Imperial College London Projects

Environmental Research Group


# HS2 BBV alternative fuel trial


Analysis undertaken independently by:
Daniel Marsh - Programme Manager and
Carl Desouza - Research Assistant
Centre for Low Emission Construction
Environmental Research Group


Centre for Low Emission Construction

# EXECUTIVE SUMMARY


The tailpipe emissions from two 20-tonne excavators, a Liebherr R920 compact and a Komatsu PC210, were measured, to determine the potential benefits of using alternative fuels, when compared with standard red diesel. The same operator used both machines and performed the same work on the different fuel types tested – red diesel with F18 fuel additive, hydro-treated vegetable oil (HVO), and HVO with fuel additive (not F18).

The Liebherr excavator tested showed a slight decrease in $CO_2$ emissions, for all fuel types, when compared with red diesel. $NO_X$ emissions showed a downward difference during machine idle but increased when the machine was operational (i.e. digging, backfill-grading, and tracking). PM emissions showed a similar difference as $NO_X$, while PN emissions showed a decreasing difference.

The Komatsu excavator tested showed minimal change in $CO_2$ emissions, for all fuel types, when compared with red diesel. A similar difference was also noted for $NO_X$ emissions. PM emissions showed a slight decrease when compared with red diesel, which were within the inter-quartile ranges of each other. No significant difference in PN emissions were noted.

This study showed no significant tailpipe emission reductions from using alternative fuels in place of standard red diesel. However, both machines had exhaust gas after-treatment technology installed to reduce tailpipe $NO_X$ and particulate emissions. Older machines, without after-treatment technology should be tested to determine the potential air quality benefits of using alternative fuels.

# Contents

# 1 INTRODUCTION

The aim of the trial was to measure the tail-pipe emissions to determine the potential benefits of using alternative fuels when compared to red diesel. The tests were carried out on two 20-tonne excavators, used on Balfour Beatty Vinci (BBV) High-Speed 2 (HS2) sublot 5, East way compound off A45 near Coventry. A test cycle was designed to replicate real world activity and allow for repeatability across all tests.

# 2 METHOD

Two 20-tonne excavators, a Liebherr R920 compact (Figure 1) and Komatsu PC210 (Figure 2), were provided for this trial. The technical specifications for both machines are shown in Table 1. To inhibit the possible influence of driver variability, the same operator was used for all tests across both machines. Both machines performed the same work on all days – machine idle, machine tracking, digging, and backfill-grading following the same route and working in the same area of an aggregate stockpile. Each activity was performed for a minimum period of 15 minutes each, forming a 1-hour test run. The test run was repeated three times each day.


**Figure 1 Liebherr R920 compact excavator.**

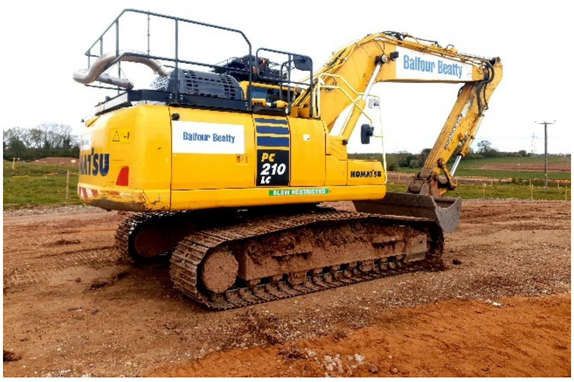


**Figure 2 Komatsu PC210 tracked excavator.**

**Table 1 Technical specifications of the machines used, and work done.**

| Parameter | Liebherr R920 | Komatsu PC210 |
|---|---|---|
| Rated power | 110kW @ 1800rpm | 123kW @ 2000rpm |
| NRMM type | Tracked excavator | Tracked excavator |
| Emission standard | Stage IIIB | Stage IV |
| Engine production date | 2018 | 2018 |
| Operational hours | 4290 | 5380 |
| Engine displacement | 4.5 litre | 6.7 litre |
| After-treatment | SCR | EGR, DOC, DPF, SCR |
| Work done | Engine idle, tracking, digging, backfill-grading | Engine idle, tracking, digging, backfill-grading |

