Research Article

# Results of recurrent in-service exhaust gas measurements with an EU stage IV forest harvester fuelled with rapeseed oil within the emission durability period

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## Abstract

The real driving emissions of an EU stage IV forest harvester were measured four times within five years to monitor long-time emission behaviour. In this period, the harvester worked 7650 h in total, thereof 6300 h with pure rapeseed oil fuel DIN 51605 (R100) and 1350 h with conventional diesel fuel initially. Data analysis according to relevant EU regulation 2017/655 shows that the emission behaviour complies with the legal requirements of exhaust gas stage IV within the five years under consideration. According to EU regulation 2016/1628 the achieved 7650 operating hours nearly correspond to the emission durability period of 8000 h. However, between the single measurements some differences in emission results are clear evident. They are primarily caused by different working profiles, and unavoidable random events. Detailed analysis of the results showed that the measured nitrogen oxides ($NO_X$), carbon monoxide, and hydrocarbons remain at the same level over time at comparable operation conditions. Thus, the operation time had no major impact on the emission behaviour of the harvester. During cold start and non-working events higher nitrogen oxides ($NO_X$) concentrations are observed in the exhaust since the exhaust aftertreatment system is not within its operation temperature. When the exhaust gas aftertreatment is within its operating range, exhaust emissions are at a very low level indicating an efficient, clean combustion. It can be concluded that the operation of the harvester with R100 did not affect the emission behaviour and functionality of the exhaust gas aftertreatment system.

## Article Highlights

- Real driving emission measurements were performed four-times in five years
- Exhaust gas aftertreatment system still works reliably in practice after 7650 operating hours
- Rapeseed oil fuel does not impair the functionality and emission behaviour of the harvester

**Keywords** Real driving emissions · Non road mobile machinery · Biofuel · Pure plant oil fuel · Long-time emission behaviour

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## 1 Introduction

The exhaust gas emission behaviour of non-road mobile machinery (NRMM) is receiving more attention. In the European Union, the legal limit values for nitrogen oxides ($NO_X$). carbon monoxide (CO), hydrocarbons (HC), and particle emissions were reduced the last years [1, 2]. The compliance of the engines with the legal requirements is assured by engine test bed measurements within the type-approval process. Furthermore, since the implementation of exhaust gas stage V beginning at 2018, the emission behaviour of engines within the power size of 56 to 560 kW shall be monitored by testing engines installed in NRMM and operated during normal work. The test procedures for monitoring the engines installed in NRMM by using portable emission measurement systems (PEMS) are specified in the delegated EU regulation 2017/655 [3]. Hereby the moving averaging window method with extraction of non-working events is defined for data analysis, since it applies better to European NRMM operation cycles [4]. This method was developed with the target to identify if the engine would meet the emission limit when extracted from the machine [4]. The values from the real emission monitoring are used to prepare an in-service conformity testing process for NRMM [2]. In contrast to this, in the literature many results are reported with the scope to evaluate the real driving emission behaviour of machines in typical operation situations to assess their environmental impact.

Desouza et al. [5] researched 30 construction machines of nine different types, featuring EU exhaust gas stages IIIA, IIIB and IV. They observed that the $NO_X$ emissions are reduced with increasing exhaust stage. But they also had to recognize that six of nine stage IV machines had higher $NO_X$ emissions in real driving operation (including cold-start and idle operation) compared to the regulatory limit values. The reasons were mainly extended idling periods where the exhaust aftertreatment was not working efficiently. In general, studies have proved that the real driving emissions of NRMM show a large variability due to differences in engine load profiles for different types of work and idle times [5–8].

For machines with exhaust gas aftertreatment (EAT) systems including a DOC (diesel oxidation catalyst), SCR (selective catalytic reduction) and DPF (diesel particulate filter) low concentrations of $NO_X$, CO, HC and particulate number (PN) emissions can be recognized, when optimal operation conditions are reached [9]. But when the exhaust gas temperature is too low, e.g. at cold start or long idle phases, SCR system efficiency is very low resulting in higher emissions [5, 8, 10–12].

The emission behaviour of internal combustion engines can deteriorate over their lifetime, which was shown for passenger cars and heavy duty vehicles [13, 14]. For NRMM only less information can be found about changes in emission behaviour over lifetime. McCaffery et al. [15] researched small off-road diesel engines equipped with SCR and DPF systems and recognized no significant deterioration over a period of 1000 h. Measurements of a forestry harvester of EU exhaust stage IV with DOC, SCR and DPF during real work at 1300 and 3250 h did not indicate significant deterioration of the emission behaviour either [16]. For comparison, in EU regulation 2016/1628 [2] an emission durability period of 8000 h is defined for engines of ≥ 37 kW but for many machines much longer lifetimes are usual. For instance for forest harvesters an economic lifetime of 18,000 h can be assumed [17].

In the study of Desouza et al. [5] one of the EU exhaust gas stage IV engines had a failure of the SCR system where no warning was reported for the operator and high $NO_X$ emissions were recognised as a consequence. The proper functioning of the engine control and exhaust aftertreatment is of crucial importance to achieve the intended emission behaviour over the lifetime [18].

Most of available research on real driving emissions was conducted using fossil fuels like diesel or gasoline. But combustion of fossil fuels e.g. for transportation is one of the major sources of greenhouse gas emissions [19]. Alternative fuels and electric drives can be one solution among others to reduce greenhouse gas emissions. However, for NRMM with high power demand and working aside from recharging or refuelling infrastructure the implementation of battery-electric drives and gaseous fuels with low energy density is a huge challenge [9, 20, 21]. Liquid fuels with high-energy density used in internal combustion engines will therefore remain important for high power NRMM in many applications in the short- and mid-term [21–23]. For NRMM used in environmental sensitive areas like agriculture and forestry, the usage of alternative fuels like biofuels is a beneficial option to protect soil and water and to reduce greenhouse gas emissions [16, 24–26]. Pirjola et al. [27] researched the real driving emissions of an agricultural tractor (EU stage IV) equipped with DOC, SCR and DPF with hydrotreated vegetable oil and recognized 20% lower $NO_X$ emissions compared to diesel fuel. Ettl et al. [28] concluded for two EU stage IV tractors and Emberger et al. [16] for an EU stage IV forestry harvester, that the real driving $NO_X$ emissions during pure rapeseed oil fuel (R100) operation indicate that the engine emissions conform to the legal limit values.

For NRMM almost no information about the long-time real driving emission behaviour is available, when using alternative fuels. This study extends the results of the previous real driving emission measurements of an EU stage IV forestry harvester operated with R100 [16].

Target of this study is to analyse and discuss the emission behaviour of this machine using the renewable rapeseed oil fuel during five years of operation up to the end of the emission durability period of 8000 h. The results of the emission measurements are analysed and discussed in different ways, using the example of $NO_X$ emissions, to show the influence of the evaluation method on the result, but also the influence of certain operational events of the machine. The data will be analysed in comparison to the former data and conclusions about the change in emission behaviour shall be drawn.

## 2 Materials and methods

### 2.1 Test machine

For the research, a John Deere 1470G harvester was used. The technical details of the engine are listed in Table 1. The harvester was operated with diesel fuel from October 2016 to June 2017 for approximately 1350 h in total. Afterwards, the engine was modified for 100% R100 operation by the John Deere European Technology and Innovation Center, Kaiserslautern, Germany. Modifications were necessary since R100 has some different physical fuel properties compared to standard diesel fuel. Main differences between R100 and diesel fuel are the higher viscosity, surface tension, density, bulk modulus, and lower net calorific value as well as a different chemical structure to diesel fuel [29–32]. In Table 2 some of these fuel properties are shown. This leads to a different behaviour in the fuel injection system and to a different mixture preparation, ignition, and combustion in the engine [33–35].

