Topsector Logistiek

Use of construction machines and the associated NO_X and CO_2 emissions

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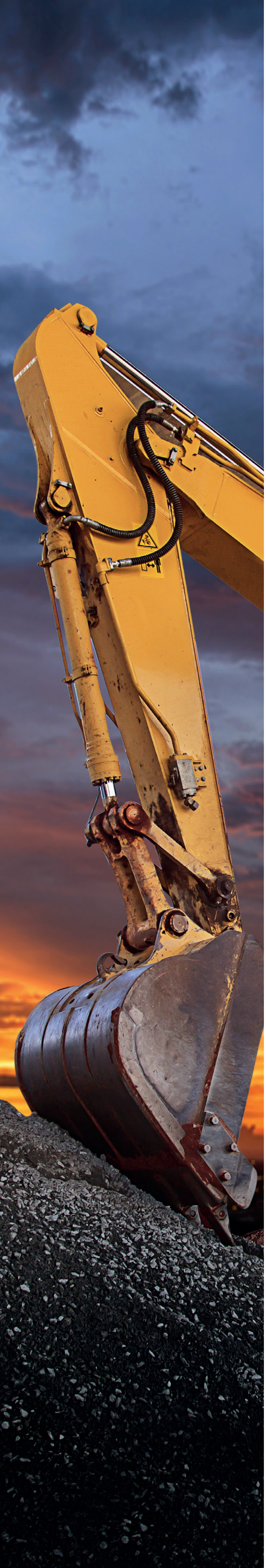

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Sponsor
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Emissions from construction machines

Project number
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Abstract

Background

Non-Road Mobile Machinery (NRMM) is the collective term used to refer to all machines with a combustion engine that do not come under the categories of road vehicles, sea-going vessels or aircraft. This group also includes diesel trains, inland vessels, generators and construction machines. Mobile machines (NRMM excluding ships, trains and aircraft) are responsible for a substantial proportion of the NO_2 air-quality problems. Estimates based on emission standards in the official laboratory test, as laid down in emissions legislation, and a generic distribution across the Netherlands indicate that around 10% of the NO_2 concentration in problem areas can be attributed to mobile machines.

At present little is known about the emissions generated by and the use of construction machines in practice. It is therefore not known whether the emissions resulting from the normal operation of such machines in practice are adequately covered by the legislation requirements for these machines. There are no legal limits for real-world emissions of these machines. From the new Stage V legislation real-world emissions have to be monitored.

Approach

This project, funded by the Top Sector Logistics and the Netherlands Pollutant Release and Transfer Register, monitored the use and emissions of four common, modern construction machines during normal operation. Normal operation covers a wide range of usage and operator behaviour. This monitoring was performed using the Smart Emission Measurement System (SEMS), a sensor-based system developed by TNO. When the machines were selected consideration was given to the applicable legislation, the age of the machines and the number of construction machines of that type in the Netherlands. The final selection consisted of two excavators, a loading shovel and a tractor. Two construction machines fall under the Stage III B legislation (introduced from 2011), while the other two are subject to the newer Stage IV legislation (introduced from 2014). Currently the first machines that have to satisfy the Stage-V legislation are entering the market.

Results

Table 1 provides an overview of the results for the four machines monitored. The last two lines of Table 1 show the average NO_x emissions in practice in g/kWh and the limit for the type-approval test in a laboratory. As you can see, the NO_x emissions in practice are around 20% to 350% higher than the limit for the laboratory test. This is not a legal requirement for these engines, as they have to satisfy only standardized laboratory emissions tests.

These higher emissions in practice are linked in part to the way the machines are used. They spend between 18% and 57% of their time idling. This is a much higher idling percentage than that taken into account during the laboratory type-approval test. During idling (little to no engine load) NO_x emissions are relatively high, while no or very little work is being performed. Consequently, fuel consumption is lower, but NO_x emissions per second are in the same range as, or even higher than, those generated at a higher load.

The difference between the emission limits and the emissions in practice could be due to the fact that the type-approval test for NRMM mainly focuses on emissions at a constant high load, while changing dynamics and a low load during practical operation are not well covered by this test. The differences between the limit for laboratory tests and the emissions in practice have not yet been regulated in law for NRMM. This is in contrast with road vehicles, for which such differences have been regulated since 2017 in RDE (Real Driving Emissions) legislation:
the emissions generated by these vehicles in practice may be up to 110% higher than in the laboratory test. With effect from 2019 the discrepancy may not exceed 50%.

Table 1:
Overview of the use and emissions of the four machines monitored.

Machine Type	1 Excavator	2 Loading shovel	3 Excavator	4 Tractor
Stage with which engine complies	IV	III B	III B	IV
Idling time [min/hr]	21	34	11	15
Average CO_2 emissions [kg/hr]	42	18	53	30
Average NO_x emissions [g/hr]	34	141	149	70
Average NO_x emissions when idling [g/hr]	49	106	91	64
Average NO_x emissions [g/kWh]	0.5	4.9	2.8	1.8
NO_x limit (lab) [g/kWh]	0.4	3.3	2.0	0.4

To date, a higher average load and possibly a shorter operating time have been assumed when calculating the emissions of mobile machines for the national Pollutant Release and Transfer Register. Furthermore, the emissions are based on the limits rather than the emissions in practice. The conversion to these g/kWh emission factors is flawed, as the substantial proportion of idling observed in practice is inconsistent with the assumed power outputs and kWh figures.

Recommendations

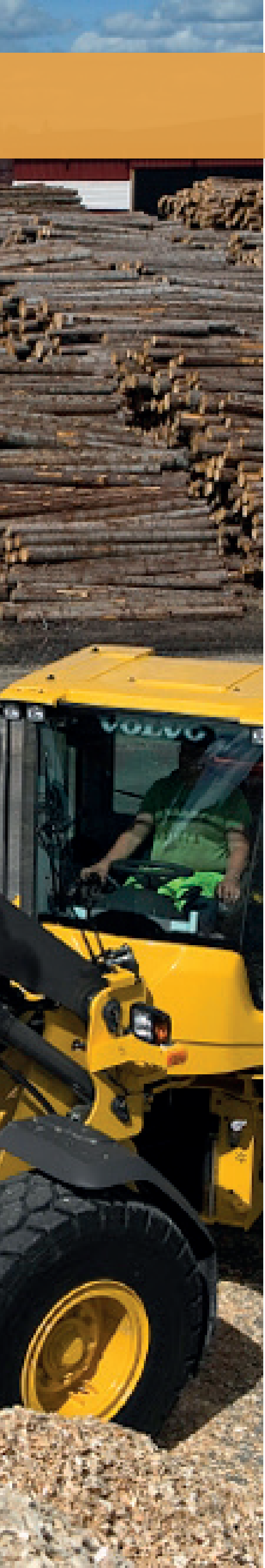
On the basis of these measurements and experiences in the area of road transport in general, the current emission factors for NO_x, based on the legislation and short tests, appear to be too low. Higher emission values have been observed for every construction machine, train and ship measured to date, in particular when the engine load is low. We recommend provisionally adjusting the emission factors upwards. Greater confidence in the level of the increase required will result in particular from an improved insight into how construction machines are used, but also the associated emissions.

ABSTRACT

It is also important to develop a similar In-Service Conformity (ISC) procedure for NRMM and to add this to the type-approval test, as is customary for road transport. The current In-Service Monitoring (ISM) procedure would provide a logical basis for this, although the existing measurements reveal that the ISM procedure is in need of some improvement. In particular the coverage of low engine load operation. The measurements performed and this report will also be brought to the attention of the European Commission with a view to improving emissions legislation applicable to NRMM.

During the test period the four machines measured were idling for between 18% and 57% of the time. The fuel consumption and CO_2 emissions during idling account for a relevant share of the total. Furthermore, idling is responsible for up to half of the total NO_x-emissions.

In the case of the more modern machines measured (Stage IV), the share during idling was greater than had previously been the case (Stage III B). Additional attention should therefore be paid to ensuring that machines are used efficiently (with short waiting times and a uniformly high engine load) and that instructions are given regarding switching off the machine.



Contents

1 Introduction

Background

The purpose of this study was to determine the use and emissions of four construction machines falling within the category of Non-Road Mobile Machinery (NRMM). Table 2 provides an overview of the fleet of mobile machines in the Netherlands and the estimated quantity of CO_2 that these machines emit on average each year. Based on current insights, mobile machines are responsible for 9% of the CO_2 emissions generated by mobile sources in the Netherlands . The total number of construction machines in the Netherlands[1] is comparable with the number of trucks and truck and semi-trailer combinations. One difference between these groups is that construction machines are generally used for longer periods in a single location, resulting in local emissions. Furthermore, many of these machines operate for long hours and have relatively large engines. Taken together, these factors can lead to a significant deterioration in air quality. In particular, the use of construction machines on major urban construction projects that extend over long periods is a cause for concern.

Table 2:
Fleet of mobile machines in the Netherlands and estimated average fuel consumption, based on an earlier study.

Type of machine	Number of machines	Average CO_2 per year [tonnes/unit]
Agricultural tractors	80,000	10
Excavators	15,000	30
Loading shovels	8,000	50
Generators, TSG (trade, services & government)	1,000	60
Generators, industry	400	160
Generators, construction	1,600	30
Dumpers	500	60
Bulldozers	200	80
Dewatering pumps	700	20
Steamrollers	1,000	10
Rough-terrain forklifts	500	25
Asphalt finishers	200	40
Vibratory plates/compactors	7,600	1
Aerial work platforms	1,000	6
Asphalt milling machines	20	110
Backhoe loaders	70	25

1 Methods for calculating the emissions of transport in the Netherlands, Klein et al., 2018

2 TNO-034-UT-2009-01782_RPT-ML and 2014-TM-NOT-0100007452

Air-quality model and local emissions

According to Dutch air-quality monitoring, mobile machines make a substantial contribution to NO_2 concentrations in problem urban areas.[3] Approximately 10% of the NO_2 can be attributed to construction machines, tractors, pumps and generators powered by diesel. In many of these problem areas it is impossible to discern the contribution from construction machines: in the modelling the contribution of these machines is distributed over the background concentration for the Netherlands as a whole. At construction sites on which these machines actually operate the contribution to air-quality problems is expected to be much higher. As this air-quality model does not reflect the local situation, it is possible that residents of districts adjacent to construction projects are exposed, over a number of years, to higher concentrations than those calculated.

Legislation and practice

The presumed emissions of these machines are based on the statutory requirements applicable to such machines. When these requirements were drawn up assumptions were made about the use of mobile machines in practice. Based on research conducted in relation to ships[4] and trains[5] it is considered possible that construction machines are used in a different way than is currently assumed for the purposes of the type-approval test and consequently also generate higher emissions. This might relate to the percentage of the time that the machines spend idling or operating with a low load; such an engine load is only taken into account to a limited extent in the statutory tests.

For several years now new emission limits have been in force in the legislation applicable to mobile machines: the Stage IV standards. This legislation has lowered the emission limits by comparison with Stage III, which should bring about a similar effect in practice. An additional positive impact is attributed to the future legislation, Stage V, in the emission estimates. To date, hardly any practical data has been collected to identify the problems that need to be addressed through legislation, which makes it difficult to determine whether the legislation is effective.

This lack of data is not limited to the area of legislation: there is little insight generally into the air-quality impacts and use of mobile machines, as well as into sustainable alternatives.

1.2 Research questions

The Netherlands Pollutant Release and Transfer Register and the Top Sector Logistics jointly financed a study to gain a greater insight into construction machines. Mobile machines represent a large, and growing, source of the overall emissions at national level. Improving the understanding of this source and better substantiating the existing figures is a key point for improvement that the Pollutant Release and Transfer Register plans to address.

3 *Aanpassing Nationaal Samenwerkingsprogramma Luchtkwaliteit 2018 (Modification of National Programme for Collaboration on Air Quality 2018),*

4 *www.platformparticipatie.nl*
European PROMINENT project, www.prominent-iwt.eu

5 *TNO 2017 R11414 Insight into the energy consumption, CO_2 emissions and NO_x emissions of rail freight transport*

The purpose of this study is to identify the use and emissions of construction machines under normal operating conditions.

The resulting knowledge can then be used to:

1 Create a basis for adjusting the emission factors used for these machines. In the Netherlands no measurements have yet been performed to determine the emissions of mobile machines during practical operation. The current emission factors are therefore based on foreign literature and the emissions legislation. Experiences gained in the area of road transport reveal that legislation is not always a good indicator of emissions in practice;
2 Identify aspects of use for which measures could be taken easily to cut CO_2 and reduce harmful emissions. It is possible that simple measures could be taken to minimise the harmful effect of these machines.

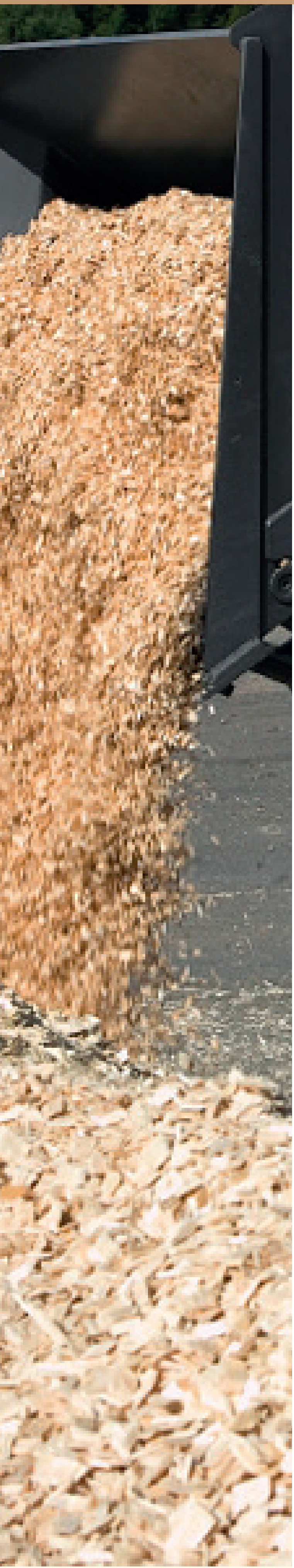
1.3 Approach

For this project companies were approached that frequently use construction machines. In the end three companies made a total of four machines available for the installation of SEMS: TNO's Smart Emission Measurement System. SEMS uses modern sensors for purposes including measuring NO_x emissions (which have an impact on air quality) and determining CO_2 emissions (which have an impact on the climate) over long periods. This data is then combined with usage data to create as complete a picture as possible of the construction machines.

1.4 Structure

Chapter 2 discusses the methodology used for this project and provides an insight into the selection of the machines and the collection and analysis of data. The results for the four different construction machines are presented in Chapters 3 to 6. Each chapter starts with a summary of the findings, before examining the various aspects of use and emissions in greater depth. The report ends with a presentation of the conclusions drawn and the recommendations made on the basis of these conclusions in Chapter 7.

2 Methodology



2.1 Selection of machines

Non-Road Mobile Machinery (NRMM) is the collective term used to refer to all machines with a combustion engine that do not come under the categories of road vehicles, sea-going vessels or aircraft. In addition to construction machines, this group also includes diesel trains, inland vessels and generators. In terms of emission limits the emissions legislation applicable to NRMM lags behind that governing road transport. There are also concerns that the legislation does not adequately cover emissions during normal use. The NO_x emission limits for the main categories of mobile machines, as described in the legislation, is combined with hydrocarbons as NO_x + HC, for Stage III A. To date, the emissions generated in practice for air-quality assessments have been assumed to roughly correspond with the emission limits.

Four different machines were selected for this project. This selection was based on the share of the different types of machine within the overall fleet (see Table 2), the age and the legal class. To gain an insight that would be valid for the foreseeable future, vehicles were selected from the two most recent legal classes: Stage III B and the current Stage IV standards. Stage IV requires a significant reduction in NO_x emissions of 80%. Whether that is actually achieved in practice is one of the questions covered in this study.

