Most of the monitored machines had average NO_x emission levels in line with expected values based on the regulatory emission limit. However, some monitored machines/vehicles (diesel passenger train and two road surface cleaners) showed NO_x emissions exceeding the regulatory emission limit. This exceedance was likely the result of a malfunctioning of the SCR system (despite sufficient engine load). There is currently no effective monitoring of the real-world NO_x emissions in place of such machines during regular operation.

The poor low load performance of SCR and the poor overall performance measured on some of the machines cause a high variability of NO_x-emissions between machines in the field.

The measurements demonstrated the lack of control of NO_x emissions at low load operation by the EU type approval tests for NRMM. It is therefore recommended to improve the tests by including low load usage in the test procedure. Moreover, it is recommended to implement stricter NO_x emission limits for machines with an engine power below 56 kW and above 560 kW.

[13] TNO 2024 R11077 - Opties voor monitoring van de NOx-emissies van mobiele werktuigen
[14] TNO 2023 R10553 - Pilot project Emissie Monitoring en Periodieke Keuring (EMPK) van bouwmachines

Also practices should be encouraged that reduce prolonged idling and low load usage of NRMM. Finally, measures can be taken to improve SCR system monitoring during real-world operation. Below the key findings are described in more detail.

Effectiveness of Selective Catalytic Reduction (SCR) systems

One of the key finding is that most of the machines with SCR systems effectively reduce NO_x emissions when they are operating at moderate to high engine loads and exhaust temperatures. For example, all monitored Stage V pavers, equipped with SCR, have emission levels below 20 grams per hour. In contrast, a Stage V roller without SCR and with an engine power which is three times lower than that of the pavers, exhibited NO_x emissions exceeding 40 grams per hour. Data showed that machinery with SCR, had low average NO_x emissions when operating consistently above 20% engine load, where SCR performance was working properly.

Another key finding is that NO_x emissions increase substantially at low engine loads and temperatures, where SCR systems cannot reach their effective working temperature. In the monitoring data this was observed at the asphalt milling machines, where extended idling led to high emissions. One of the asphalt milling machines is equipped with two Stage V engines. This machine demonstrated varying emissions levels between the two engines. The engine operating under a high load emitted an average of 1.3 grams of NO_x per litre of fuel, while the other engine, running at lower loads, emitted 2.8 grams of NO_x per litre of fuel. This variability underscores the limitations of current SCR technologies for machinery frequently used in low-load applications.

Two Stage IIIB engines in diesel-powered passenger trains are also equipped with SCR. However, their average NO_x-emissions were during the monitoring period higher than the regulatory limit value. The measurements confirm that the engines operate within the correct SCR-temperature range, yet NO_x concentrations remain above 300 ppm, indicating poor SCR performance. The same trend was observed for two smaller road surfacecleaning vehicles with an Euro VI engine. The monitoring data suggests that the SCR system on these monitored road cleaners did not function effectively, despite of having sufficient engine load. In contrast, a large highway road surface cleaner with an Euro VI engine demonstrated low NO_x-emissions.

High variability in emissions across machinery types

NO_x emissions varied widely between different NRMM types. For example, the monitored dieselloc, with on older engine without SCR, showed average NO_x emissions of 1450 grams per hour. In contrast the best performing paver showed average NO_x emissions of 11 grams of NO_x per hour.

Another example involves two asphalt milling machines: one with a single large Stage V engine and the other with two smaller Stage V engines. The machine with the single engine has an engine power rating above 560 kW, where emission limits are less stringent and SCR is not required. In contrast, the other machine's two smaller engines, each with a power rating below 560 kW, are equipped with SCR due to a more stringent emission limit. Both machines were monitored for approximately the same number of operating hours. The NO_x emissions for the machine with the single large engine (no SCR) totaled 134 kg over the entire period, while the machine with two smaller engines (with SCT) emitted only 16 kg—a difference by a factor of eight. CO_2 emissions were similar, indicating comparable engine loads.

Emission monitoring for insights in real-world emissions

The study used TNO's Smart Emissions Measurement System (SEMS) for long-term and short-term monitoring, capturing emissions data directly from the machinery. This real-world monitoring approach provided critical insights that lab-based tests often miss, such as the high NO_x emissions observed during idling or low load conditions.

While the CANbus connection used in TNO's SEMS system provided valuable data, reliance on CANbus signals is challenging due to the lack of standardisation and inconsistent data availability across machinery. The study suggests that equipping a machine with a Mass Air Flow (MAF) measuring sensor could be a promising alternative to the CAN-bus connection. The MAF enables a more direct determination of exhaust flow without needing CANbus data, simplifying monitoring and enhancing data accuracy. However, further research is necessary to test MAF sensors' feasibility in real-world applications, particularly for high-power machinery with larger intake diameters.

Another simplified alternative is to use the data provided by the (external) NO_x-sensor only. With these data, the NO_x/CO_2 ratio can be calculated. This allows useful conclusions to be drawn about the emission levels of a machine. The calculation method is very simple, as it only involves dividing the measured NO_x concentrations by the CO_2 concentrations, for which no CANbus signals are required. The NO_x/CO_2 ratio clearly shows the distinction in emission levels, the functioning of the SCR catalyst and emissions under varying engine loads. Due to its simplicity and independence from CANbus signals, this ratio is an interesting option for simplified emission monitoring. This is currently being investigated in more detail.

Implications for policy and regulation

The results underscores the need for European emission regulation that better reflects the real-world operating conditions of NRMM, especially for machinery which are frequently used at low loads or in urban settings.

Key policy implications are:

- Improving European emissions tests for non road engines accounting for low-load conditions where SCR technology is presently less effective;
- Include low-load conditions in In-Service Monitoring for NRMM;
- Introduce more stringent NO_x-emission limits for NRMM categories with an engine power below 56 kW and above 560 kW;
- Encouraging practices that reduce prolonged idling and low-load operation as this could improve SCR performance and lower emissions;
- Investigating possibilities for inspection on emission performance and SCR-functioning in real-world circumstances

Signature

TNO ⟩ Mobility & Built Environment ⟩ The Hague, 7 March 2025

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