For reaching the same cold-start and power performance with R100 as with diesel fuel some changes in the engine control unit and the low-pressure fuel system were made. Changes to the engine control unit software increased the injection rate to compensate for the slightly lower calorific value of R100. In addition, minor adjustments in the injection timing at some operating points were made. In the low-pressure fuel system, the series fuel feed pump was replaced by a more powerful one and some pressure control valves were installed to provide the fuel for the high-pressure pump at the required pressures. Since R100 begins to crystallise in the temperature range of +5 to –5 °C and the harvester is used all year round, all fuel-containing components were insulated or electrically heated or heated by the cooling fluid. In Fig. 1, the modified low-pressure fuel system is shown.

The exhaust gas aftertreatment (EAT) system consisting of a DOC, DPF and SCR as well as the regeneration strategy of the EAT remained in series configuration. The regeneration of the EAT is made by external dosing of diesel fuel in the exhaust pipe. The harvester is equipped with a park heating system, mainly to preheat the hydraulic system before engine start for preventing the machine from excessive wear due to cold hydraulic fluid. The park heating and regeneration system of the EAT were operated with a hydrotreated vegetable oil fuel (HVO) according to DIN EN 15940 until 2019 and with diesel fuel according to DIN EN 590 afterwards, because of limited availability of HVO on filling stations. The combustion engine itself was

**Table 2** Fuel properties of R100 and diesel fuel [30, 31]

| Property | Unit | R100 | Diesel fuel |
|---|---|---|---|
| Density at 15 °C | $kg\ m^{-3}$ | 920 | 835 |
| Kinematic viscosity at 40 °C | $mm^2\ s^{-1}$ | 35.5 | 2.31 |
| Net calorific value | $MJ\ kg^{-1}$ | 37.1 | 42.6 |
| Surface tension σ at 50 °C | $mN\ m^{-1}$ | 31.7 | 25.5 |
| Carbon | $kg\ kg^{-1}$ | 0.774 | 0.865 |
| Hydrogen | $kg\ kg^{-1}$ | 0.117 | 0.136 |
| Oxygen | $kg\ kg^{-1}$ | 0.109 | – |

**Table 1** Technical data of the diesel engine of the harvester

| Parameter | Value |
|---|---|
| Engine | John Deere<br>PowerTech Plus 6090 |
| Cylinder | 6 |
| Displacement in $dm^3$ | 9 |
| Rated power in kW | 200 |
| Rated speed in $min^{-1}$ | 2000 |
| Injection system | Common-Rail |
| Year of manufacture | 2016 |
| Exhaust gas stage | EU IV |
| Exhaust gas aftertreatment | Cooled, external exhaust gas recirculation, oxidation catalyst, diesel particle filter, selective catalytic reduction system |

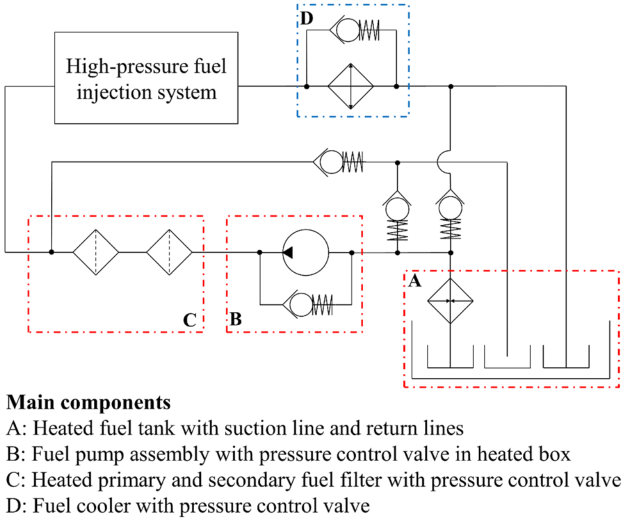


**Fig. 1** Scheme of the low-pressure fuel system of the harvester

operated with 100% R100. Further details about the modifications are reported in Emberger et al. [16].

## 2.2 Fuels

Before modification of the engine for R100 operation, diesel fuel according to DIN EN 590 [36] was used and later R100 originating from a small-scale oil mill in Bavaria using cold pressing technology. The R100 fulfilled the requirements of DIN 51605 [37]. According to the standard only low content of contaminants like sulphur ($< 10$ mg kg$^{-1}$), phosphor ($< 3$ mg kg$^{-1}$), potassium ($< 1$ mg kg$^{-1}$) and magnesium ($< 1$ mg kg$^{-1}$) are allowed, which is basis for a failure free operation of the engine and EAT. Furthermore, the "John Deere Fuel-Protect Diesel Conditioner Winter" was added at a concentration of 0.001 m$^3$ m$^{-3}$. The additive was used precautionary to inhibit potential fuel deposition in the high-pressure fuel injection system of R100. Deposits in the high-pressure fuel injection system have also been observed for diesel fuel [38] and such kind of additives are mostly included in standard diesel fuel.

## 2.3 Emission measurement

The real driving emission measurements were performed using a Semtech® Ecostar portable emission measurement system (PEMS) from Sensors Inc., USA. The PEMS fulfils the requirements of UN-ECE R-49 [39]. Table 3 shows some technical information about the gas analysers of the measurement equipment. Additionally, at 7650 operation hours the particle number concentration was measured using a Semtech® CPN condensation particle counter. The minimum particle size of detection is 23 nm ($d_{50}$). The PEMS was in a protective box with an autonomous power supply that was installed in the rear of the harvester. The measurement set up is shown in Fig. 2.

The measurement data were analysed using EMROAD 6.03 B3 of the Joint Research Centre, according to EU 2017/655 [3] and applying the work-based method for the pollutant emissions calculation of the moving averaging windows (MAW). Engine work was calculated using actual percent torque, friction torque and reference engine torque provided by the CAN data of the harvester. The engine's full torque curve for diesel and R100 operations were provided by John Deere.

The non-road transient cycle (NRTC) reference work of the installed engine is 24 kWh for diesel and R100

**Fig. 2** John Deere 1470G harvester with installed PEMS at the rear

**Table 3** Technical data of the gas analysers of the PEMS

| Parameter | Measurement principle | Measurement range | Accuracy |
|---|---|---|---|
| Nitrogen monoxide | Non-dispersive ultraviolet analyser | 0–3,000 ppm | < ± 2% of reading or<br>< ± 0.3% of measurement range |
| Nitrogen dioxide | | 0–1,000 ppm | |
| Carbon monoxide (CO) | Non-dispersive infrared analyser | 0–8% by vol | < ± 2% of reading or<br>< ± 50 ppm by vol |
| Carbon dioxide | | 0–18% by vol | < ± 2% of reading or<br>< ± 0.1% by vol |
| Hydrocarbons (HC) | Flame-ionisation detector | 0–100 ppm $C_1$<br>0–30,000 ppm $C_1$ | < ± 2% of reading or<br>< ± 0.3% of selected range |

operation. In accordance with EU 2017/655, the analysed test duration was six times as long as the work of the NRTC that was performed, beginning from the engine start. The data analysis was conducted in two ways: in the first case, cold-start and non-working events were identified and excluded from the emission calculation as specified in EU 2017/655; for the second case, all recorded data were used for the emission calculation and no data were excluded. The results are shown using the frequency distribution of the work-based emissions of every valid averaging window.