Table 3:
Emission limits for mobile machines.

Year	Stage	Power [kW]	NO_x [g/kWh]
2006	III A	130 - 560	4.0*
2007		75 - 130	4.0*
2011	III B	130 - 560	2.0
2012		75 - 130	3.3
2014	IV	75 - 560	0.4

** NO_x + HC*

The final selection consisted of two excavators, a loading shovel and a tractor. Two of these machines were equipped with a Stage IV engine and two with a Stage III B engine. The Stage III B engines incorporated an exhaust gas recirculation system (EGR), while the Stage IV engines had been fitted with an SCR (selective catalytic reduction system) as NO_x-reducing technology. In addition, all four engines had a soot filter to reduce PM emissions. An overview of the selected machines is presented in Table 4.

Table 4:
Overview of selected machines

#	Type of machine	Stage	Aftertreatment	Power [kW]
1	Excavator 1	IV	SCR, DPF and EGR	152 kW
2	Loading shovel	III B	EGR and DPF	129 kW
3	Excavator 2	III B	EGR and DPF	159 kW
4	Tractor	IV	SCR and DPF	114 kW

2.2 Data collection and analysis

The use and emissions of the four selected construction machines were monitored using SEMS. Sensor-based monitoring system, SEMS, which TNO has been developing since 2012, uses modern sensors in the hot and wet exhaust stream to determine NO_x and CO_2 emissions, amongst other things, robustly and over a long period of time.

Performing measurements on construction machines is no easy task, partly due to the difficulty in determining the total outflow of exhaust gas. A number of processing steps are needed to create a clear and complete picture of machine use on the basis of the measurement data. The engine speed plays an important role here: in the case of mobile machines a higher engine speed is linked to a higher engine load. Breaking down the data by engine speed therefore allows much of the variability in harmful emissions to be seen.

The processing steps required to achieve a complete picture depend on the parameters that can be read out from the engine management system and may differ from one construction machine to the next. Annex A contains a more detailed overview of the processing used during this project.

3 Excavator 1

After tractors, excavators are the largest group of mobile machines in the Netherlands. Excavator 1 complies with the latest requirements, Stage IV, and incorporates an SCR.

Excavator of the same type and model as the one measured during this project.
source: https://www.cat.com/en_US/products/new/equipment/excavators/medium-excavators/1000024903.html

Type of machine	Excavator
Stage with which engine complies	Stage IV
Engine power	129 kW
Aftertreatment system	SCR and EGR

3.1 Summary of findings

The following findings resulted from the monitoring of excavator 1:

1. The engine spends 35% of the time idling. If the engine is idling for more than a few minutes, the SCR no longer appears to work and the NO_x emissions reach their highest value.
2. Above 1,400 revolutions per minute this excavator complies with the Stage IV emissions requirements. At lower speeds the emissions are not only higher in relative terms, but also in absolute terms.

Fuel consumption during idling is approximately 10% of the maximum fuel consumption.
In principle, this results in a situation whereby the 35% of the time spent idling accounts for at least 3.5% of the total fuel consumption. In practice, however, the figure is typically a factor of 2 higher due to the lower engine load: almost 8% of fuel consumption can be attributed to idling, in view of the way this excavator is used.

The key figures resulting from the measurement have been grouped together in Table 5. A more detailed discussion of the various aspects can be found in the following sections.

Table 5:
Key figures resulting from measurement of machine 1 (excavator)

Amount of data collected	131 hours
Time spent idling per hour	21 minutes/hour
Average CO_2 emissions per hour	42 kilograms/hour
Average NO_x emissions per hour	34 grams/hour
Average NO_x emissions during idling (~900 and 1,000 RPM)	49 grams/hour
Average NO_x emissions per kWh	0.5 grams/kWh

3.2 Results

1 Use

To determine how the machine is being used, the engine speed is examined (in RPM - revolutions per minute). A histogram of the RPM of the engine is presented in Figure 1. From this it is possible to distinguish two different usage profiles: idling (RPM~900 and RPM~1,000, the higher speed being a stand-by mode) and actual use (1,400<RPM<1,700).
Idling accounts for around 35% of the time, or 21 minutes per hour.

2 NO_x emissions

The average NO_x emissions measured per RPM bin are presented in Figure 2. The total NO_x emissions per RPM bin were determined by combining these values with the time the engine spends operating in a particular RPM bin (Figure 3). It is notable here that a large proportion of NO_x emissions are generated during idling at RPM~1,000: 30%. Idling at RPM~900 also accounts for a substantial share of NO_x emissions (20%). This means that 51% of total NO_x emissions are the result of the machine idling, while 49% are a consequence of the actual work performed by the machine.

3 CO_2 emissions

The measured CO_2 values are presented in the same way as the NO_x values (see Figure 4 and Figure 5). In Figure 5 the same three peaks can be seen. As CO_2 emissions are directly dependent on the quantity of fuel consumed, and fuel consumption is low during idling, idling accounts for a significantly smaller share of CO_2 emissions than NO_x emissions: the two idling peaks contribute less than 10% to total CO_2 emissions.

4 Ratio between NO_x emissions and CO_2 emissions

Figure 6 presents the ratio between the NO_x emissions and CO_2 emissions. This is a good parameter in relation to the type-approval requirements. The excavator measured has a Stage IV engine; in accordance with the requirements for Stage IV engines, this may emit around 0.6 grams of NO_x per kilogram of CO_2 during the test. Above 1,400 revolutions per minute the NO_x emissions appear to be below this limit. At low speeds and during idling the power delivered and the CO_2 emissions are limited. However, the NO_x-CO_2 ratio reveals that below 1,000 RPM the NO_x-reduction system is not particularly effective.
Consequently, these speeds make a significant contribution to total NO_x emissions (Figure 3). From approximately 1,400 RPM the NO_x emission control system functions well and emissions are low. Higher emissions are observed below a level of 1,400 RPM.

5 NO_x emissions and speed over time

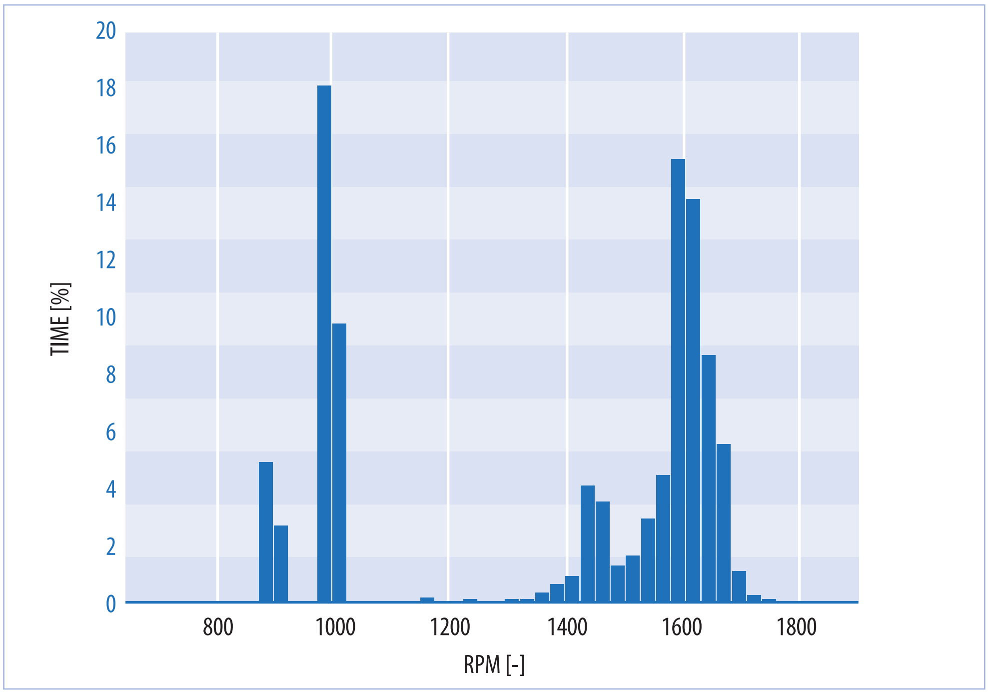
In Figure 7 the NO_x emissions and associated speed have been plotted for two different periods. The same behaviour was observed during both periods: if the machine idles for a while (150-250 seconds), the NO_x emissions go up.

This behaviour was measured at both the idling speed of ~900 RPM and the idling speed of ~1,000 RPM. The cause of this increase was not determined. It seems that the SCR stops injecting AdBlue during idling. The injection of AdBlue during idling is generally difficult or impossible, as the exhaust gas temperature is too low.

After a while the SCR's ammonia buffer becomes empty, which means NO_x can no longer be converted into harmless components. This issue could possibly be addressed using the EGR system, but this measure is not required under the current legislation.

Figure 1:

Frequency of engine speeds over time. The total measurement period covers 131 hours. Over an average hour the excavator spends 65% of the time working (and 35% of the time idling).



6 Calculated on the basis of the limit of 0.4 g/kWh in combination with an average engine efficiency.

EXCAVATOR 1

Figure 2:
Average NO_x emissions per RPM bin.

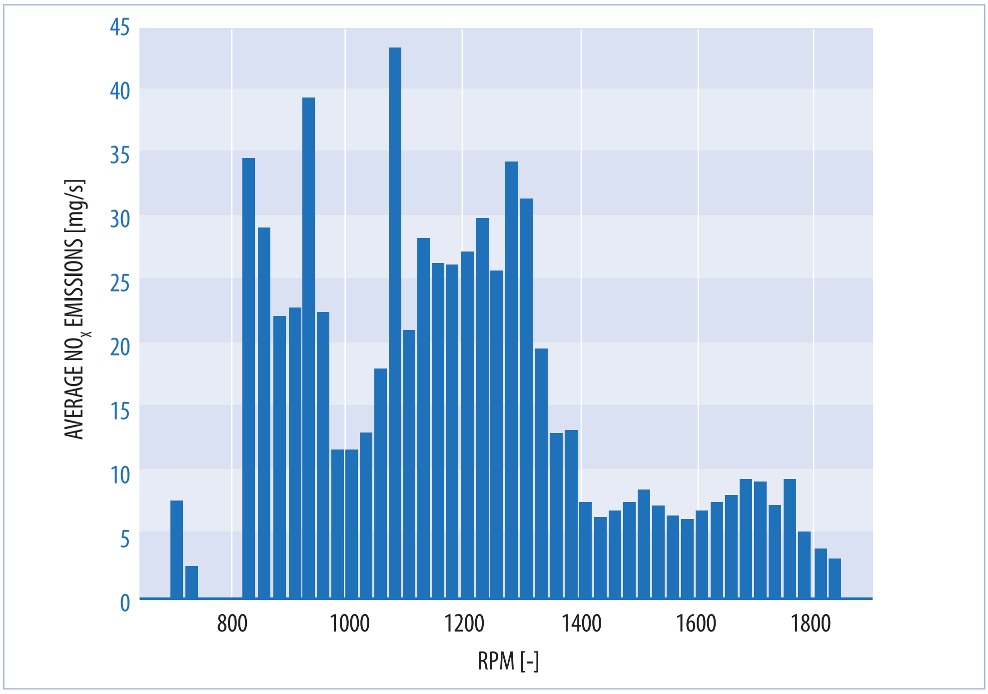
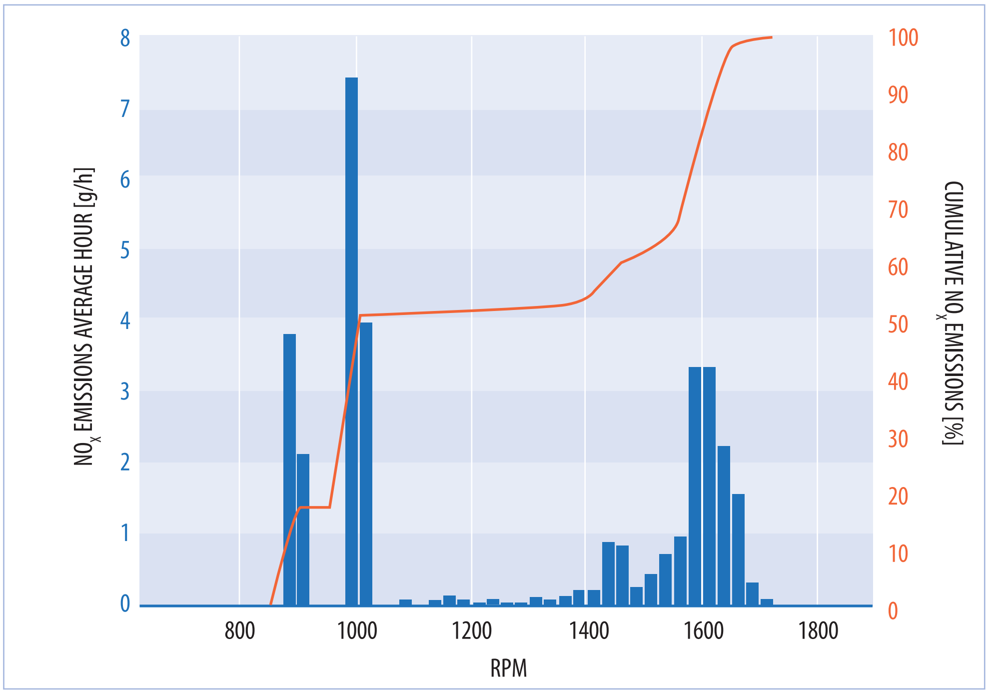


Figure 3:
NO_x emissions and cumulative NO_x emissions vs engine speed, for an average hour of operation. The total NO_x emissions per hour amount to an average of 34 grams.



EXCAVATOR 1

Figure 4:

Average CO_2 emissions per RPM bin.

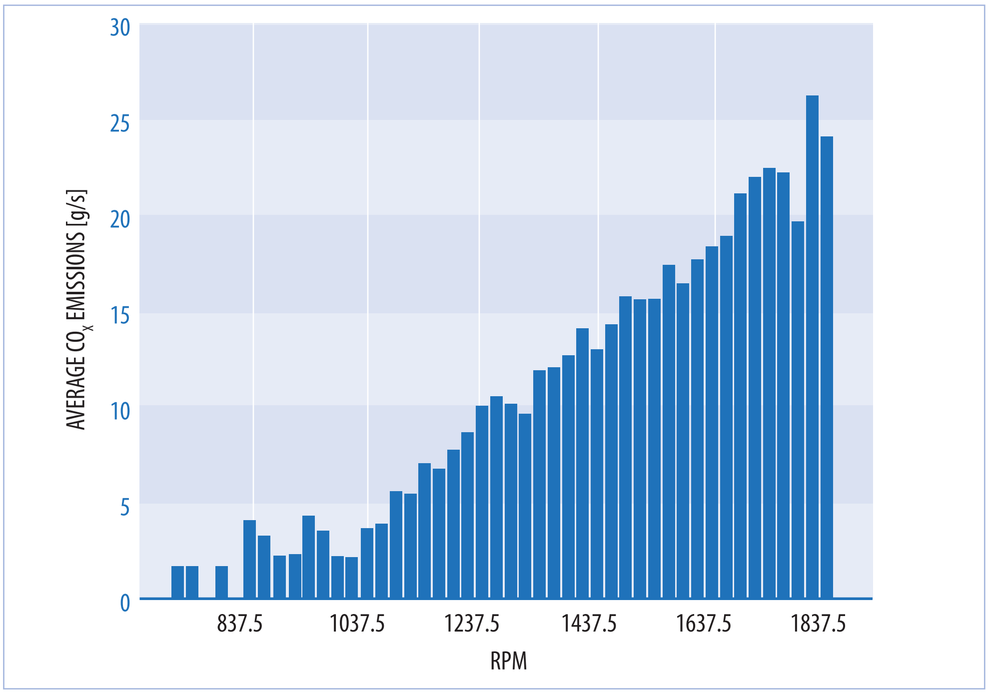


Figure 5:

CO_2 emissions and cumulative CO_2 emissions vs engine speed, for an average hour of operation.
The total CO_2 emissions per hour amount to an average of 42 kilograms.