Three different types of fuels were compared with industry standard red diesel (EN590), which was also tested to generate a baseline on Day1. The fuel tank was fully drained, and new fuel filters were fitted, before the machine was filled with the next fuel to be tested; to ensure a complete purge of the fuel delivery system, the machine was operated for a couple of hours before the next test procedure was carried out on the following day. Red-diesel with F18 fuel additive was tested on Day2, hydro-treated vegetable oil (HVO) was tested on Day3, and Green D+ (HVO with fuel additive) was tested on Day4. The Liebherr R920 compact excavator was tested on Week 1 and the same test procedure was repeated on Week 2 for the Komatsu PC210 tracked excavator, described in Table 2.

**Table 2 Test protocol for the different fuels used in both machines over a 2-week trial period.**

| Test Day | Liebherr R920 | Komatsu PC210 |
|---|---|---|
| **Week 1** | | |
| **Day 1** | Red Diesel | - |
| **Day 2** | Red Diesel with F18 fuel additive | - |
| **Day 3** | HVO | - |
| **Day 4** | Enhanced HVO | - |
| **Week 2** | | |
| **Day 1** | - | Red Diesel |
| **Day 2** | - | Red Diesel with F18 fuel additive |
| **Day 3** | - | HVO |
| **Day 4** | - | Enhanced HVO |

A 3DATX parSYNC® integrated portable emissions measurement system (iPEMS) was used to measure the carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen monoxide (NO), nitrogen dioxide ($NO_2$), particle mass (PM), and particle number (PN) concentrations in the exhaust, using a sample probe mounted inside the tailpipe. A flowmeter was connected to the tailpipe of the Komatsu PC210 excavator on Week2, to measure the exhaust mass flow. There was insufficient space on the back of the Liebherr R920 compact excavator to mount the flowmeter, and due to safety issues regarding access and working at height, the flowmeter was not used on Week1, described in Table 3.

Engine speed, fuel rate, estimated power, intake air temperature and intake air pressure were recorded from the engine CANbus port using proprietary engine diagnostic software (provided and logged independently by Liebherr and Komatsu engineers). These parameters were subsequently time-aligned with the measured emissions data and used to convert the measured concentrations to mass-based values, to allow for direct comparison with the EU emission standards.

**Table 3 Test equipment used on both machines over a 2-week trial period**

| Test Day | Liebherr R920 | Komatsu PC210 |
|---|---|---|
| | **Week 1** | |
| **Day 1** | Engine data-logger, iPEMS | - |
| **Day 2** | Engine data-logger, iPEMS | - |
| **Day 3** | Engine data-logger, iPEMS | - |
| **Day 4** | Engine data-logger, iPEMS | - |
| | **Week 2** | |
| **Day 1** | - | Engine data-logger, iPEMS, flowmeter |
| **Day 2** | - | Engine data-logger, iPEMS, flowmeter |
| **Day 3** | - | Engine data-logger, iPEMS, flowmeter |
| **Day 4** | - | Engine data-logger, iPEMS, flowmeter |

# 3 RESULTS

The results have been reported individually for each of the machines tested. Gaseous emission concentrations for $CO_2$ (%) and $NO_X$ (ppm), particle emission concentrations for PM (µg/m$^3$) and PN (#/cm$^3$), engine parameters engine power (kW) and fuel used (mg/stroke for the Liebherr excavator and litre/hour for the Komatsu excavator), gaseous emission standards for CO (g/kWh) and $NO_X$ (g/kWh), and particle emission standards for PM (g/kWh) and PN (#/kWh), are shown in the subsequent sections of the report.