Since diesel fuel and R100 are characterised by different elementary composition specific molar fuel ratios were used for data analysis, as shown in Table 4.

In 2017 the real driving emissions of the harvester were measured with diesel fuel at 1300 h of operation before the modifications to the R100 operation were made. The emission measurements with R100 were performed immediately after the modifications at 1350 h in 2017. From that point, the harvester engine was solely operated with R100. Further measurements were made in 2018 at 3250 h and 2021 at 7650 h. Every measurement was repeated four times (two cold-starts and two hot-starts after a break), using the same two professional drivers in the same operational forest area. The two machine operators have been working with the R100 harvester since 2016, partly in two-shift operation, so that both can operate the machine with similar efficiency, and an influence of the machine operator can be largely excluded in this study. However, it should be mentioned that real driving emission measurements cannot be performed under fully repeatable ambient and operation conditions, especially when some years are between the measurements.

**Table 4** Fuel specific input data for emission calculation using EMROAD 6.03 B3

| Parameter | Diesel fuel | R100 |
|---|---|---|
| C content in g $g^{-1}$ | 0.855 | 0.775 |
| H content in g $g^{-1}$ | 0.135 | 0.116 |
| O content in g $g^{-1}$ | – | 0.109 |
| β in mol $mol^{-1}$ | 1.00 | 1.00 |
| α in mol $mol^{-1}$ | 1.85 | 1.78 |
| ε in mol $mol^{-1}$ | – | 0.11 |
| Density (15 °C) kg $m^{-3}$ | 0.84 | 0.92 |

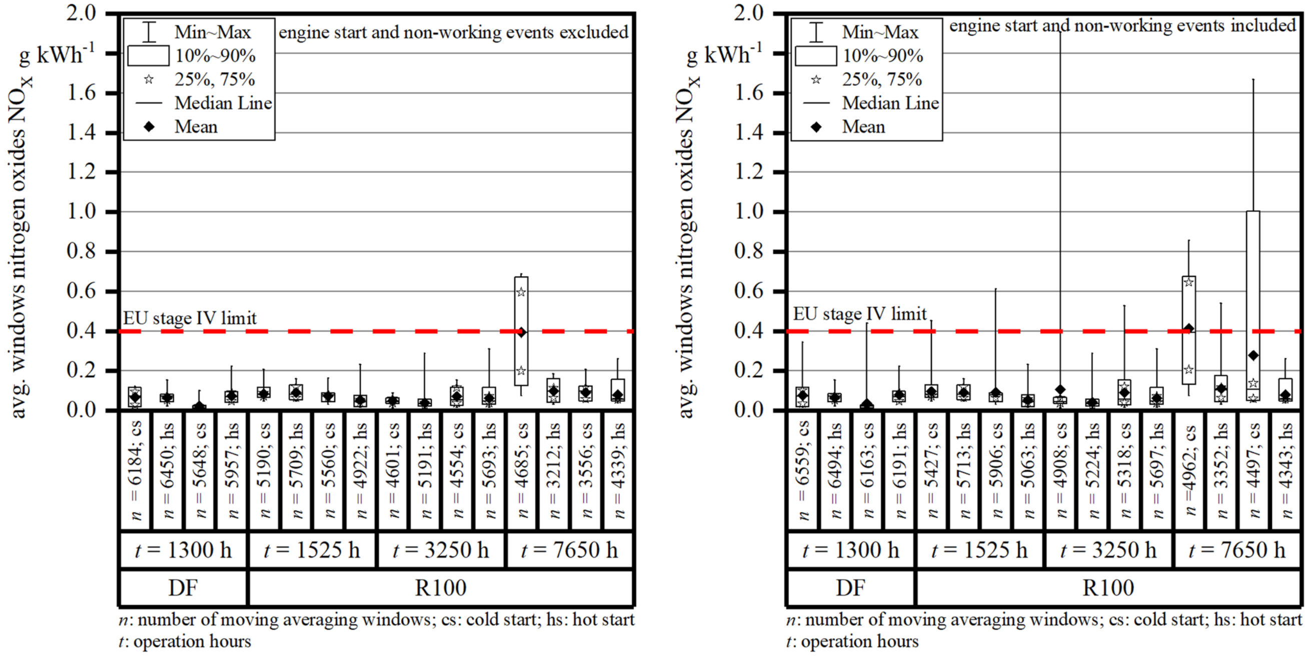
β: molar ratio of C related to C; α: molar ratio of H related to C; ε: molar ratio of O related to C

## 3 Results

### 3.1 Averaging windows emissions

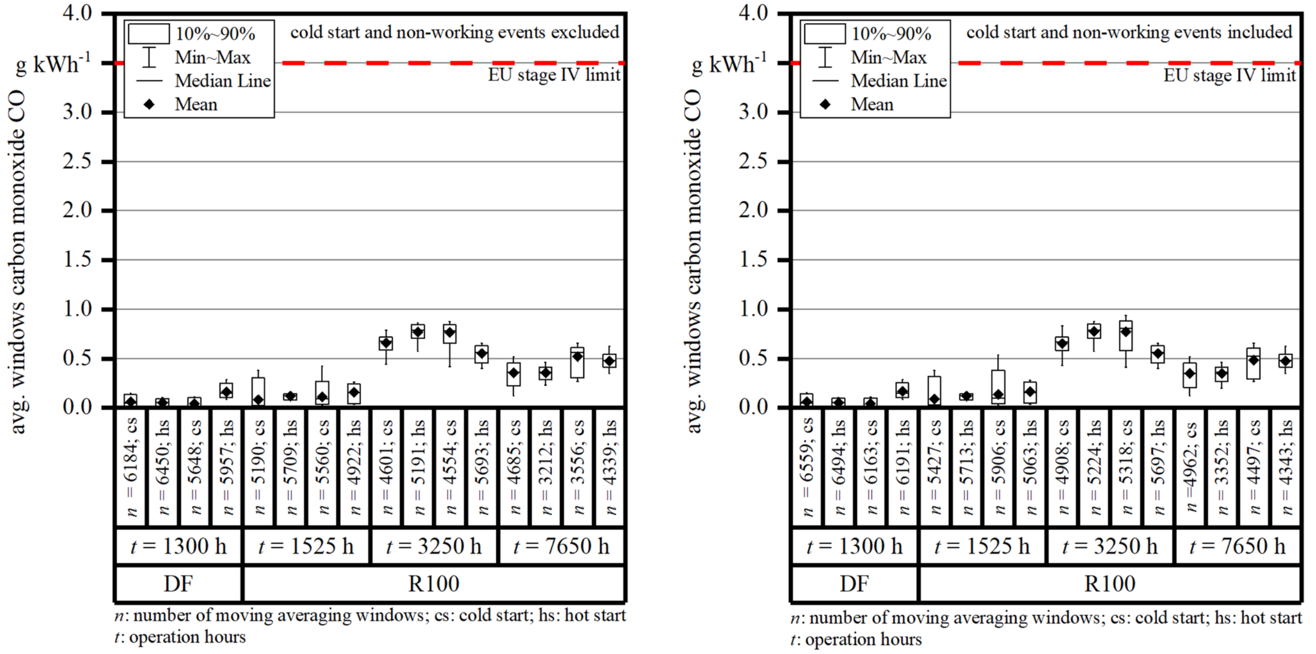
The results of the nitrogen oxides ($NO_X$) emissions during real driving operations are shown in Fig. 3, using the frequency distribution of the work-based emissions of the moving averaging windows. The results on the left-hand side are shown excluding the cold start and non-working events. Except for one measurement at 7650 h, the $NO_X$ emissions of all averaging windows were far below 0.4 g $kWh^{-1}$, which is the legal limit value of the EU exhaust gas stage IV for the type approval measurements on the engine test bench. For these measurements the 90th percentiles of the averaging windows NOX were even below 0.2 g $kWh^{-1}$ and the maximum value of a single averaging window was not higher than 0.31 g $kWh^{-1}$. However, for the first measurement at 7650 h the mean of the averaging windows $NO_X$ emissions was 0.4 g $kWh^{-1}$ ranging from 0.13 to 0.67 g $kWh^{-1}$ from the 10th to 90th percentiles. For this single measurement higher emissions were detected compared to the other measurements, which will be discussed later. When the complete measurement data is analysed including cold starts and non-working events (right side of Fig. 3) for most of the measurements the average and 90th percentile of the averaging window $NO_X$ emissions are similar to the values where the exclusions were made (left side of Fig. 3). For the measurements performed including a cold start, the maximum $NO_X$ emissions were higher because at cold start and engine warm up the exhaust after treatment is not within its operation temperature. For the measurements, conducted with hot start even the maximum averaging windows $NO_X$ emissions were in the same range as for the results with the engine start excluded. Only for the first hot start measurement at 7650 h a higher $NO_X$ maximum was observed. The reason for this was a longer break in harvester operation, in this case for maintenance of the harvesting head, which caused the engine to cool down to a coolant temperature of 52 °C in comparison to 71 to 79 °C for all other hot start measurements. This indicates that real driving emission results are influenced by the machine operator and coincidental events affecting the optimal operation conditions of the exhaust gas aftertreatment.