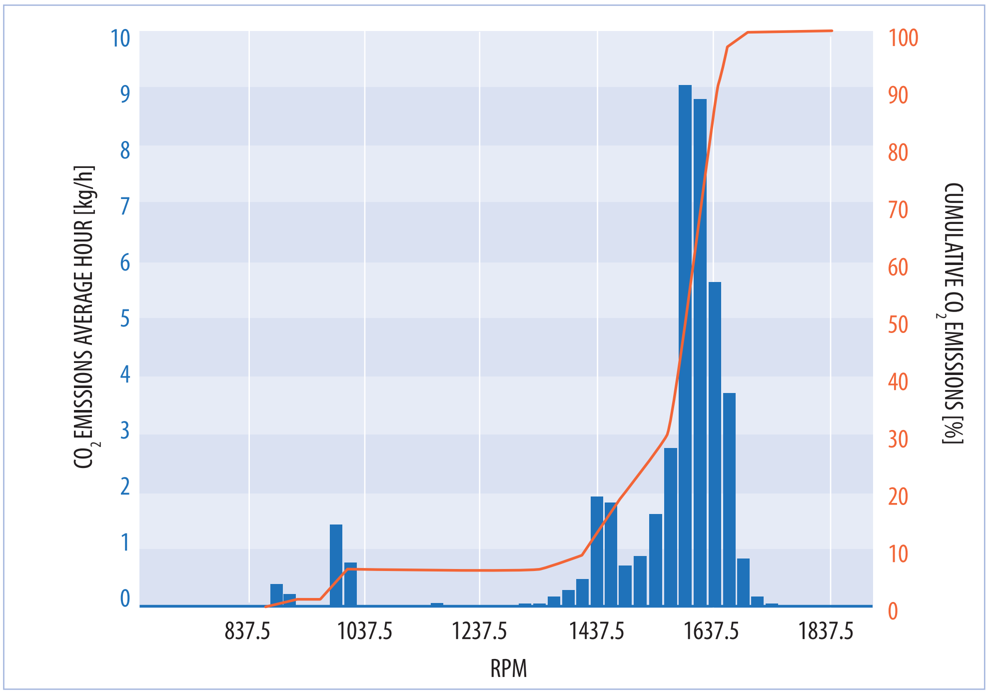


Figure 6:

Ratio between NO_x emissions and CO_2 emissions per RPM bin. The red line provides an indication of the NO_x limit on the totals emissions in the official laboratory test for this engine at a higher load: 0.4 g is the limit for NO_x emissions per kWh, while 0.69 kg is the figure for CO_2 emissions per kWh.

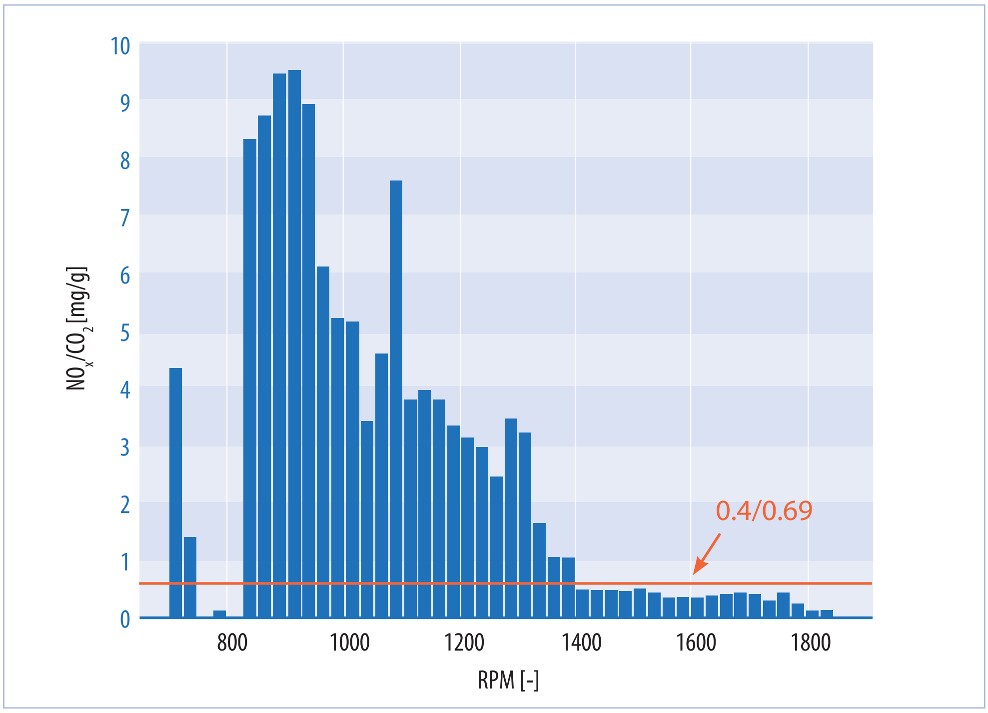
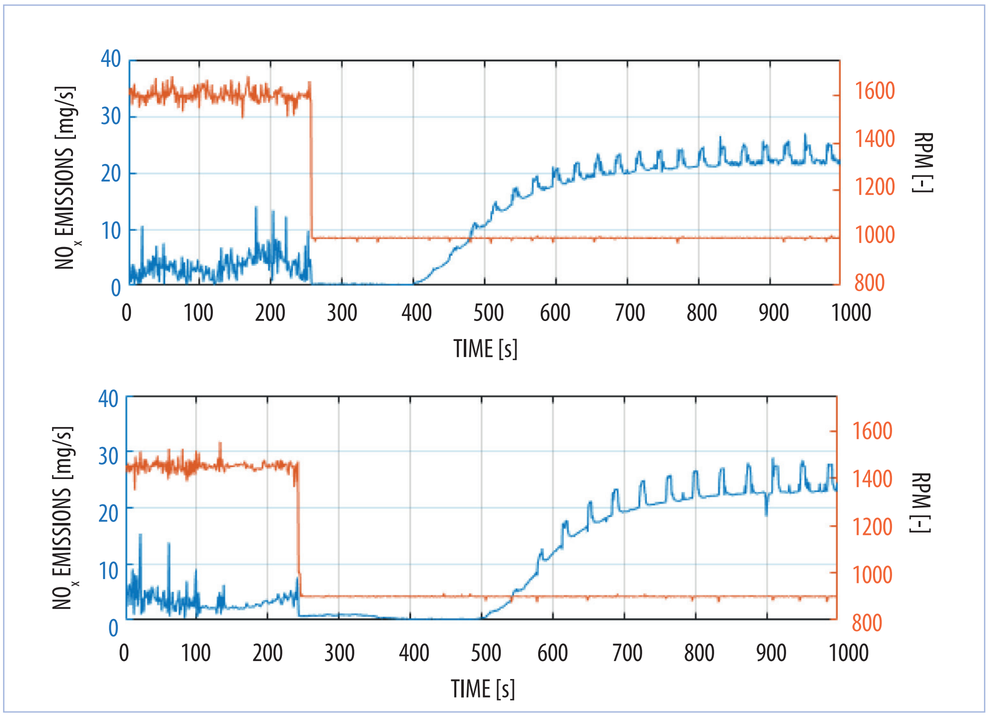


Figure 7:

NO_x emissions and the associated engine speed over time, in two cases where the engine starts to idle. This behaviour can possibly be attributed to AdBlue injection being stopped in the SCR.



4 Loading shovel

Loading shovels are the third largest group in terms of the number of mobile machines in the Netherlands. The selected loading shovel complies with the second most recent set of statutory requirements: Stage III B.
That means this machine can have higher NO_x emissions than the excavator discussed in the previous chapter.

Loading shovel of the same type and model as the one measured during this project.
source: https://www.flickr.com/photos/volvocena/sets/72157630607958352/

Type of machine	Loading shovel
Stage with which engine complies	Stage III B
Engine power	129 kW
Aftertreatment system	EGR

4.1 Summary of findings

The following findings resulted from the monitoring of the loading shovel:

- The loading shovel monitored has no SCR. As a consequence the ratio between NO_x emissions at a high and low engine load is smaller than in the case of the Stage IV excavator discussed in Chapter 4.
- As the loading shovel spends over half its time idling, idling is also responsible for a large proportion of the emissions of this machine: 17% of total fuel consumption and almost half of total NO_x emissions.
- The ratio between NO_x emissions and CO_2 emissions increases by a factor of 3 if the load is reduced from a high load to zero. In the case of the Stage IV SCR technology in the previous chapter this was a factor of 10. For a Stage III B engine it therefore seems that, assuming the engine idles for a similar proportion of the time, the contribution of idling to emissions is less significant.

The key figures resulting from the measurement have been grouped together in Table 6.

Table 6:
Key figures resulting from measurement of loading shovel.

Amount of data collected	344 hours
Time spent idling per hour	34 minutes/hour
Average CO_2 emissions per hour	18 kilograms/hour
Average NO_x emissions per hour	141 grams/hour
Average NO_x emissions during idling (~700 RPM)	106 grams/hour
Average NO_x emissions per kWh	4.9 grams/kWh

4.2 Results

1 Use

On the basis of the engine speeds measured (see Figure 8), it is possible to conclude that the loading shovel is idling for the majority of the time. The load on the loading shovel's engine varies considerably, which translates into a wide range of engine speeds, all of which occur with similar frequencies. Only the idling speed (around 700 revolutions per minute) stands out as a particularly common engine speed.

2 NO_x emissions

Figure 9 presents the average NO_x emissions per RPM bin. Here it can be seen that at the relatively constant idling speed of 700 RPM the machine's NO_x emissions are lower than during dynamic operation. However, if this data is combined with the time the machine spends idling (see Figure 10), the NO_x emissions generated during idling account for 41% of total emissions.

3 CO_2 emissions

An analysis of the loading shovel's CO_2 emissions reveals a standard picture (Figure 11 and Figure 12). The CO_2 emissions generated during idling represent around 10% of the maximum CO_2emissions at the highest powers. If the machine is used with only a limited proportion of idling, the CO_2 emissions resulting from idling therefore play a less significant role. In this case 3 kilograms of CO_2 out of the 18 kilograms of CO_2 per hour are the result of idling. This represents 18% of the total fuel consumption.
A certain proportion of idling will always form part of normal use, but in view of the high percentage observed, instructing drivers to switch off the engine during longer periods of inactivity is certainly worth considering.

4 Ratio between NO_x emissions and CO_2 emissions

The increase in NO_x/CO_2 at lower engine speeds can be seen clearly in Figure 13. This ratio would be constant without NO_x emission control technology. The decrease at higher speeds is possibly linked to a control strategy, which functions better when the load is higher. The flat line suggests that the control strategy also functions reasonably well in the event of dynamic changes in the engine load. The line on the graph is based on a connection between the power delivered and CO_2. At higher engine loads 650-750 g of CO_2 are typically emitted for one kWh of work in the case of a larger diesel engine under normal usage conditions.

This makes it possible to translate the emission limit of 3.3 g/kWh into grams of NO_x per kilogram of CO_2. At lower engine loads the quantity of CO_2 per kWh is higher and the line would have to bend downwards if the emission limit applied to all engine loads. Instead, low loads are not, or only barely, represented in the statutory requirements.
The consequence of this seems to be that NO_x emissions are higher.

For certain engines high NO_x emissions are caused by the dynamic load, e.g. when the engine is building up speed. This is evident from a higher NO_x/CO_2 ratio at speeds at which the engine is running with a limited load. That does not appear to be the case for this engine. Only in a few cases does the NO_x/CO_2 ratio briefly rise above the average when the engine picks up speed again from idling.

Figure 8:
Engine speed vs time. The total measurement period covers 344 hours. Over an average hour the loading shovel spends 43% of the time working (and 57% of the time idling).

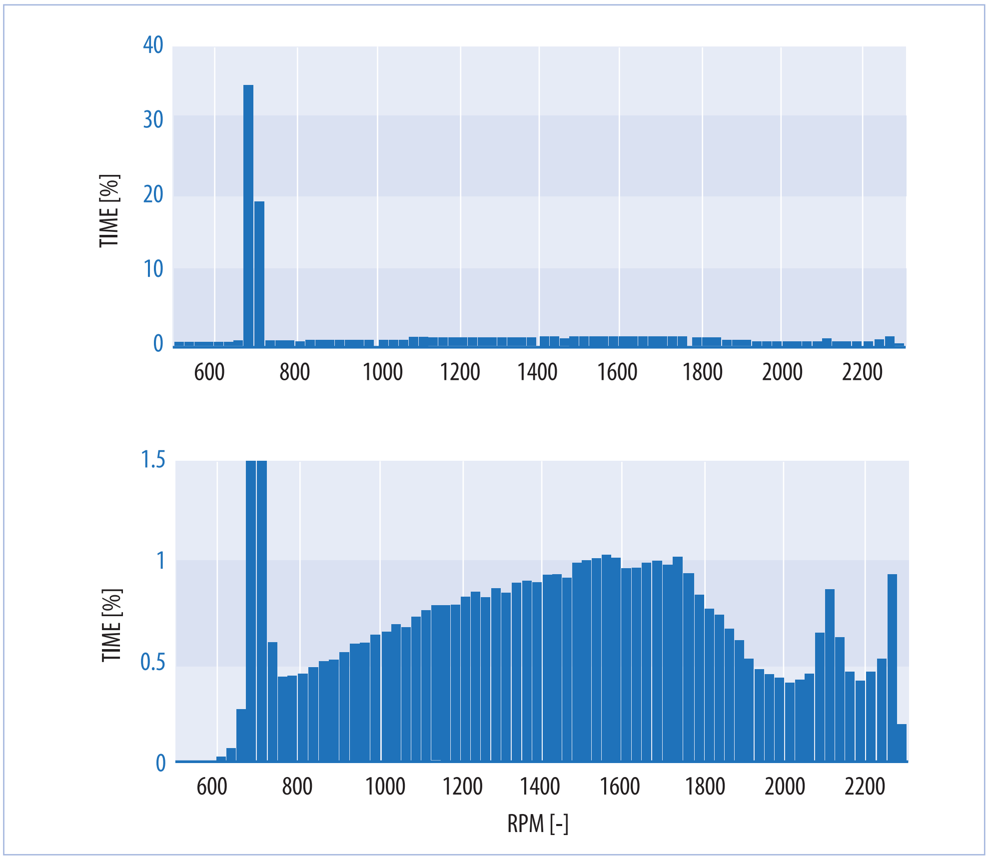


Figure 9:
Average NO_x emissions per RPM bin.