## 3.1 LIEBHERR EXCAVATOR

The data is presented with each fuel type having a unique bar chart colour and disaggregated by the activity performed. Boxplots are plotted in Appendix for the emissions, with the median instead of the mean, to eliminate the influence of any outliers. The median value is then plotted as a bar chart, and the error bars are calculated from the difference to the inter-quartile range (25$^{th}$ and 75$^{th}$ percentile) of the boxplots.

### 3.1.1 EMISSION CONCENTRATIONS

$CO_2$ emissions are shown in Figure 3 and Figure 23. When working (tracking, digging, and backfill-grading), the excavator emitted more emissions than machine-idle, which is consistent with normal engine emissions. This difference is noted for all fuel types used. For idle emissions, the excavator emitted the lowest $CO_2$ when operating on red diesel with the F18 fuel additive. For working activity, a general decreasing difference was noted for all types of fuels, when compared with Red-Diesel, respectively.

$NO_X$ emissions are shown in Figure 4 and Figure 24. During post-processing, a data quality issue was noted with the data from the $NO_X$ analyser for a majority of Day4 (enhanced HVO) and hence, only $NO_X$ emissions for engine idle is shown for this fuel. The highest $NO_X$ emissions were noted when the machine was idling, which is caused due to selective catalytic reduction (SCR) after-treatment system not functioning effectively at this lower exhaust temperature range. This is common across all diesel engines, which use SCR to reduce $NO_X$ emissions. When working under load, the excavator emitted lower $NO_X$, when compared to idle, for all respective fuel types. When working, F18 and HVO was higher than Red-Diesel during backfill-grading; lower during digging; and F18 increased while HVO decreased when compared to Red-Diesel respectively, during tracking. On average while working, emissions from F18 additive increased, and emissions from HVO decreased, when compared with Red-Diesel, respectively.

PM emissions are shown in Figure 5 and Figure 25. A similar issue was noted during post-processing, with the data from the PM analyser for a majority of Day4 (enhanced HVO) and hence, only PM emissions for engine idle is shown for this fuel. During machine idle, F18 additive and HVO emissions were lower when compared with Red-Diesel, but enhanced HVO was higher than Red-Diesel. When working, on average, both F18 additive and HVO showed an increasing difference in emissions, when compared to Red-Diesel, respectively.

PN emissions are shown in Figure 6 and Figure 26. Unfortunately, the same issue was noted with the data from the PN analyser, for the entire Day4 (enhanced HVO) and no data was available, to make a comparison. Data from the other Days were compared with Red-Diesel. A decreasing difference across all fuel types and all activities was noted.