The averaging windows carbon monoxide (CO) emissions were always on a low level below 0.93 g $kWh^{-1}$ (Fig. 4), which is much lower than the EU stage IV test bench limit value of 3.5 g $kWh^{-1}$. Between the data analysis with engine start and non-working events included and excluded no relevant differences are recognised.



*n*: number of moving averaging windows; cs: cold start; hs: hot start
*t*: operation hours

**Fig. 3** Frequency distribution of averaging windows $NO_X$ emissions for diesel and R100 operation (engine start and non-working events according to EU 2017/655 excluded (left) and included (right))



*n*: number of moving averaging windows; cs: cold start; hs: hot start
*t*: operation hours

**Fig. 4** Frequency distribution of averaging windows CO emissions for diesel and R100 operation (engine start and non-working events according to EU 2017/655 excluded (left) and included (right))

The highest mean CO emissions of 0.77 g kWh$^{-1}$ were observed during the measurements at 3250 h, at 7650 h the mean was 0.48 g kWh$^{-1}$.

In Fig. 5 the frequency distributions of HC emissions are shown. The average values and the 90th percentiles were always below the EU stage IV limit value of 0.19 g kWh$^{-1}$. In the second measurement period, which was the first one with R100, significant higher HC emissions were observed. As described in [16], the emissions were caused by a faulty setting of

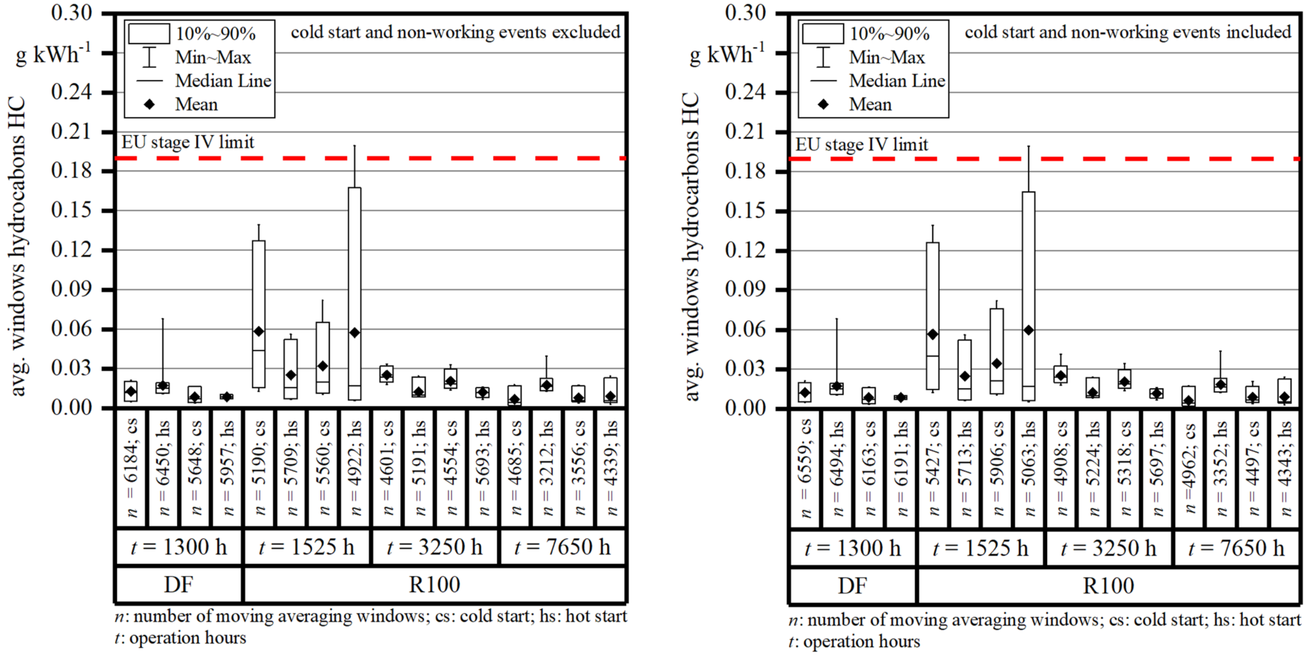


**Fig. 5** Frequency distribution of averaging windows HC emissions for diesel and R100 operation (engine start and non-working events according to EU 2017/655 excluded (left) and included (right))

the fuel injection nozzle for EAT regeneration during the modification to R100 operation. The diesel fuel amount for flushing the injector regularly after a certain time to prevent the nozzle from sticking was too high. This caused, high peaks of HC concentrations in the exhaust that led to the reported higher HC emissions. After the failure was detected and corrected the emissions were on the same low level as before the modifications were made. Excluding this measurement period, the maximum averaging windows HC emissions of 0.07 g kWh$^{-1}$ were observed during the first measurements with diesel fuel. The highest 90th percentile value for HC emission was 0.03 g kWh$^{-1}$ at 3250 operating hours. Since there was no deterioration recognisable, the results indicate that the oxidation catalyst has been working effectively over the entire investigation period to reduce CO and HC emissions.