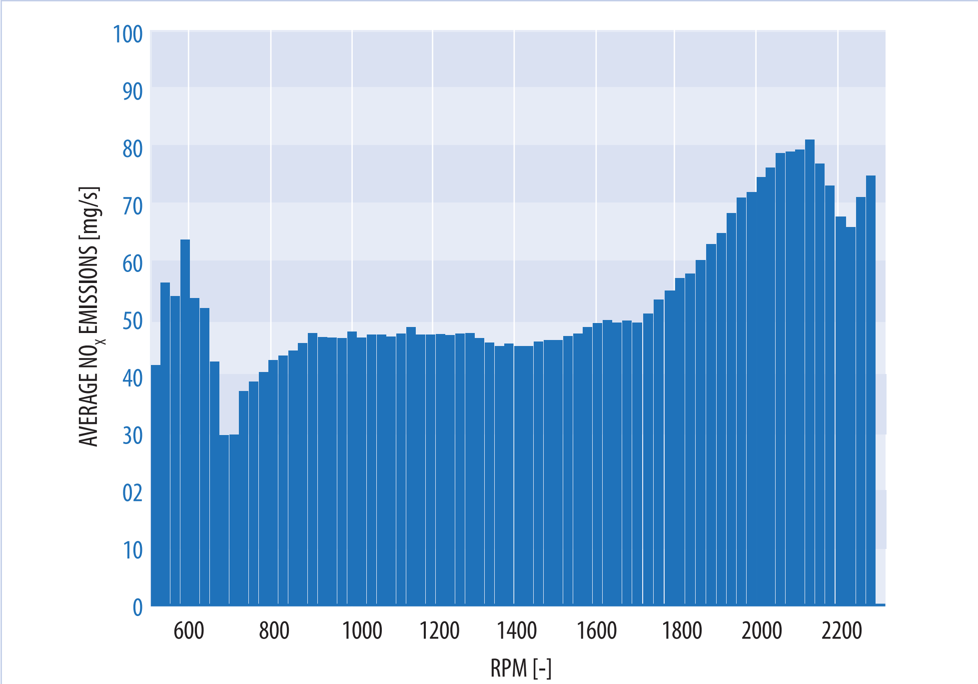
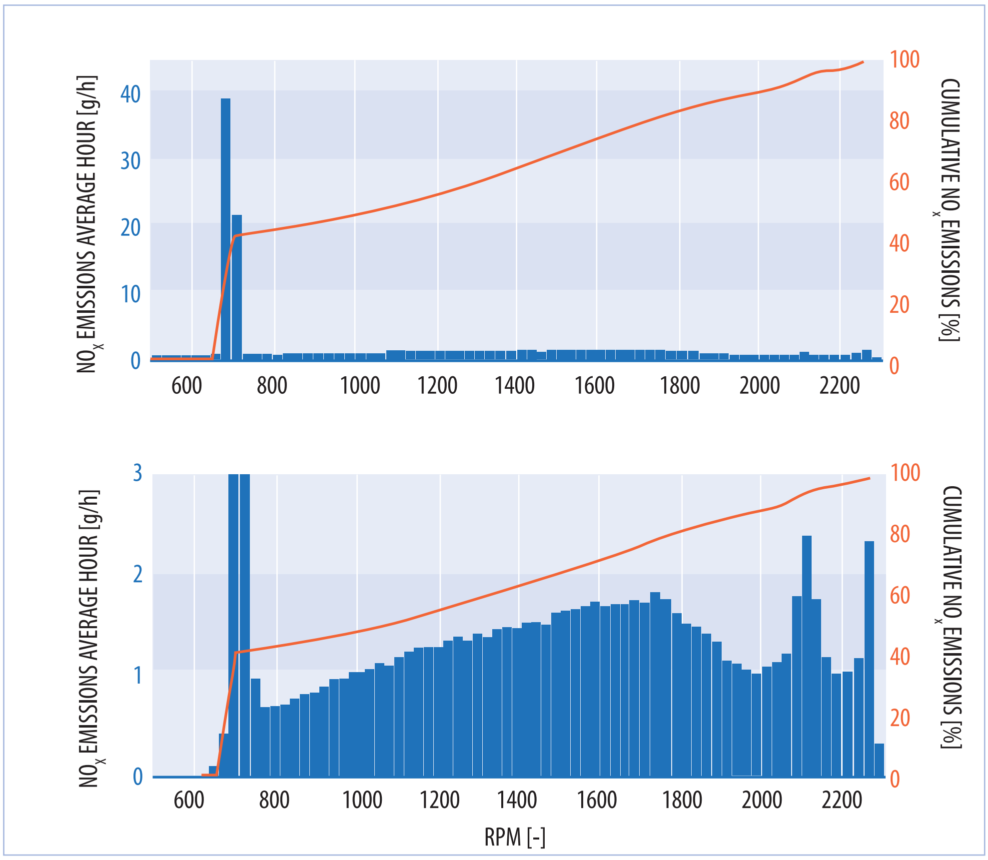


Figure 10:
NO_x emissions and cumulative NO_x emissions vs engine speed, for an average hour of operation. The total NO_x emissions per hour amount to an average of 141 grams.



LOADING SHOVEL

Figure 11:
Average CO_2 emissions per RPM bin.

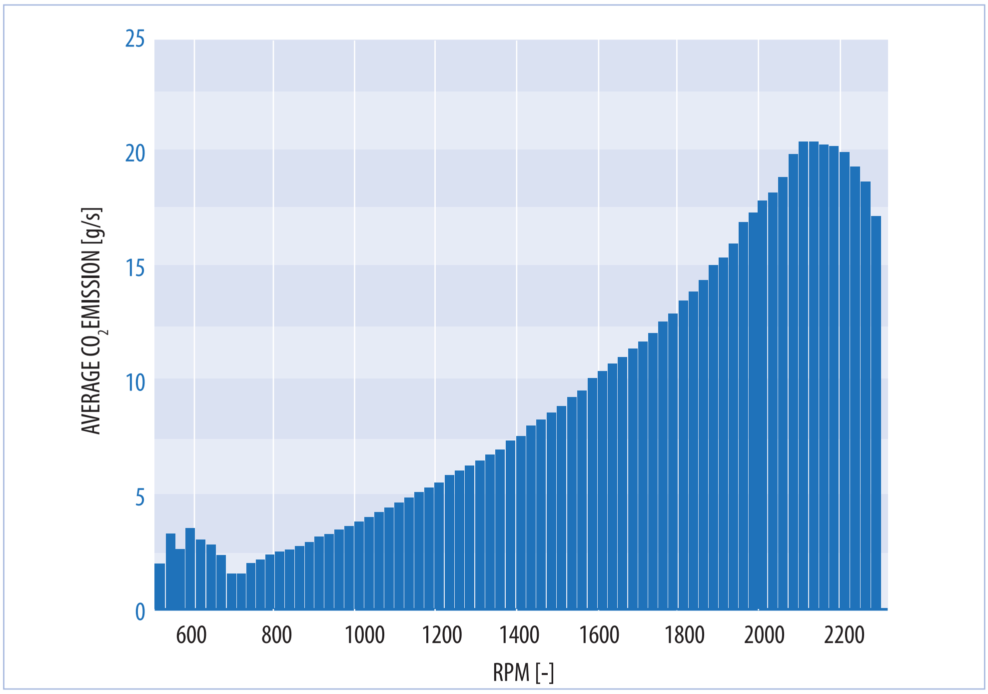


Figure 12:
CO_2 emissions and cumulative CO_2 emissions vs engine speed, for an average hour of operation.
The total CO_2 emissions per hour amount to an average of 18 kilograms.

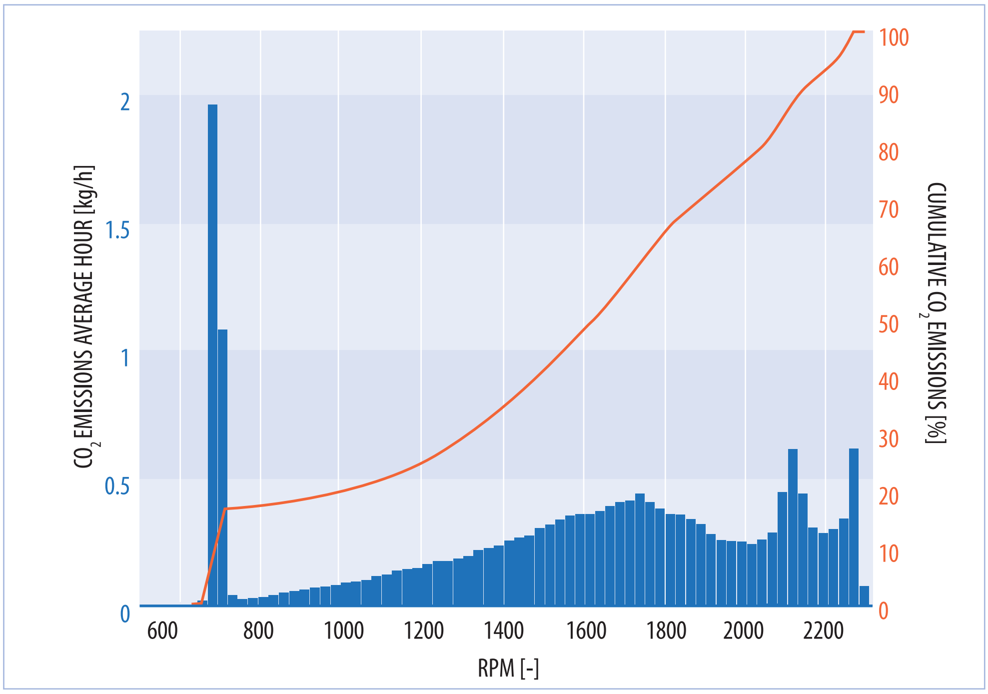


Figure 13:

Ratio between NO_x emissions and CO_2 emissions per RPM bin. The red line provides an indication of the NO_x limit on the totals emissions in the official laboratory test for this engine at a higher load: 3.3 g is the limit for NO_x emissions per kWh, while 0.69 kg is the figure for CO_2 emissions per kWh.

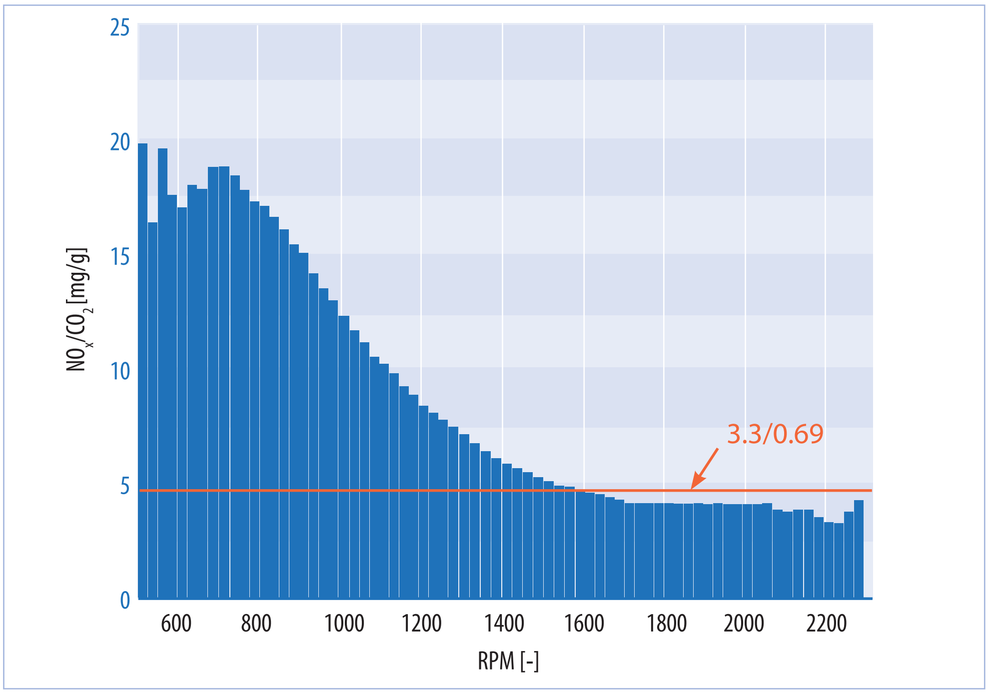
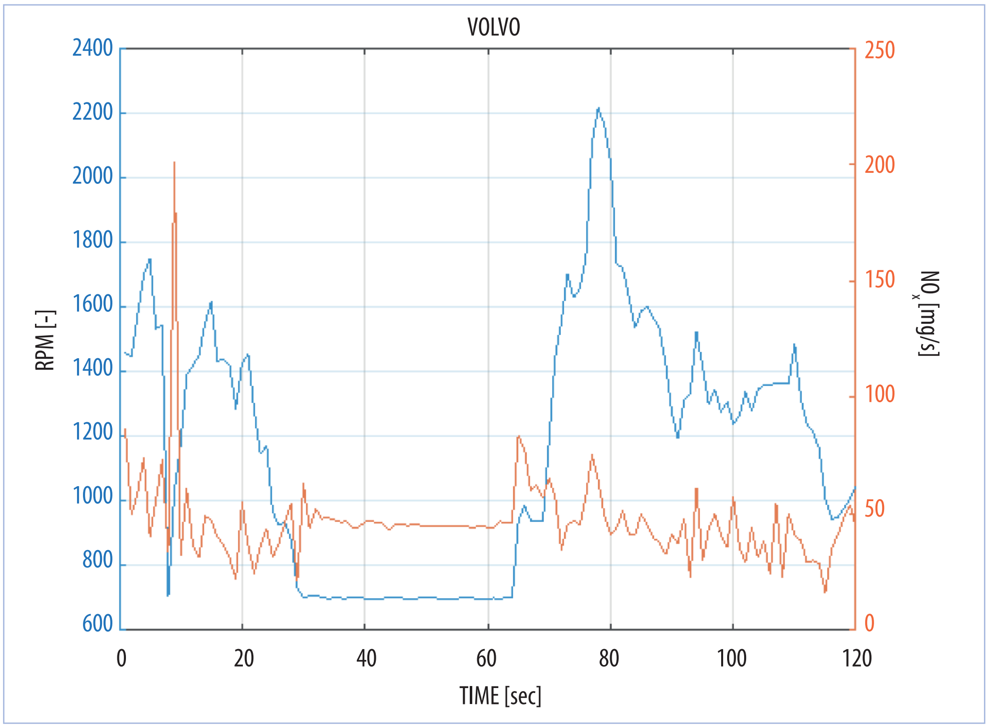
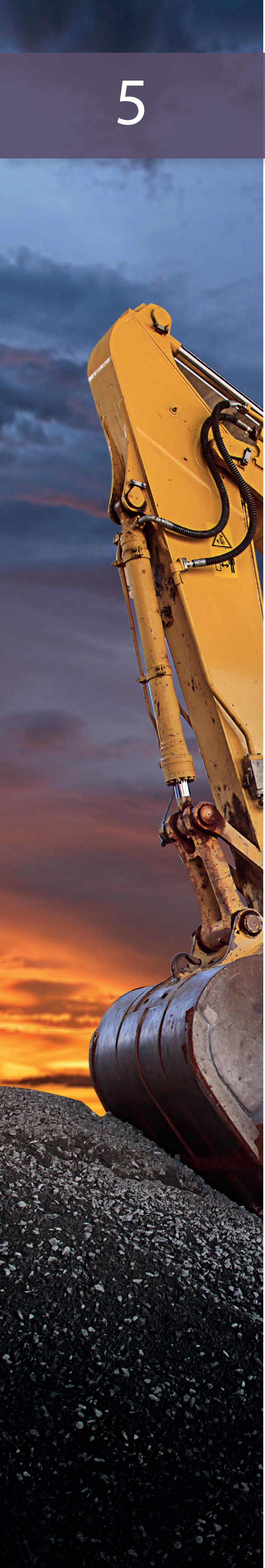


Figure 14:

NO_x emissions and associated speed over time. If the load is low, the NO_x emissions are stable at a high level. CO_2 emissions per hour amount to an average of 18 kilograms.





5 Excavator 2

As excavators represent a large group of machines, a second excavator was selected. This excavator complies with Stage III B, like the loading shovel in the previous chapter.

Excavator of the same type and model as the one measured during this project.
source: https://www.lectura-specs.com/en/model/construction-machinery/crawler-excavators-komatsu/pc290lc-10-1147798

Type of machine	Excavator
Stage with which engine complies	Stage III B
Engine power	159 kW
Aftertreatment system	EGR

5.1 Summary of findings

The following findings resulted from the monitoring of excavator 2:

- Overall the emissions characteristics of this Stage III B machine are similar to or slightly lower than the previous Stage III B machine, although NO_x emissions appear to be higher in the event of a dynamic load than is the case with the loading shovel. This specific type of use, alongside idling, was therefore an important factor in the emissions generated.
- Here again the NRMM emissions legislation appears to be decisive with regard to the difference in emissions at the different engine loads. The requirements are stricter for engine loads at constant speeds than they are for dynamic usage.
- This machine idles for only a limited amount of time. The contribution of idling to total NO_x emissions is around 12%, while its contribution to total fuel consumption is approximately 4%.