The particle number (PN) emissions were only measured at 7650 h. The frequency distributions of the averaging windows PN results are shown in Fig. 6. In general, PN emissions were at a very low level $< 0.07 \times 10^{12}$ kWh$^{-1}$, independent from the type of analysis with or without exclusion of engine start or non-working events. The stage IV engine already fulfilled the requirements of stage V, where a PN limit of $1.0 \times 10^{12}$ kWh$^{-1}$ is defined. This proves that the diesel particle filter is still working properly after 7650 h of engine operation and 6250 h thereof with R100 as fuel. The results also show that according to DIN 51605 for R100 the defined limit values for the ash building elements P, Ca, and Mg are appropriate for a long-time operation of the applied exhaust gas aftertreatment system.

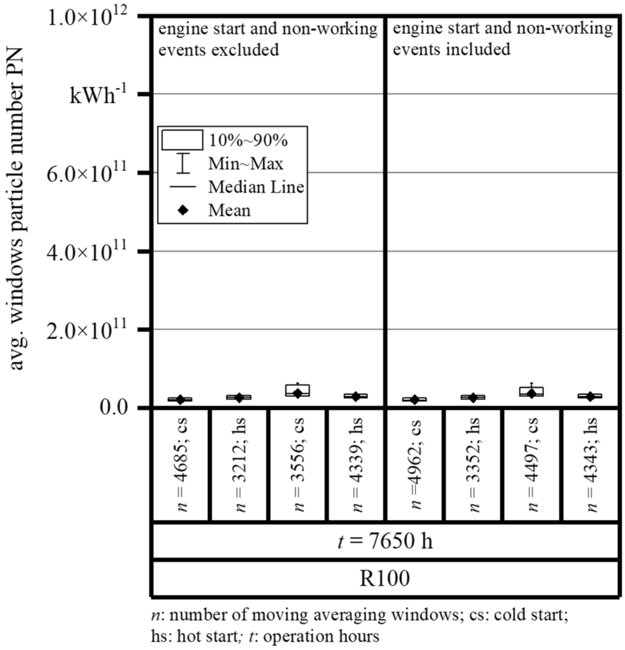


**Fig. 6** Frequency distribution of PN emissions of the moving averaging windows for diesel and R100 operation (engine start and non-working events according to EU 2017/655 excluded (left) and included (right))

### 3.2 $NO_X$ emission comparison between selected single measurements

Noticeable, the $NO_X$ emission behaviour within the last measurement period was different from the previous ones and therefore a more detailed analysis and discussion of the measurement data is provided in this section to clarify the reasons for these results.

Figure 7 shows detailed data on engine speed, relative power, averaging windows power, exhaust temperature, $NO_X$ concentration in the exhaust and averaging windows $NO_X$ emissions of the harvester, fuelled with R100 at 1525 and 7650 h of operation for the first measurement of the campaign each. The data is shown from the beginning of the measurement until 144 kWh of work were done, which took 6758 s at 1525 h and 5565 s at 7650 h. No data was excluded for averaging windows analysis. The measurements were differing in engine speed and load profiles. The measurement at 1525 h is characterised by a quite constant speed and average power during the measurement, whereas at 7650 h a higher share of low speed and low load segments was recognised. However, at 7650 h mean relative engine power and mean averaging windows power were higher compared to the measurement at 1525 h. At 1525 h the harvester was used for thinning and therefore had to cut smaller trees than at 7650 h where mature trees were logged. Furthermore at 7650 h an unplanned maintenance of the harvesting head was necessary with the engine running and some shorter logging stops because of persons working in the danger area of the harvester. But even with those interruptions with a mean averaging windows power of 47% at 7650 h versus 38% at 1525 h the 144 kWh of work were completed 1193 s faster at 7650 h resulting in 465 less averaging windows. Since every second a new averaging window is created the shorter measurement time has an impact on the frequency distribution of the averaging windows emission results. Another important difference between

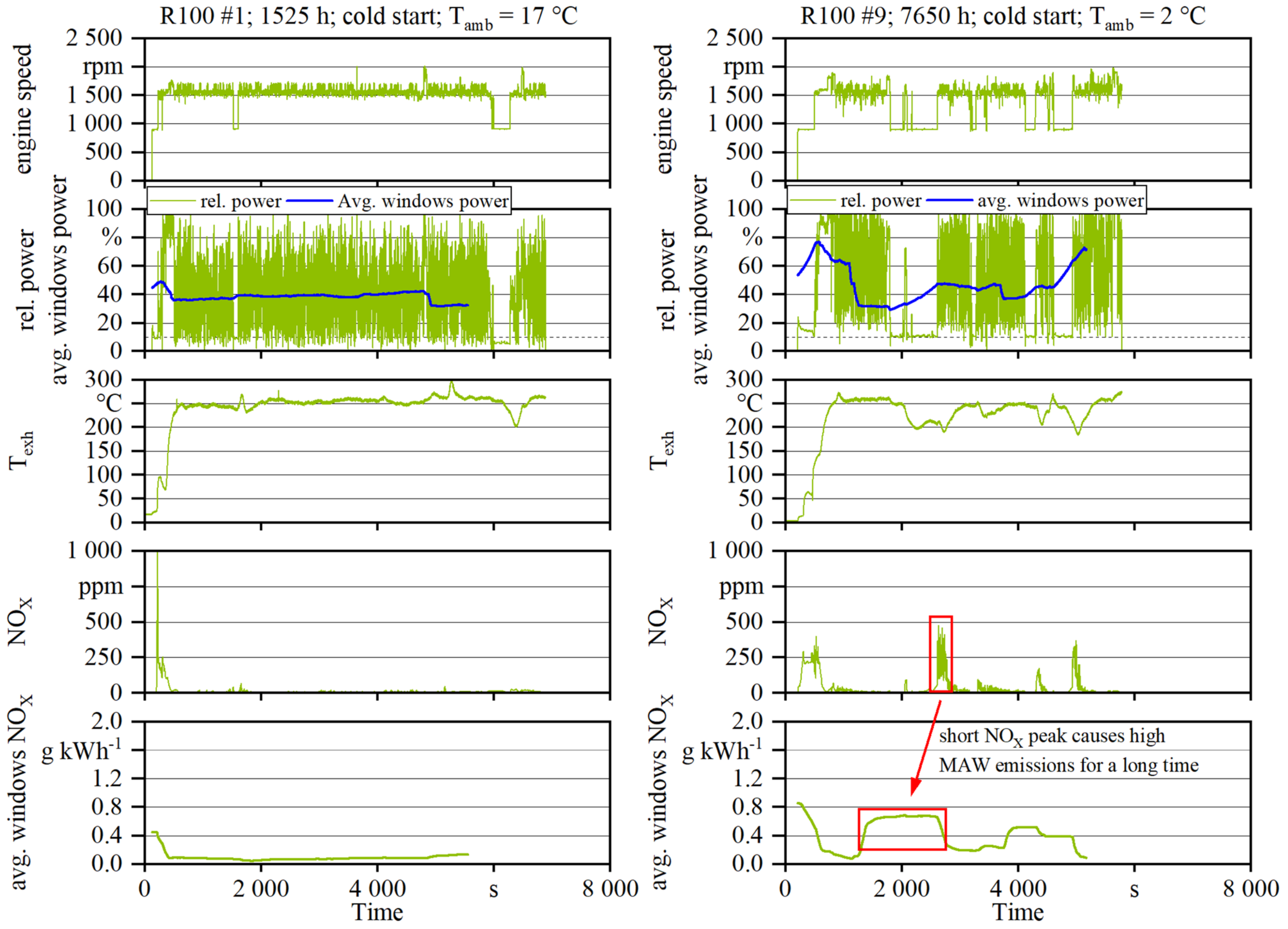


**Fig. 7** Detailed data on engine speed, relative power, averaging windows power, exhaust temperature, $NO_X$ concentration in the exhaust and averaging windows $NO_X$ emissions in R100 operation at 1525 and 7650 operation hours (cold start, first measurement of the campaign each)

the measurements is the power at idle. For MAW calculation with exclusion of non-working events (shown in left chart in Fig. 3), the power limit for non-working events is at 10% of maximum power. At 1525 h at the end of the measurement the machine was in idle below the 10% threshold, whereas at 7650 h it was slightly above. Reasons for this observation could be differences in power requirements during idle caused for example by different auxiliary settings, component deterioration or environmental conditions. The consequence is that at 7650 h the long machine idle phases were not excluded in data analysis according to EU 2017/655.