The key figures resulting from the measurement have been grouped together in Table 7. A more detailed discussion of the various aspects can be found in the following sections.

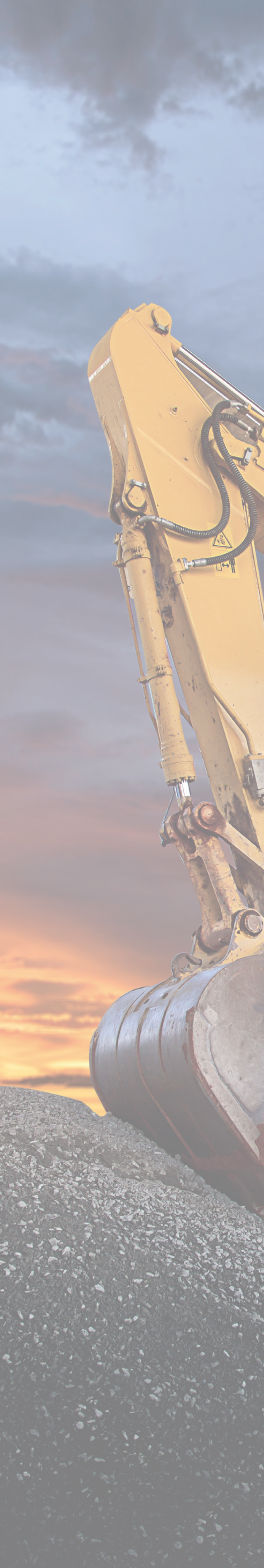


Table 7:
Key figures resulting from measurement of excavator 2.

Amount of data collected	291 hours
Time spent idling per hour	11 minutes/hour
Average CO_2 emissions per hour	53 kilograms/hour
Average NO_x emissions per hour	149 grams/hour
Average NO_x emissions during idling (~1,050 RPM)	91 grams/hour
Average NO_x emissions per kWh	2.8 grams/kWh

1 Use

This machine also spends some of the time idling, although not as much as the machines discussed in the previous chapters. Its engine idles for around 18% of the time. This still has a relevant impact on total NO_x emissions: around 12% of NO_x emissions can be attributed to idling.
In the case of CO_2 emissions the proportion resulting from idling is much lower at around 4%.

2 NO_x emissions

The second excavator appears to struggle more with dynamic behaviour than the loading shovel in the previous chapter. Its NO_x emissions are higher at engine speeds that are less common and that probably only occur at transitions between different engine operating points (see Figure 16).
The operating point at 1,700 RPM accounts for a significant share of the time, but, as can be seen in Figure 16, it is the increase in speed to 1,700 RPM from 1,600 RPM that generates the highest NO_x emissions for this engine. A second peak at 1,200 RPM could be linked to the transition from idling to an engine load, but due to the limited share of time this represents, it is of barely any relevance to total emissions (see Figure 17).

3 Ratio between NO_x emissions and CO_2 emissions

At all higher engine loads this machine complies with the Stage III B emission limits (see Figure 20). At lower engine loads emissions are, proportionally, 3 to 5 times higher. If the engine is operated infrequently at these lower loads, this is not a problem. However, this machine spends a quarter of its time operating with a lower engine load, a not insignificant proportion.

4 NO_x emissions and speed over time

The time signal of the engine (Figure 21) shows that the variable load has an impact on NO_x emissions. The NO_x emissions vary at higher engine speeds and it takes a while for these NO_x emissions to drop below the initial peak in the event of a change of speed and load.

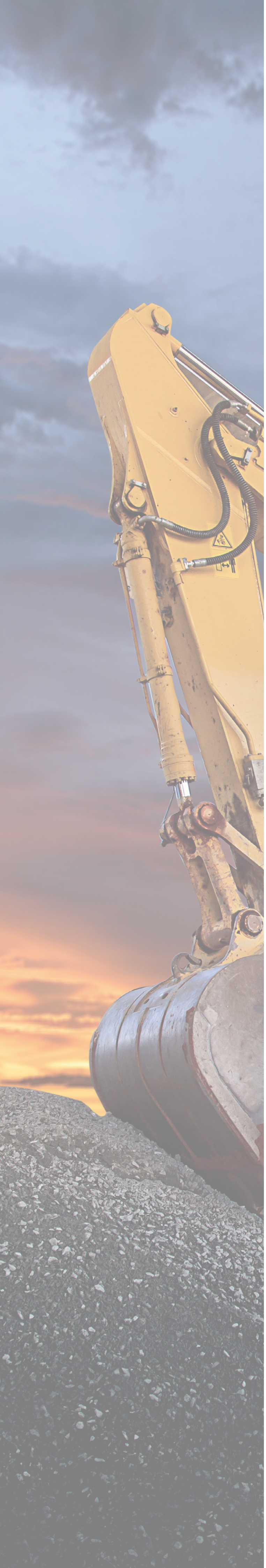


Figure 15:

Engine speed vs time. The total measurement period covers 291 hours. Over an average hour the excavator spends 82% of the time working (and 18% of the time idling).

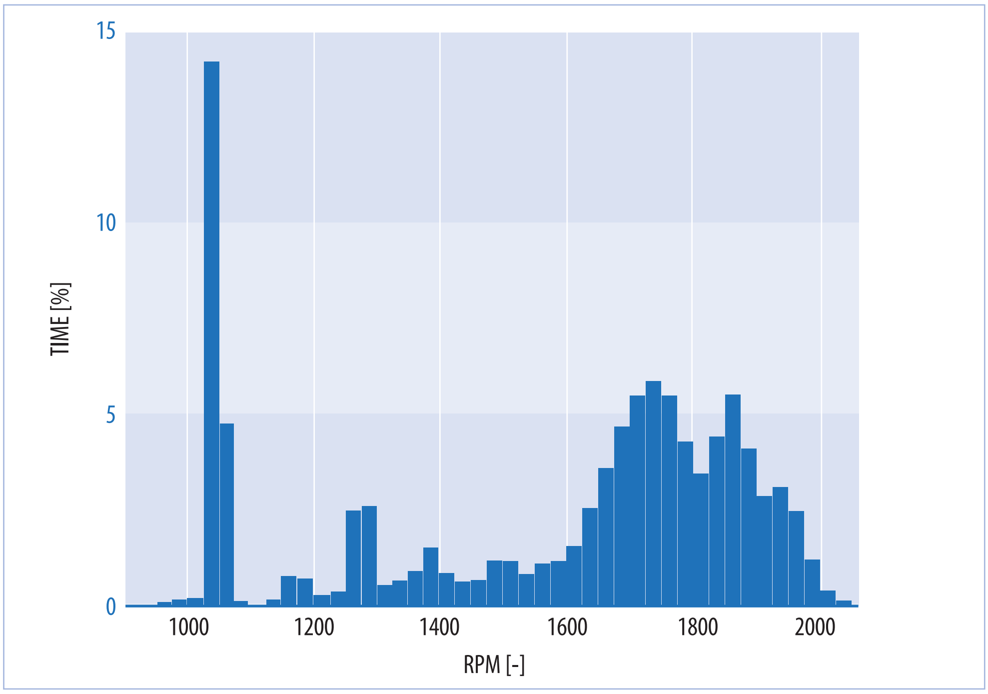
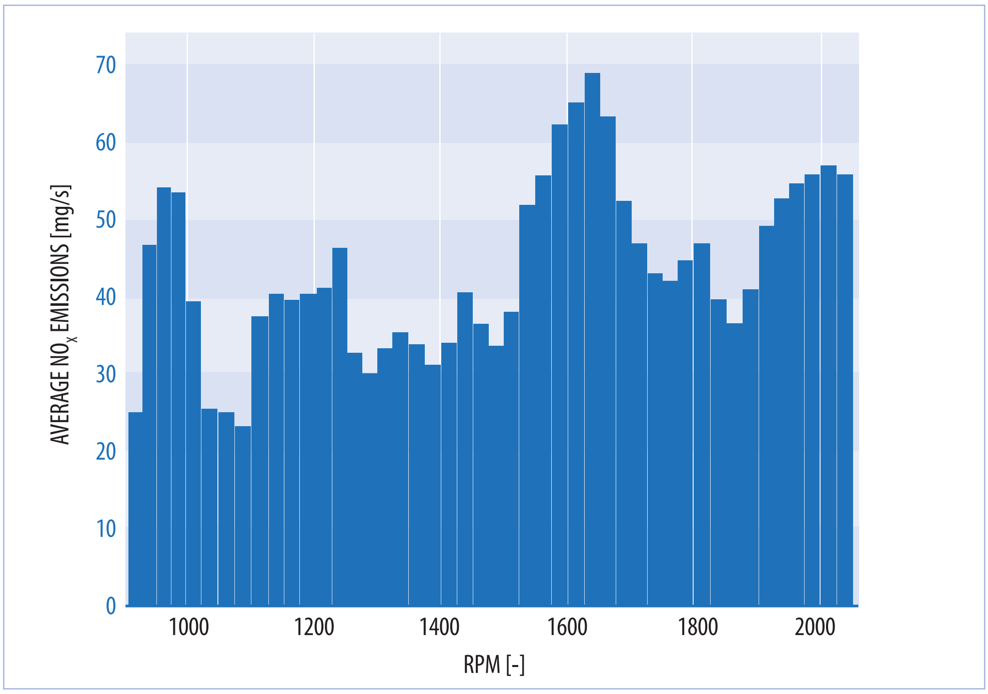


Figure 16:

Average NO_x emissions per RPM bin.



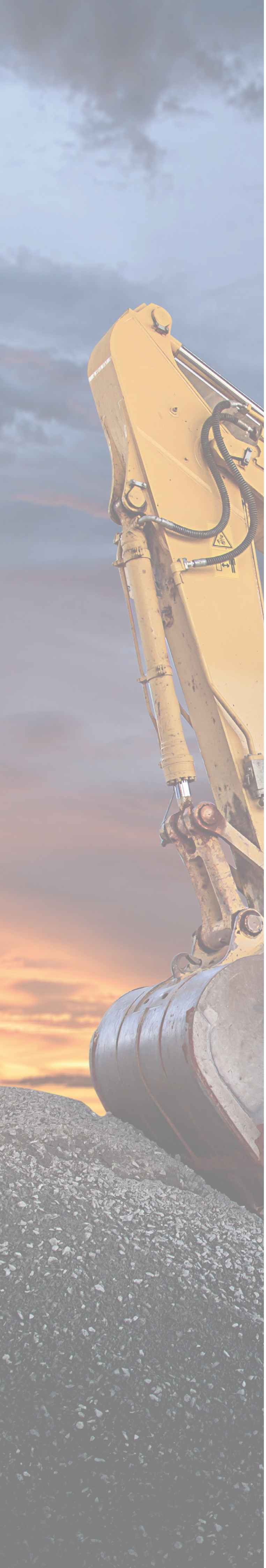


Figure 17:

NO_x emissions and cumulative NO_x emissions vs engine speed, for an average hour of operation. The total NO_x emissions per hour amount to an average of 149 grams.

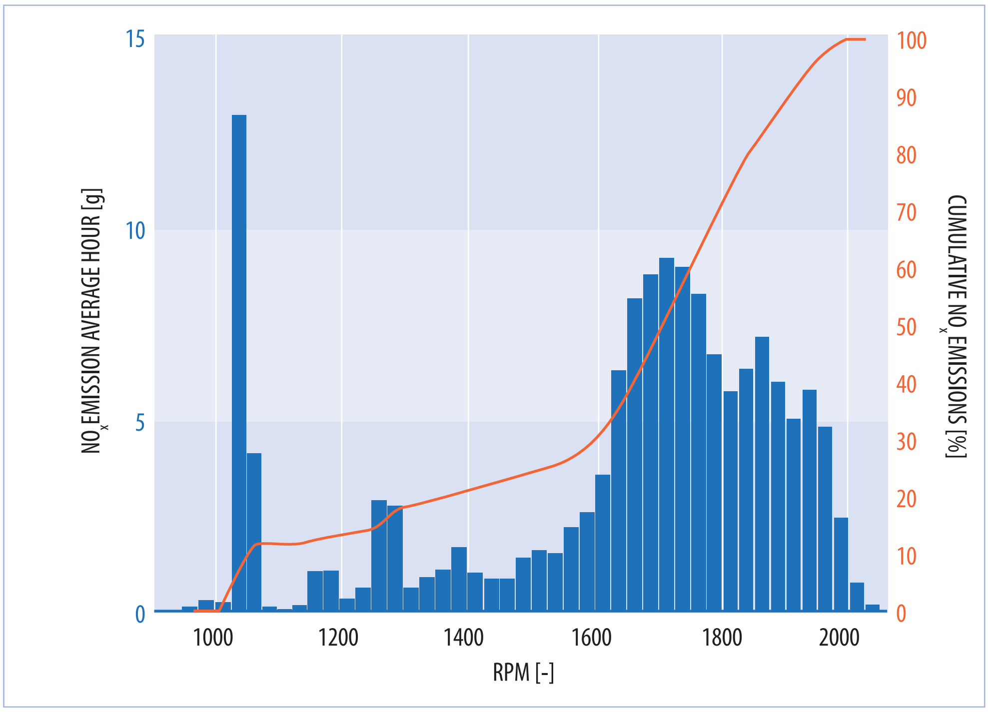
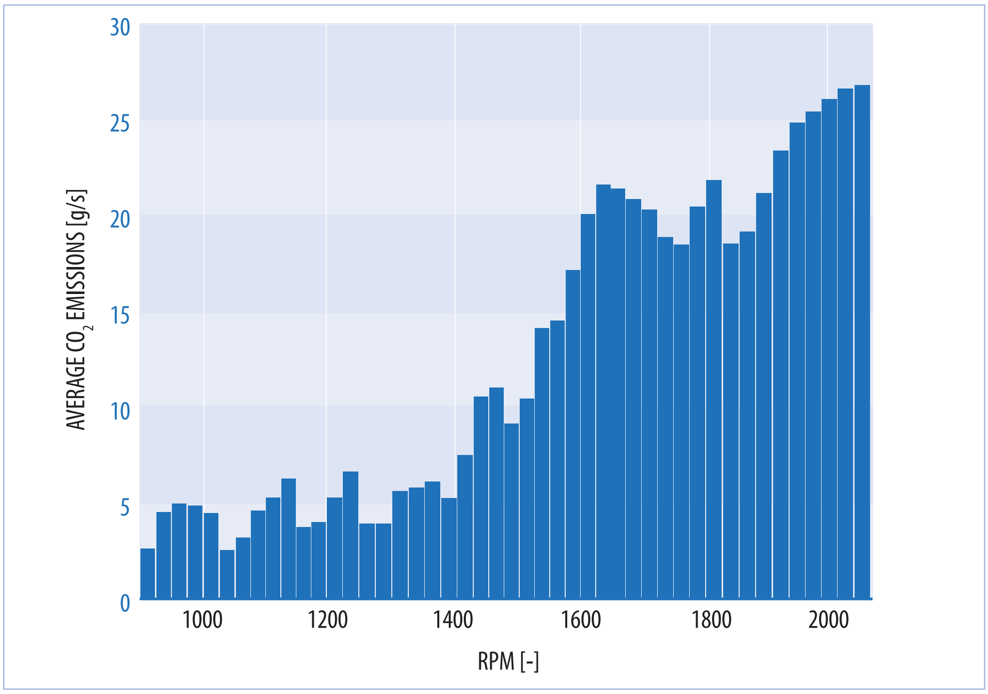


Figure 18:

Average CO_2 emissions per RPM bin.



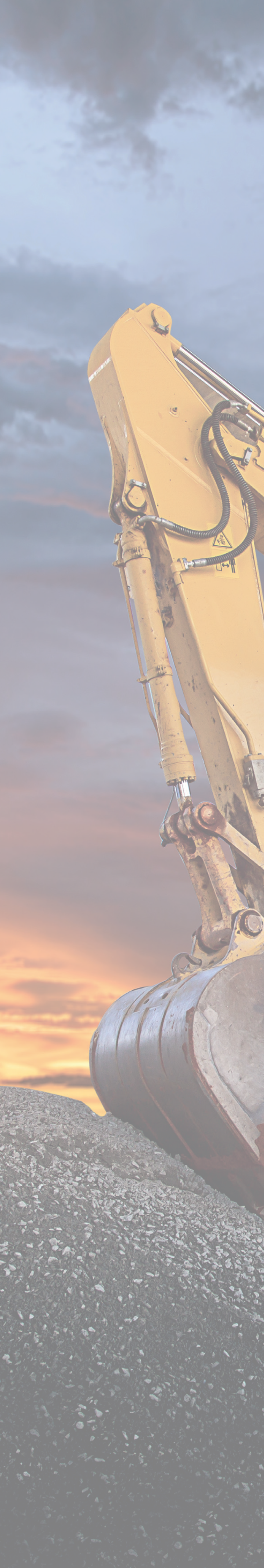


Figure 19:

CO_2 emissions and cumulative CO_2 emissions vs engine speed, for an average hour of operation. The total CO_2 emissions per hour amount to an average of 53 kilograms.

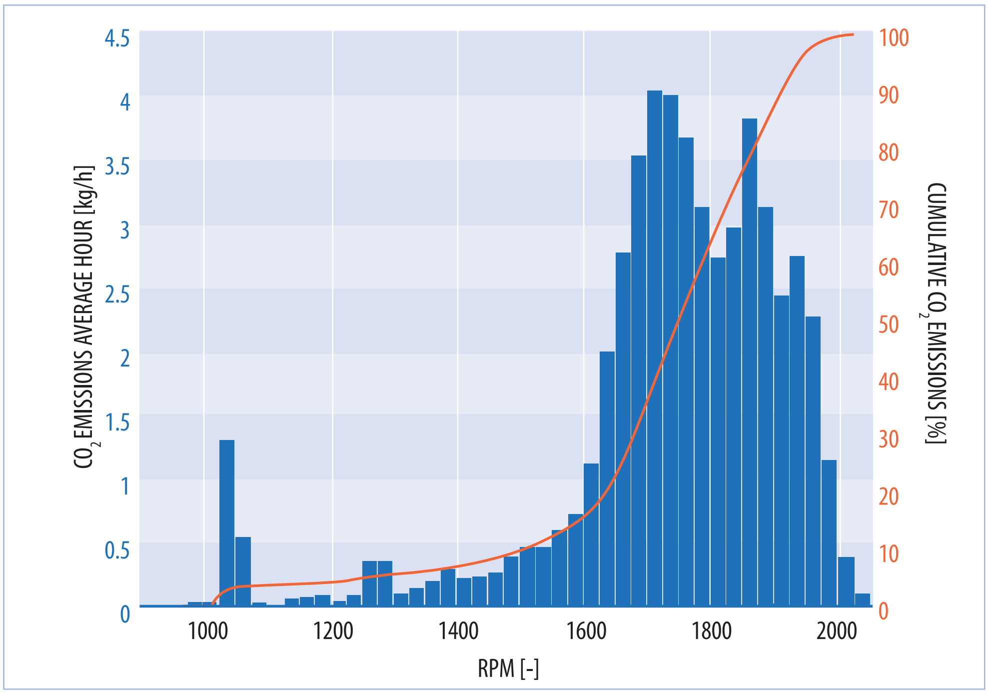
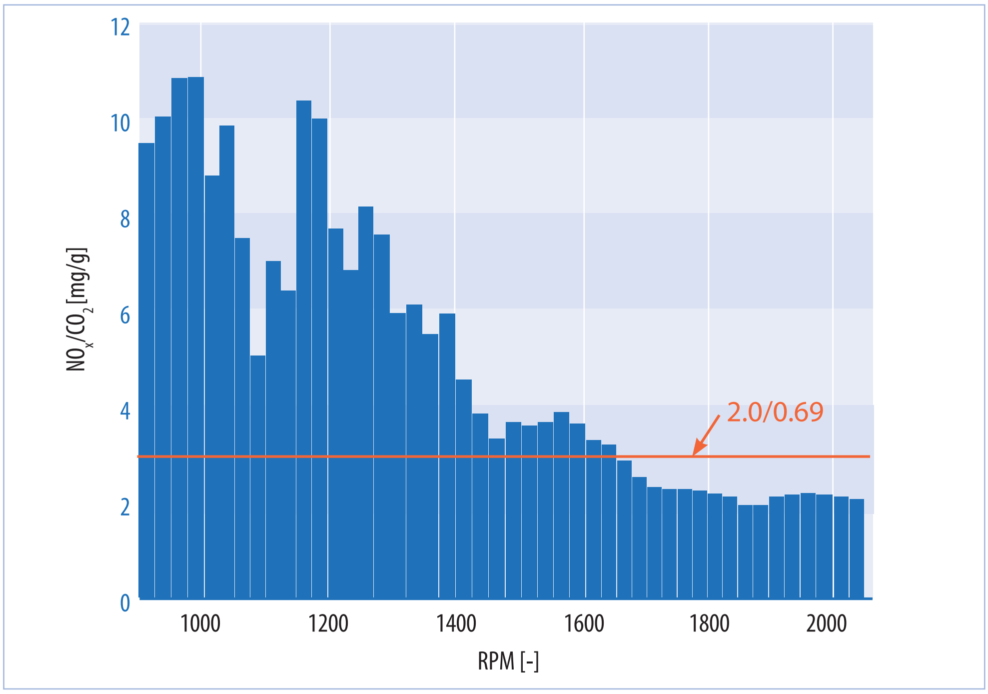


Figure 20:

Ratio between NO_x emissions and CO_2 emissions per RPM bin. The red line provides an indication of the NO_x limit on the totals emissions in the official laboratory test for this engine at a higher load:2.0 g is the limit for NO_x emissions per kWh, while 0.69 kg is the figure for CO_2 emissions per kWh.



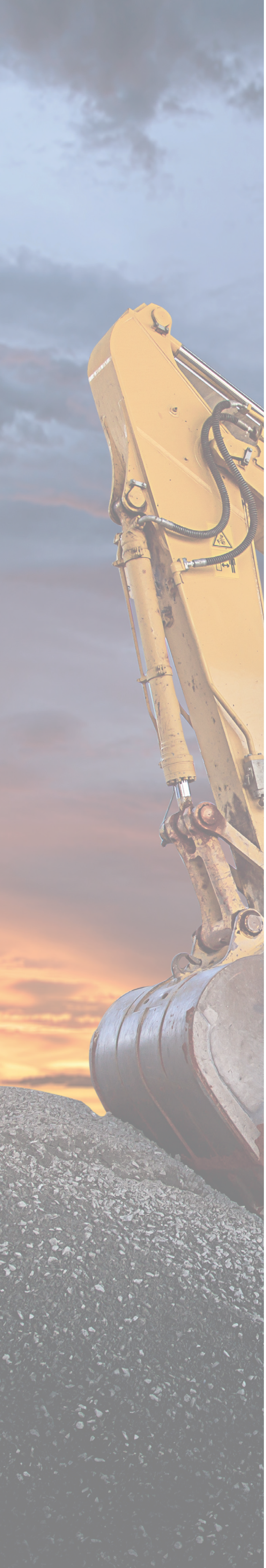
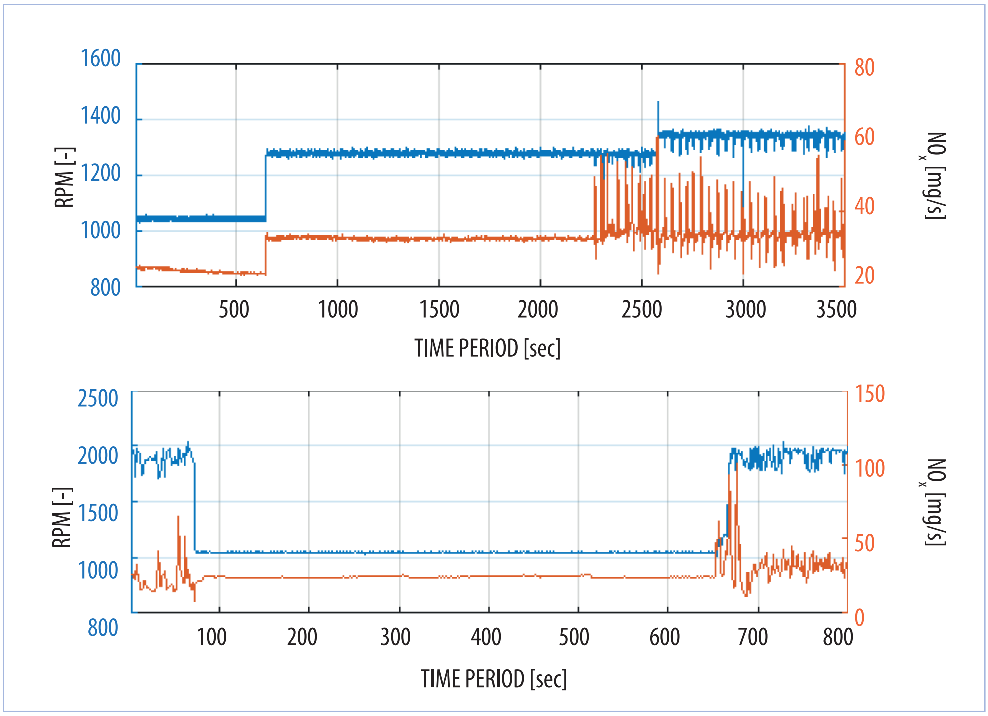
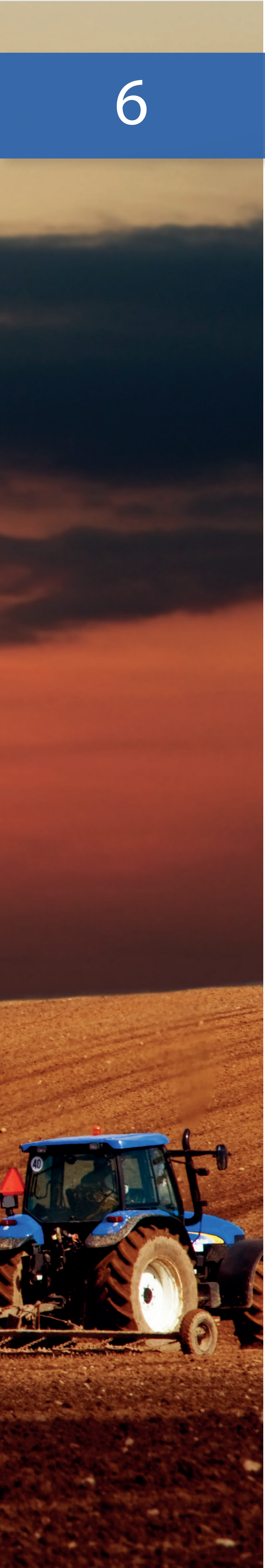


Figure 21:
NO_x emissions and associated speed over time.





6 Tractor

Although tractors are mainly thought of as agricultural vehicles, they are also used for earth-moving activities in the construction industry, for example. They represent one of the largest groups of machines in the Netherlands. The tractor that was monitored belonged to a contractor operating in the infrastructure and earth-moving sectors. This vehicle is subject to the Stage IV emissions requirements.

Tractor of the same type and model as the one measured during this project.
source: http://www.valtra.com/wwwresources/literature/com/N4_ENG_18092015.pdf

Type of machine	Tractor
Stage with which engine complies	Stage IV
Engine power	114 kW
Aftertreatment system	SCR

6.1 Summary of findings

The following findings were made while monitoring the tractor:

- This tractor spends a quarter of its time idling.
- The machine has to comply with the most rigorous Stage IV emissions requirements. On average, it does not meet these requirements at any engine speed in practice. While the Stage IV excavator complies with the emissions requirements at a high engine speed and high load, that is not the case with this Stage IV tractor.
- Its emissions increase proportionally (on the basis of fuel consumption) by a factor of ten at a lower engine load. The consequence of this is that the 25% of the time that the machine spends idling is also responsible for a similar percentage of its total NO_x emissions.

The key figures resulting from the measurement have been grouped together in Table 8. A more detailed discussion of the various aspects can be found in the following sections.

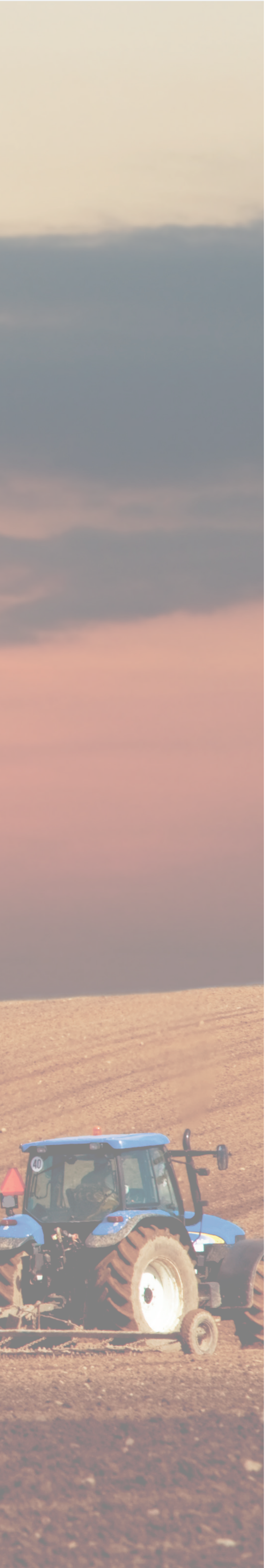


Table 8:
Key figures resulting from measurement of tractor.

Amount of data collected	44 hours
Time spent idling per hour	15 minutes/hour
Average CO_2 emissions per hour	30 kilograms/hour
Average NO_x emissions per hour	70 grams/hour
Average NO_x emissions during idling (~1,050 RPM)	64 grams/hour
Average NO_x emissions per kWh	1.8 grams/kWh

6.2 Results

1 Use

This machine spends a quarter of its time idling. During idling the engine speed is around 700 revolutions per minute. With this machine NO_x emissions are also highest at 1,600 RPM (associated with a dynamic engine load, or the speeding up of the engine).

2 NO_x emissions

The NO_x emissions during idling (see Figure 23 and Figure 24) account for a greater share of total NO_x emissions than was the case with the previous machine, as the specific emissions during idling are higher. In absolute terms the emissions are lower, as this is a smaller engine than that of the excavator discussed in the previous chapter.

The peaks in emissions at 1,000 and 1,600 RPM are due to the dynamic load on the engine. It operates at these speeds for only a limited proportion of the time, but the two peaks are clear enough to demonstrate the effect of a dynamic load. The NO_x emissions of this tractor will depend to a great extent on two aspects related to usage: the proportion of idling and the dynamics of the engine load. This is confirmed by looking at the signals for NO_x emissions in the event of variations in engine speed (see Figure 28). When the engine speeds up emissions are higher for a minute or more before the NO_x emissions stabilise around a lower value.

3 Ratio between NO_x emissions and CO_2 emissions

Figure 27 presents the ratio between the NO_x emissions and CO_2 emissions. As was the case with the other machines, this value decreases as engine speed increases. At around 1,900 RPM, the speed at which this machine operates for the majority of the time, the machine approaches the emission limit. The variations in NO_x/CO_2 emissions across the different speeds appear to be linked to the dynamic load.