A comparison of the tailpipe exhaust gas temperature shows, that at 1525 h the temperature was constant at 250 °C for a long time, whereas at 7650 h it fell several times down to around 200 °C for a longer time because of the work interruptions. Consequently, the SCR system was deactivated since the exhaust temperature was outside of the operation mode of the catalyst and with a time delay the $NO_X$ concentration in the exhaust was rising. Altogether there were four major peaks in $NO_X$ concentration at the 7650 h measurement and only one at 1525 h caused by the cold start.

These peaks in $NO_X$ concentration in the exhaust cause all averaging windows where the peaks are included to be above 0.4 g $kWh^{-1}$ $NO_X$ at 7650 h. Since the power was slightly above the threshold no data was excluded for averaging window calculation according to EU 2017/655, except for cold start. Furthermore, since only less work was done during idle the averaging windows were longer to reach the 24 kWh (NRTC reference work) and there were more windows, that include the peaks.

The detailed results of the third measurements at 1525 and 7650 h are shown in Fig. 8 and again a different operation profile of the machine can be recognised. At the third measurement at 7650 h the harvester was in idle mode for more than 15 min after engine start. The exhaust temperature was increasing slowly during this period. Because of

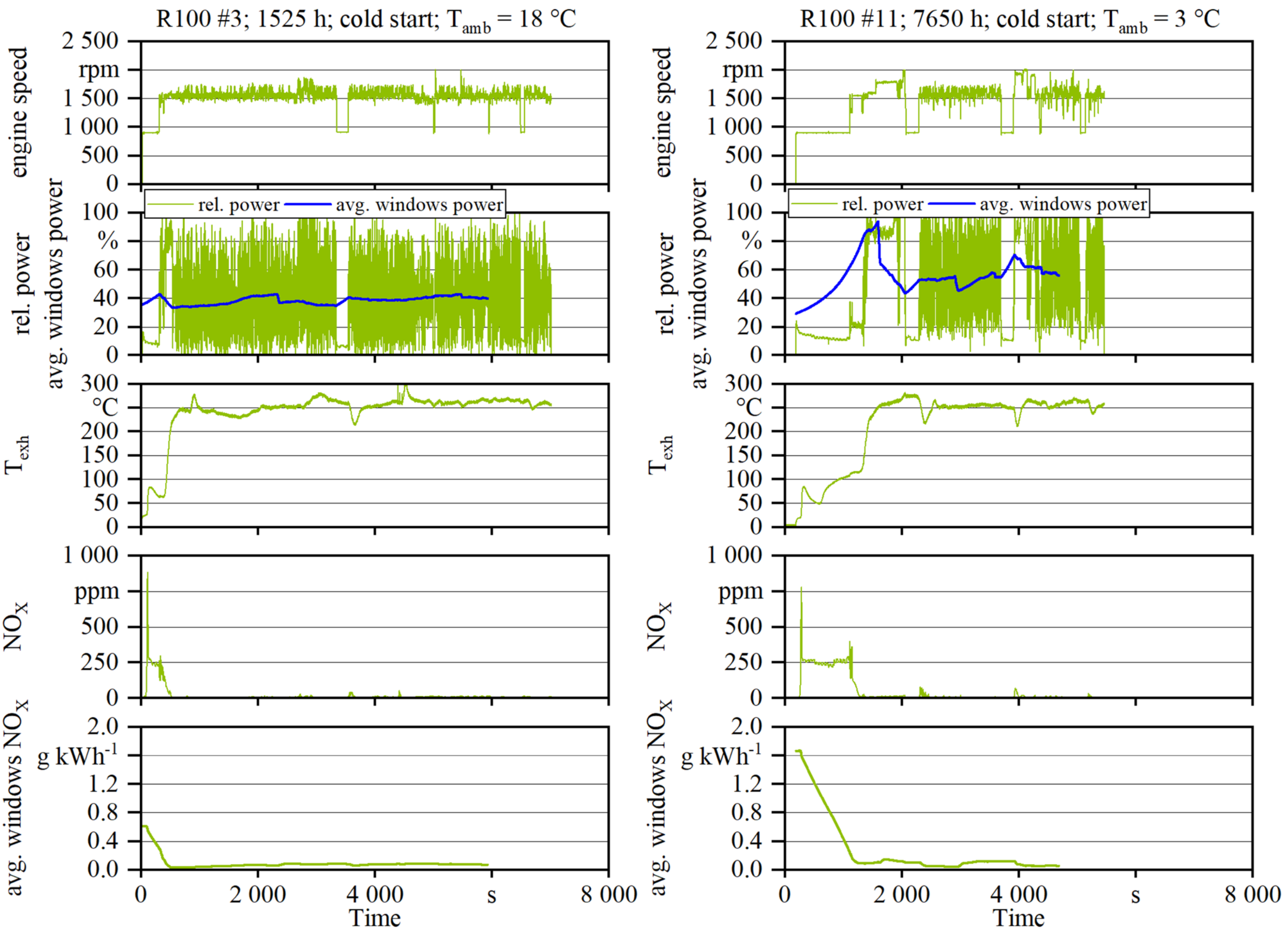


**Fig. 8** Detailed data on engine speed, relative power, averaging windows power, exhaust temperature, $NO_X$ concentration in the exhaust and averaging windows $NO_X$ emissions in R100 operation at 1525 and 7650 operation hours (cold start, third measurement of the campaign each)

the long idle mode many averaging windows include the cold start $NO_X$ peak. When the harvester is beginning to work, the exhaust temperature is beginning to rise quickly and the $NO_X$ concentration in the exhaust is falling close to zero. In contrast to the first measurement at 7650 h the workflow of the harvester had only short interruptions, the exhaust temperature was quite constant and the $NO_X$ concentrations and averaging windows $NO_X$ emissions remained at a low level comparable to the measurement at 1525 h. Since the cold start emissions are excluded in data analysis according to EU 2017/655, the impact of this long idle phase is not observable (left chart in Fig. 3).

Detailed data for the two hot start measurements at 1525 and 7650 h are shown in Figs. 9 and 10. Main differences in the operation profiles of the harvester are the higher average MAW load and the colder ambient temperature at 7650 h. But since no major workflow interruptions were recognized at any of these measurements the EAT is activated quickly and the MAW $NO_X$ emissions are at a very low level.

For an assessment, if the engine emissions underly a significant deteriorating over time two operation areas can be taken. The first one close after the cold start, before the exhaust temperature is rising up to a level, where the EAT is activated. After a very short first peak the $NO_X$ concentration in the exhaust stay at a level of about 250 ppm until the EAT is activated. This was observed for all cold start measurements, independent of the operation hours. This indicates that the $NO_X$ reduction measures like exhaust gas recirculation are still working at operation points without EAT and there are no major deposits in the exhaust gas recirculation path affecting its efficiency. The second operation area for the assessment is, when the exhaust temperature is high and the EAT is working. For this operation points the $NO_X$ concentration in the exhaust is reduced to a level of almost zero for all measurements. This suggests, that the EAT has

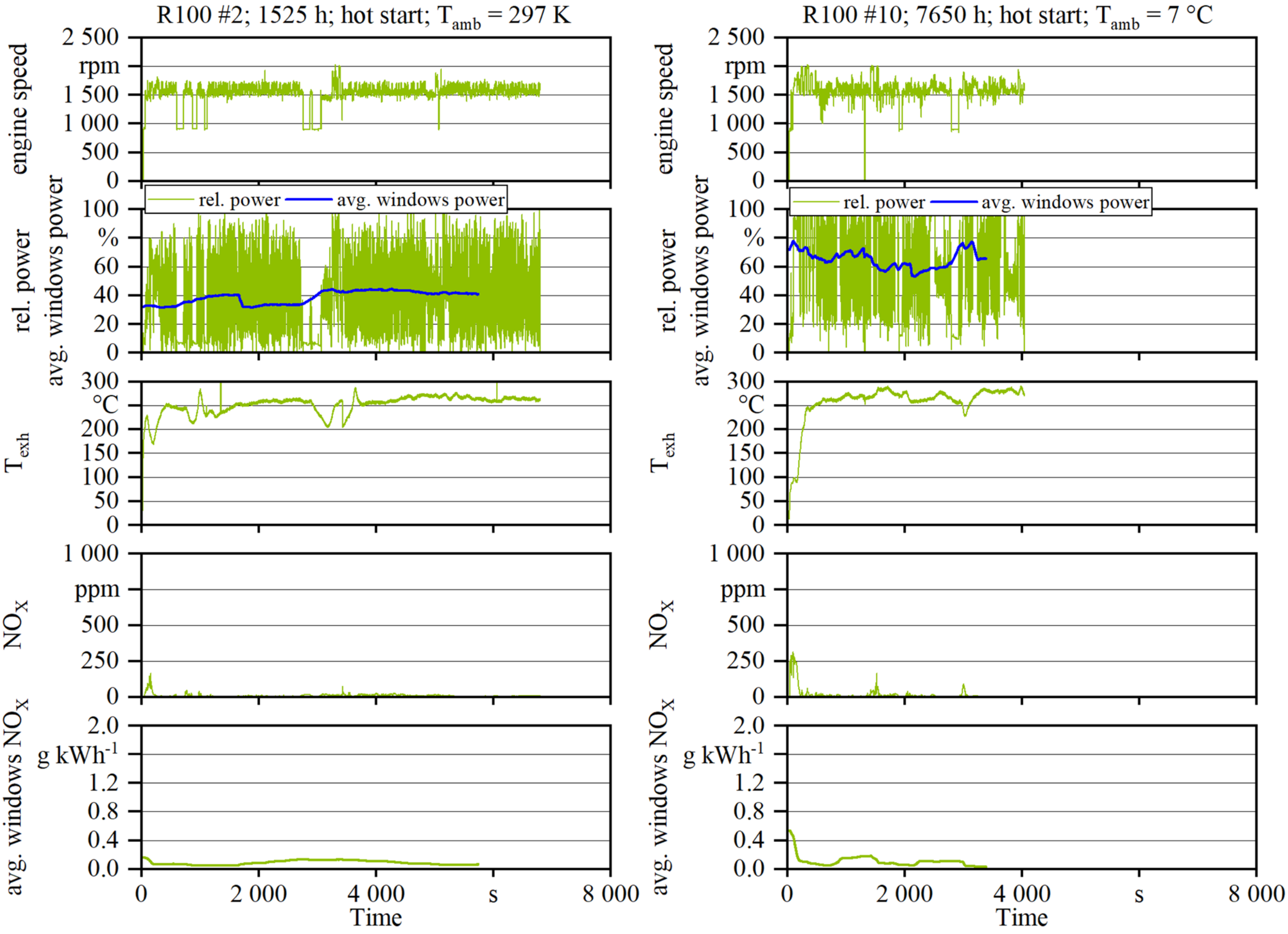


**Fig. 9** Detailed data on engine speed, relative power, averaging windows power, exhaust temperature, $NO_X$ concentration in the exhaust and averaging windows $NO_X$ emissions in R100 operation at 1525 and 7650 operation hours (hot start, second measurement of the campaign each)