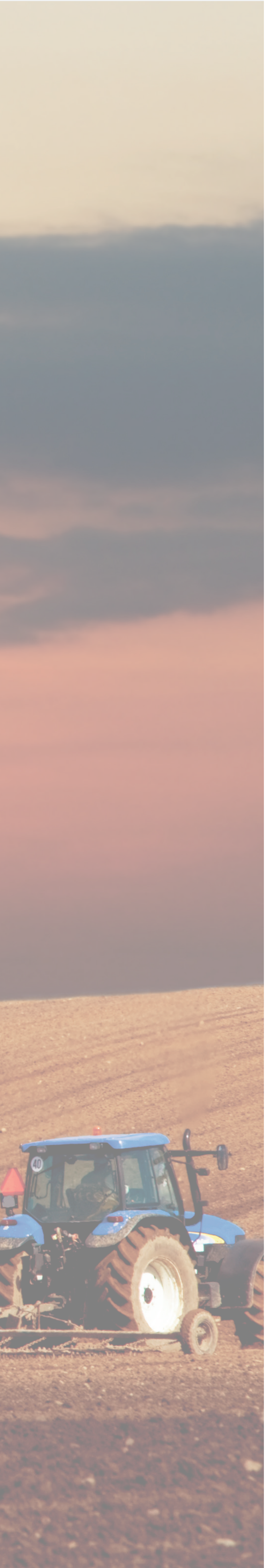


Figure 22:

Engine speed vs time. The total measurement period covers 44 hours. Over an average hour the tractor spends 75% of the time working (and 25% of the time idling).

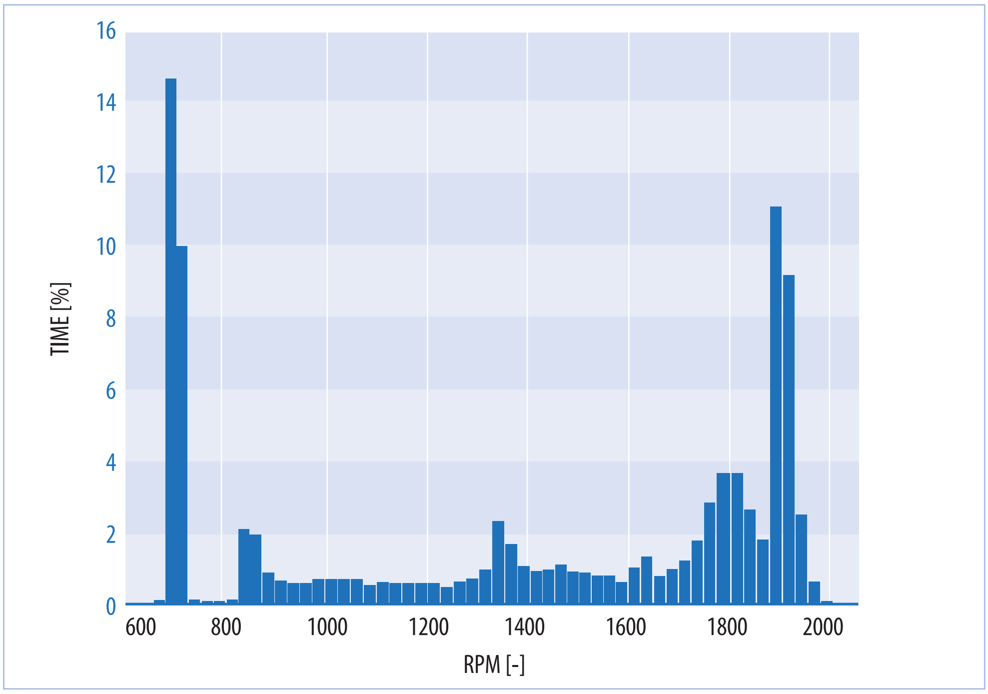
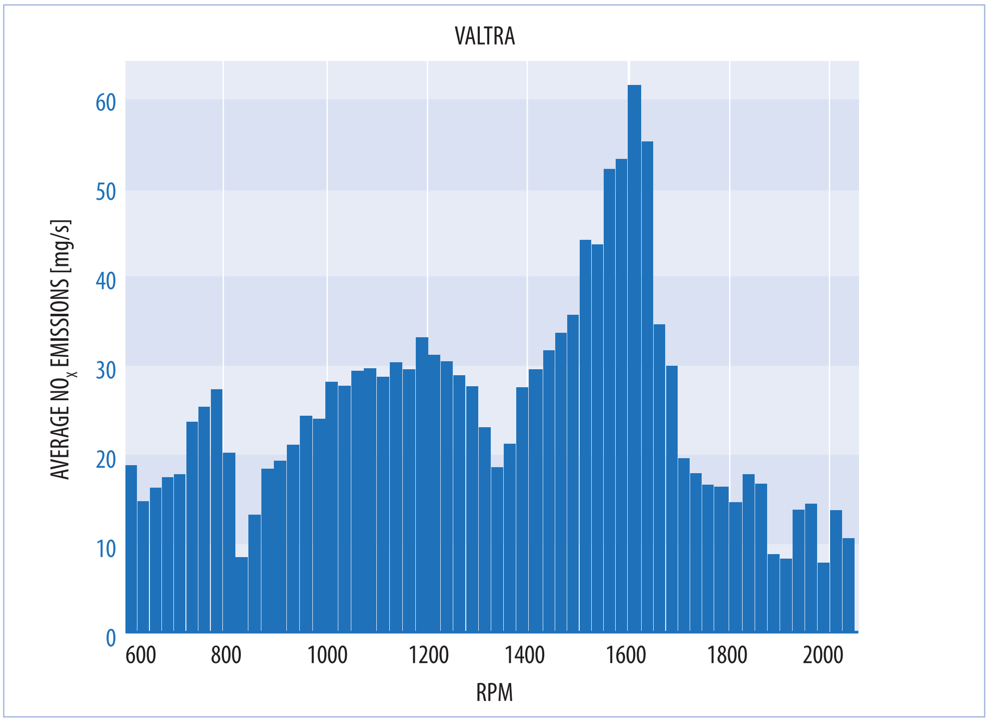


Figure 23:

Average NO_x emissions per RPM bin.



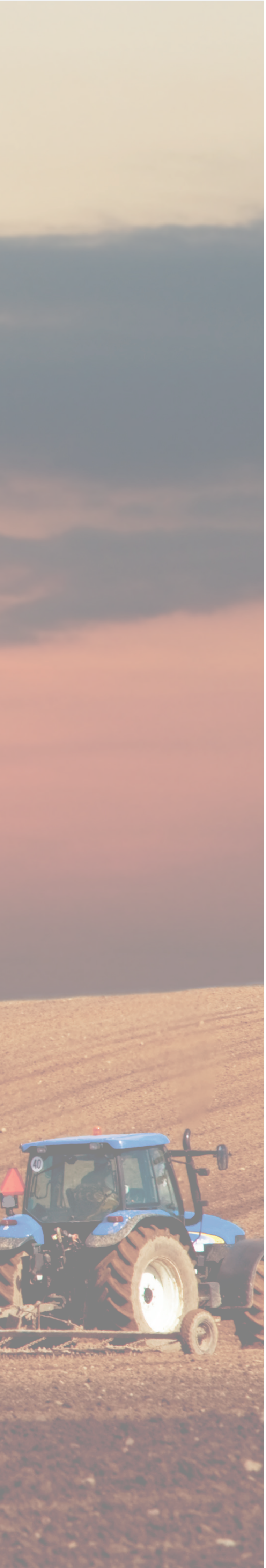


Figure 24:

NO_x emissions and cumulative NO_x emissions vs engine speed, for an average hour of operation. The total NO_x emissions per hour amount to an average of 70 grams.

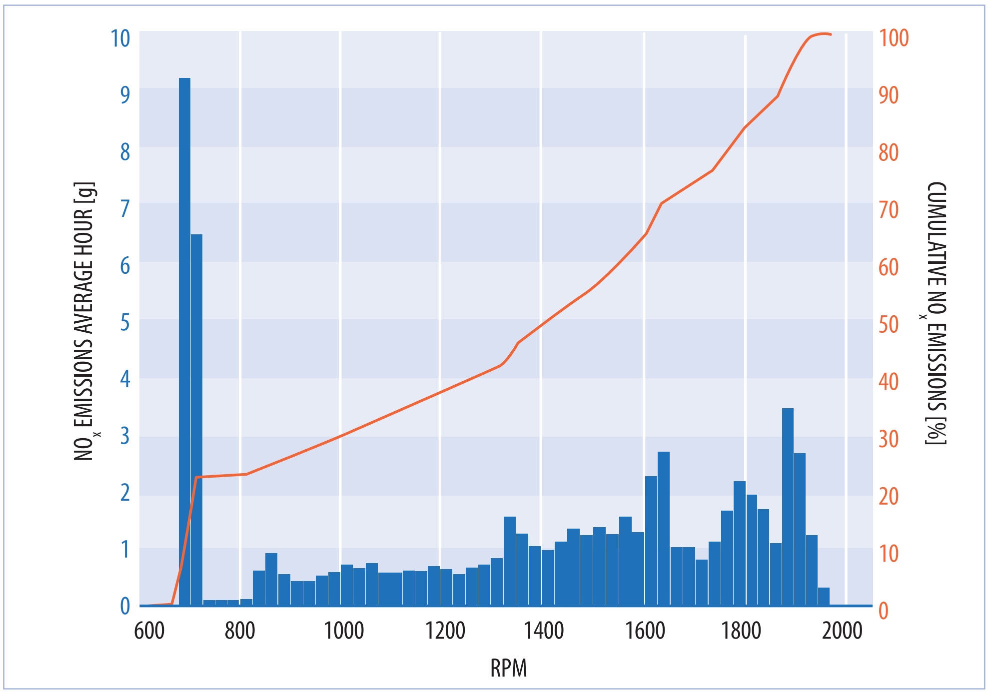
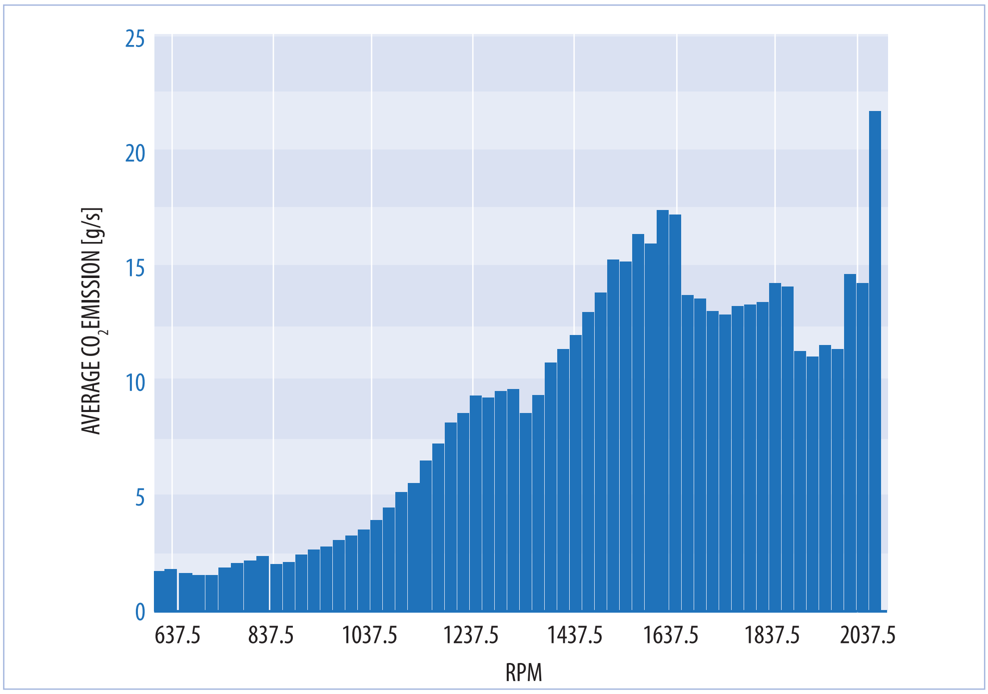


Figure 25:

Average CO_2 emissions per RPM bin.



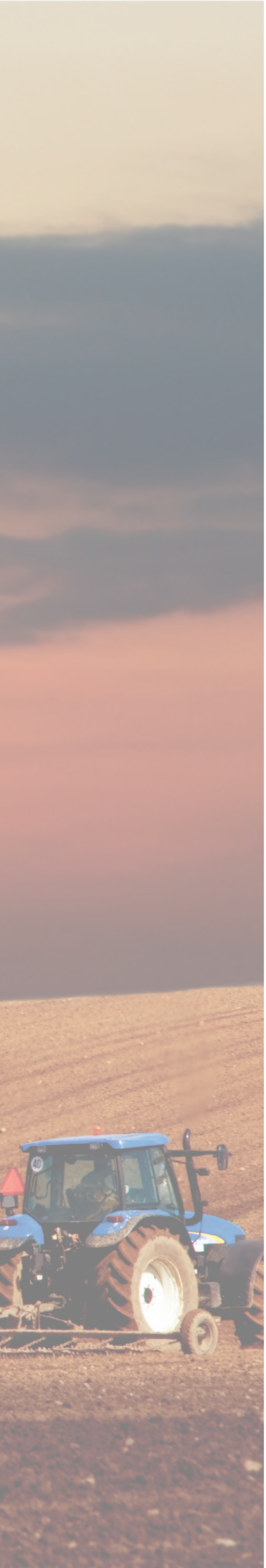


Figure 26:

CO_2 emissions and cumulative CO_2 emissions vs engine speed, for an average hour of operation. The total CO_2 emissions per hour amount to an average of 30 kilograms.

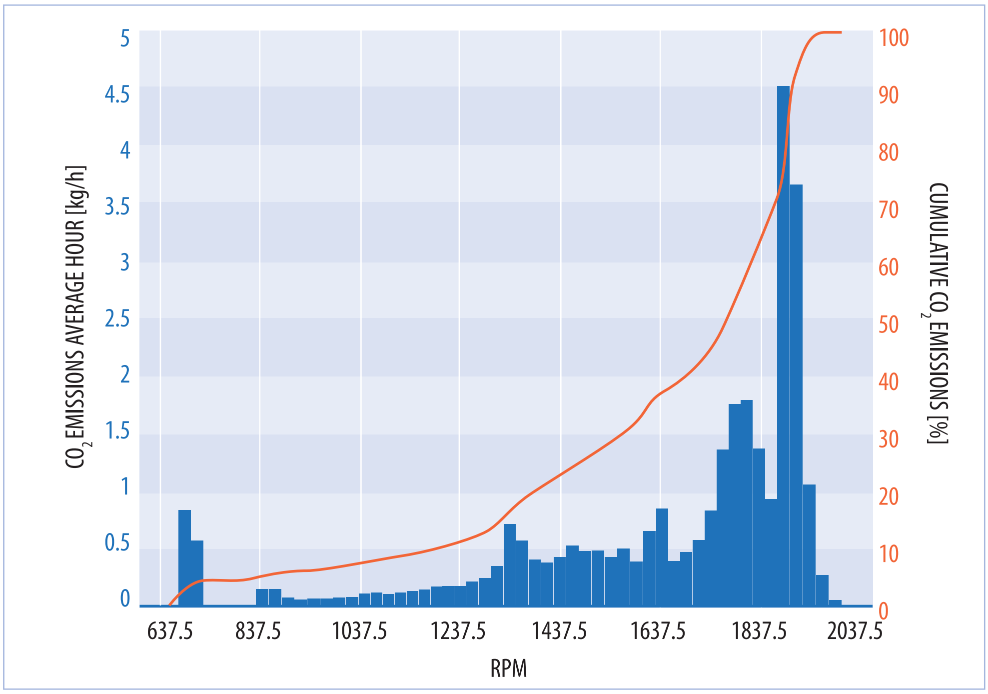
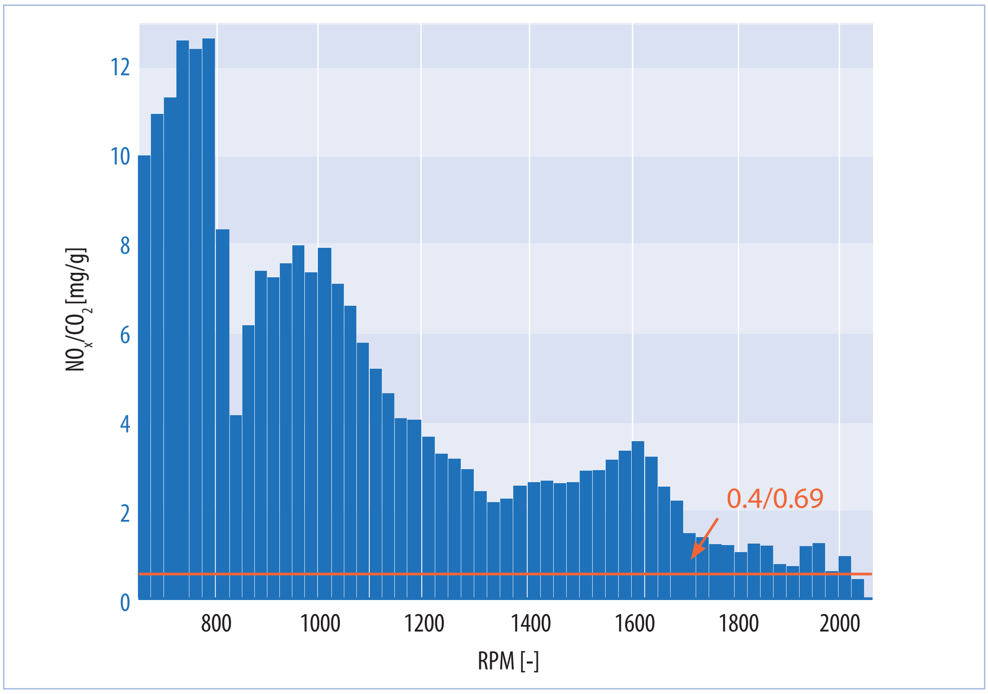


Figure 27:

Ratio between NO_x emissions and CO_2 emissions per RPM bin. The red line provides an indication of the NO_x limit on the totals emissions in the official laboratory test for this engine at a higher load: 0.4 g is the limit for NO_x emissions per kWh, while 0.69 kg is the figure for CO_2 emissions per kWh.