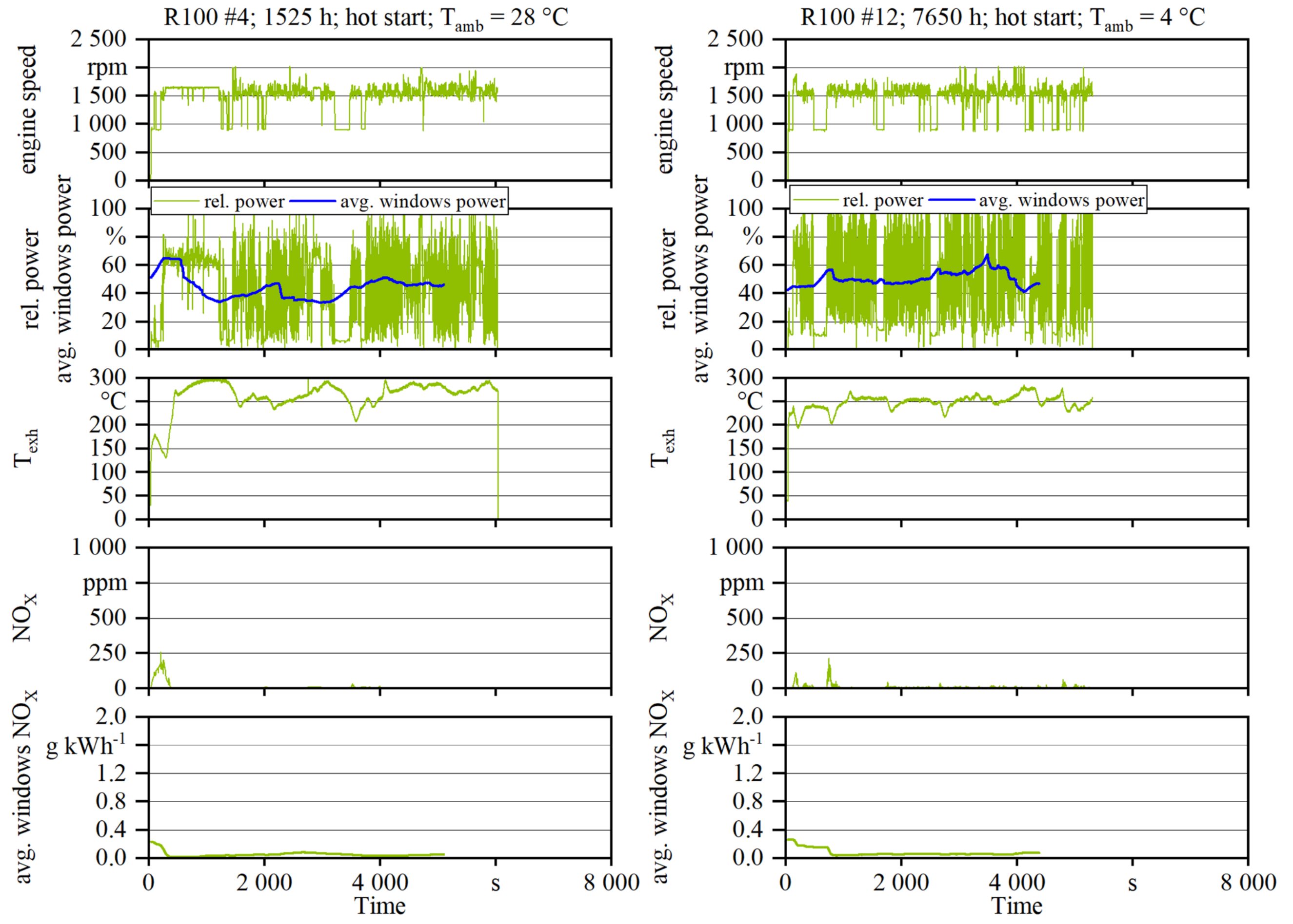


**Fig. 10** Detailed data on engine speed, relative power, averaging windows power, exhaust temperature, $NO_X$ concentration in the exhaust and averaging windows $NO_X$ emissions in R100 operation at 1525 and 7650 operation hours (hot start, fourth measurement of the campaign each)

still its full functionality and is working without failures after 7650 h of operation.

To summarize, the operation time of the R100 driven harvester had no observable impact on its exhaust emission behaviour within the monitored time. Observed differences in real driving emissions according to EU 2017/655 for single measurements are caused by different operation profiles between the recurrent measurements. Because of the nature of real driving emission behaviour, it is impossible to always have comparable operation profiles. This is particularly true for measurements where some years of operation are between, as it was for this study.

## 4 Discussion

In this study, emission data analysis was made using the moving averaging window method described in EU 2016/655. The results indicate that the emission behaviour of the R100-operated harvester engine meets the requirements of EU stage IV (and stage V for PN) during regular operation even after 7650 operating hours. The data evaluation was carried out firstly with the exclusion of cold start and non-operating events (as described by EU 2016/655) and secondly by including them. Since the literature on non-road-mobile machines primarily contains data on real-world exhaust emission behaviour without the exclusion of data, these data are primarily discussed. The discussion focuses on $NO_X$ and particle emissions since these are the most relevant for modern diesel engines. The mean values of the averaging windows are used to classify the results in the existing literature, as they correspond best with the real-world emission factors mainly reported in the literature. Since the speed and load profiles during the operation of NRMM have a major impact on the resulting real-world emissions [5–8], this has to be considered when comparing studies.

Previous research of EU stage IIIA forestry harvesters operated with conventional diesel in real-world operation showed that the combined $NO_X$ and HC emissions were more than 100% [40] above the type-approval limits. The type-approval of the engine is carried out using the non-road steady cycle (NRSC) and the non-road transient cycle (NRTC) on the engine test bench [1, 3]. Also, in [41] real-world emissions of an EU stage IIIA forestry harvester and a forwarder were investigated with diesel fuel. Both machines were in new condition and had performed only 500 operation hours before the measurements. The harvester's combined $NO_X$ and HC emissions were 50% above the type-approval limit, and the $NO_X$ and HC emissions of the forwarder within it. The particle mass emissions were recognized to be 2.1 and 1.5 times above the type-approval limit. The different engine operation profiles in real-world and type-approval tests are mentioned as a reason for the observed differences [40, 41]. The EU stage IIIA engines were not equipped with exhaust gas aftertreatment systems unlike the researched harvester of the present study. The SCR and DPF system implemented in the EU stage IV harvester effectively reduces $NO_X$ and particle emissions in the exhaust, and the mean averaging windows $NO_X$ and PN emissions are close to or below the type-approval limits of EU stage IV. Only during cold start and long low load or idle operation higher $NO_X$ emissions were observed because the operation temperature of the SCR system was not reached. The measured PN emissions of the harvester were even below the EU stage V requirements and indicated full functionality of the DPF after 7650 h of operation.

In the study of Desouza et al. [5], six of nine EU stage IV non-road mobile machines at construction sites exceeded the regulatory $NO_X$ limit of 0.4 g $kWh^{-1}$ during their usual work using diesel fuel. The reason for this was the occurrence of extended idle periods between the work cycles. They cause the exhaust gas temperature to cool down below the operating temperature of the SCR system to reduce $NO_X$. The other three machines did not exhibit long idling phases during their regular operation and thus met the requirements of EU stage IV. This observation corresponds to the results of Zhu et al. [8], who researched ten diesel fuelled non-road construction machines of US Tier 4F (equivalent to EU stage IV) and Lee et al. [42], who researched seven K-tier4 (equivalent to EU stage IV and US Tier 4F) construction machines. Since the usual operation profile of the researched harvester is without extended idle periods (except for the last measurement period), the exhaust temperature was high enough for an efficient operation of the SCR system, and the resulting $NO_X$ emissions were below the legal requirements most of the time.

Comparable operating conditions were identified from the data to assess the deterioration of the emission behaviour over the operating period. After 7650 h, no major deterioration of the emission behaviour, e.g. due to possible exhaust gas aftertreatment system aging, was observed. Zhu et al. [41] identified the $NO_X$ emissions of a crawler dozer after 3654 h operation hours to be within the certification limits, indicating no major deterioration as well. Thermal ageing and poisoning of the catalysts and thus deterioration of the emissions can be expected as reported e.g. by Deka et al. [43], but do not yet seem to have any observable effect on the emissions of the researched harvester. The emission results indicate that the low allowed amounts of sulphur and phosphor in the used R100, according to DIN 51605, prevent fast catalyst poisoning.

## 5 Conclusion

The real driving emission behaviour of the researched forest harvester was measured four times between the years 2016 and 2021. In this period, it worked for 7650 h, thereof 6300 h in R100 operation. During cold start and non-working events higher $NO_X$ concentrations are observed in the exhaust since the exhaust aftertreatment system is not within its operation temperature. When the data is analysed according to EU 2017/655 with cold start and non-working events excluded the emission behaviour is at a very low level for almost every measurement within the five years and close to the end of the emission durability period of 8000 h according to EU 2016/1628.

But the results also show, that between the measurement periods some differences in the emission results exist. They are primarily caused by differing exhaust gas temperatures that influence the efficiency of the exhaust gas aftertreatment system. The exhaust gas temperature is dependent on the engine operation profiles. For the researched harvester in the last measurement period major differences in the engine operation profiles were observed compared to the other measurement periods, because of random events (unplanned work interruptions) and different workloads. This led to a different result in emission behaviour of the harvester when the data is completely analysed with cold start and non-working events included.

Detailed analysis of the results showed that the $NO_X$, CO, and HC emissions are at the same level at comparable operation conditions and so far, the operation time had no major impact on the emission behaviour of the harvester. When the exhaust gas aftertreatment is within its operating conditions the $NO_X$, CO and HC emissions, as well as the particle number emissions are at a very low level indicating a correct functioning of the exhaust aftertreatment system after 7650 h of engine operation and being close to the end of the emission durability period as defined by EU 2016/1628 [3]. The operation of the harvester with R100 did not affect the emission behaviour and functionality of the exhaust gas aftertreatment system.

Since the economic lifetime of a forestry harvester is 18 000 h, still more information about the long-time emission behaviour would be valuable.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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