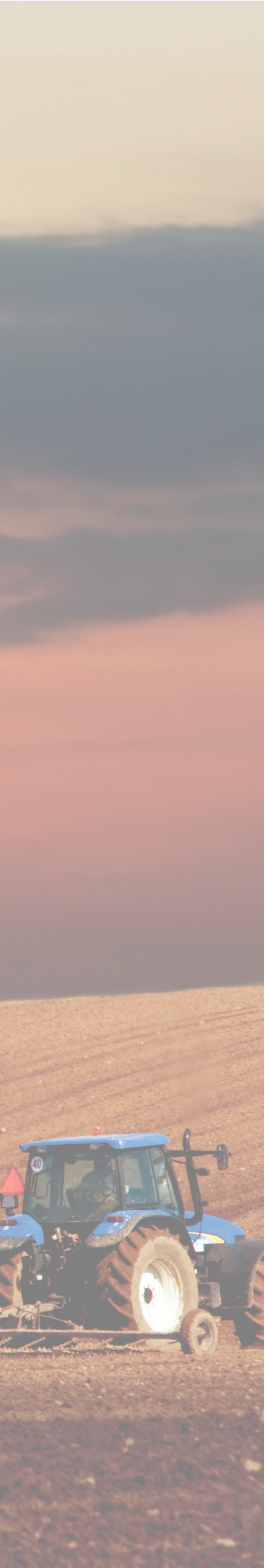
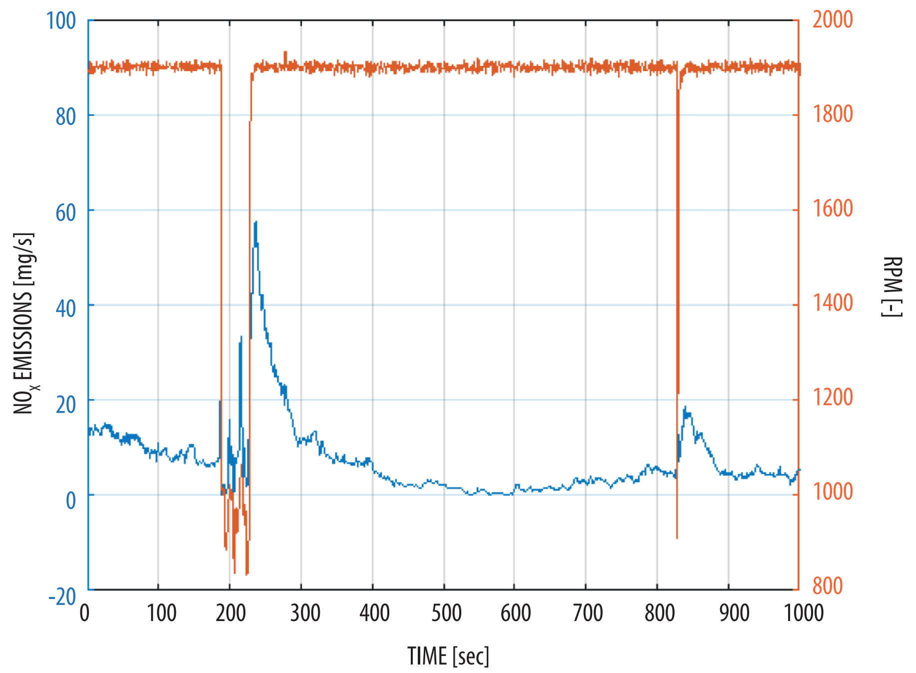


Figure 28:

The NO_x emissions and associated speed over time reveal that after the engine has been running at a low speed temporarily the NO_x emissions are then higher for several minutes.



7 Conclusions

The four machines selected represent groups that account for a large proportion of the total emissions from machines in the Netherlands. From the measurements performed on these machines over a number of weeks the following points emerge:

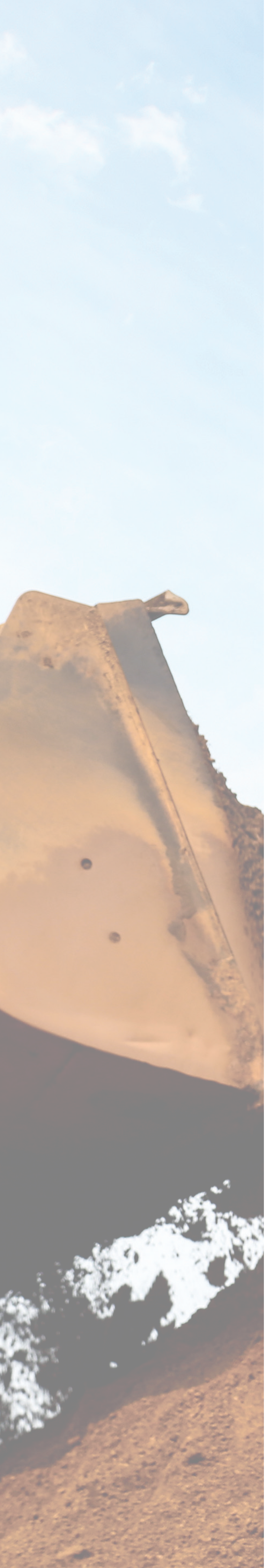
- The machines measured spend a significant proportion of their time idling: the share of idling varies between 18% and 57% of the total operating time.
- The machines emit a substantial portion of their total NO_x emissions during idling: 12% to 51% of the total NO_x emissions of these machines can be attributed to idling.

The construction machines were equipped with various emission control technologies. In the case of construction machines with the same emission control technology differences were nevertheless observed in terms of efficiency. The high emissions at a low load are a uniform problem that appears to become greater as the emissions requirements become more rigorous. This is probably due to the fact that low loads are of little importance when it comes to passing the laboratory type-approval test. The same phenomenon also applied for decades to HD vehicles (trucks and buses). In the Euro-VI legislation this was ultimately resolved by making the In-Service Conformity road test in normal traffic part of the type-approval test. However, idling also remains a critical factor for heavy duty vehicles. In addition, higher emissions during dynamic use - when the load on the engine varies - also appear to be a problem in some cases for NRMM.

Idling still accounts for a substantial share of fuel consumption, ranging from a few per cent to twenty per cent. Consequently, this study also provides a better insigh into how fuel can be saved and emissions reduced in a simple way. It is possible that there may be differences between one company and operator and another. A larger-scale study will be needed to identify these.

Legislation and practice

In practice, the average NO_x emissions of the four construction machines are higher than the emission limit of the controlled laboratory type-approval test. Although in the case of the stricter Stage IV limit the absolute emissions are lower than with the less rigorous Stage III B limit, the relative deviation from the limit is greater. It can therefore be stated that the emissions legislation is effective only to a limited degree when it comes to reducing NO_x emissions. Part of the deviation can be attributed to the use of these mobile machines in normal practice. Idling in particular contributes disproportionately to total NO_x emissions by comparison with the type-approval test. Reducing idling is therefore an effective measure that could cut the emissions of the current fleet of construction machines. This would also have a positive impact on CO_2 emissions and fuel consumption.



As highlighted by this study, it is important that normal usage is taken into account in the requirements included in the future legislation (Stage V). Machines are, of course, intended to be used to deliver power to carry out work. However, given that NO_x emissions are connected to a large extent with idling (during which no notable work is performed), it is important that the actual operating conditions are taken into account.

This is all the more relevant as in the case of the construction machines measured with the increasing share of NO_x emissions during idling increases from Stage III B to Stage IV.

Emission factors

The emission factors employed nationally for mobile machines could be adjusted on the basis of these figures. The emissions measured in practice for the four construction machines are higher than the level assumed to date on the basis of the statutory requirements. TNO therefore advises applying a greater increase to the limit than is currently the case. Increasing the current emission factors for NO_x by 30% above the emission limit for Stage III B and 60% above the emission limit for Stage IV would seem to be the minimum adjustment required. There is a good chance that this picture applies uniformly across all NRMM and is not unique to the construction machines measured.
A more fundamental point is that longer idling periods need to be taken into account for all these machines. The proportion of idling is high, but also shows a certain amount of variation. Data on operating hours, use and fuel consumption for a larger group of machines could allow the current findings on use to be better substantiated.

As the test procedure underestimates the amount of time that a machine spends idling, a period during which there can still be substantial NO_x emissions, the outcome of the test procedure is not directly representative of a machine's actual emissions. This means that the test procedure can no longer serve as a basis for the expected load profiles of a mobile machine. The test procedure depends on the legal class and the application. Up to and including Stage II the engine was only tested at constant speeds, typically from an engine load of 25%. From Stage III a dynamic test is also performed, although this again focuses on higher engine powers, while in many practical situations the average engine load does not even reach 25% of the rated power. This approach is related to the fact that the emission limit in g/kWh actually becomes stricter if the engine load is lower.

The current method of expressing emission factors in g/kWh is inadequate, as no power is delivered during idling. This could be taken into account by expressing the limits in terms of duration instead of in g/kWh; a formula such as that shown below would be more applicable:

$$NO_x \text{ [g]} = \text{idle emissions [g/h]} * \text{idle duration [h]} + \text{work emissions [g/kWh]} * \text{work [kWh]}$$

With data on total fuel consumption, the percentage of idling and the engine load under normal practical usage conditions, a representative emissions value could be determined in this way.

A Processing

Various parameters are available for the different construction machines to determine the mass flow and emissions. General information on the processing of SEMS is discussed in the article *A smart and robust NOx emission evaluation tool for the environmental screening of heavy-duty vehicles*[7]. The additional steps taken for the machines measured in this project are discussed below.

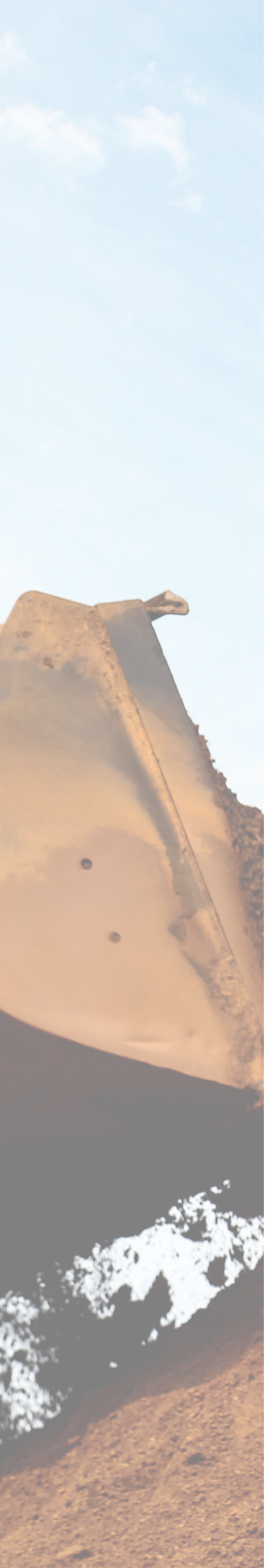
- **Processing 1**
  (applied to machine 1 - excavator, and machine 4 - tractor)
  The concentration of NO_x and the concentration of O_2 in the exhaust were measured directly using the SEMS sensors. The fuel consumption, engine speed and pressure and temperature at the engine inlet were determined by means of the machine's ECU (Engine Control Unit). With the help of this data the standard SEMS processing could be applied to determine the mass of the emissions resulting from, primarily, fuel consumption and the concentration of CO_2 in the exhaust gas.

- **Processing 2**
  (applied to machine 2 - loading shovel)
  The parameters monitored by SEMS were the same as those under processing 1: the concentration of NO_x/CO_2. The ECU was used to determine the engine speed, pressure and temperature, but unfortunately fuel consumption could not be read out. The following steps were followed to determine the mass of the emissions:

  1 By applying the ideal gas law, the gas density in the engine was determined.
  2 This density was combined with the engine speed, the cylinder capacity and the engine efficiency (for which a fixed value was used) to approximate the mass flow through the engine.
  3 The mass flow was corrected to take the increase in volume resulting from the chemical reactions in the cylinder into account. The correction value was dependent on the instantaneously measured O_2 concentration, which provides an indication of the amount of fuel consumed.
  4 The mass flow was corrected by a fixed factor to allow for the actual reduction in cylinder capacity due to the EGR and the filling of the cylinder with air.
  5 The mass flow and measured concentrations were then combined to determine the mass of the emissions.

- **Processing 3**
  (applied to machine 3 - excavator)
  For machine 3 the fuel consumption was again unavailable. In addition, there was no data on the pressure and temperature at the engine inlet; consequently, it was not possible to correct the density in the cylinder.

7 A smart and robust NOx emission evaluation tool for the environmental screening of heavy-duty vehicles, R.J. Vermeulen, N.E. Ligterink, W.A. Vonk, H.L. Baarbé (2012)



PROCESSING

In this case the mass flow was determined as follows:

1. The instantaneous power delivered by a machine was determined on the basis of the torque and engine speed.
2. By determining how the instantaneous power delivered and the CO_2 mass flow relate to the amount of fuel consumed, it is possible to estimate the amount of CO_2 released at a particular power.
3. The CO_2 concentration was determined using the steps described
4. in the article referred to above. By combining the CO_2 concentration with the CO_2 mass flow, it is possible to determine the total mass flow.
5. Combining this total mass flow with the measured NO_x concentration allows the NO_x mass flow to be established.

In a number of cases several processing methods were compared to allow the most robust and accurate method to be selected. Variations between the methods did not exceed 20%. The mass flow during idling is an especially critical aspect to which particular attention should be paid, especially in view of the outcomes of the study.

Topsector Logistiek

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TNO innovation for life

Connekt

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