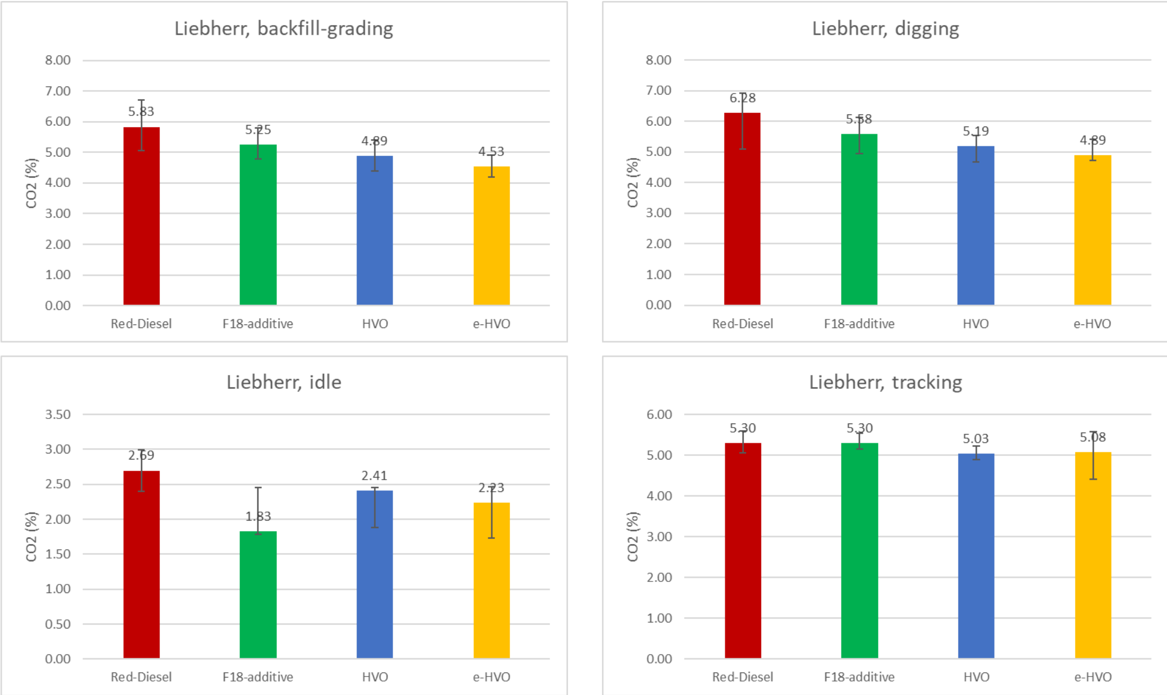


**Figure 3 Bar charts of $CO_2$ emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

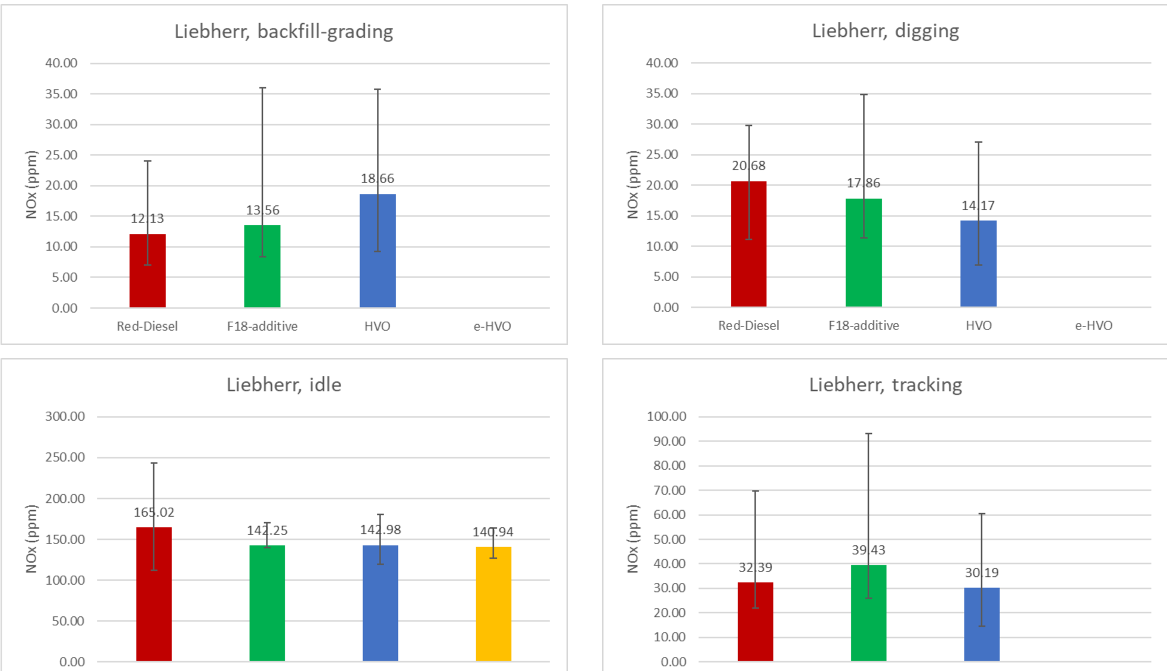


**Figure 4 Bar charts of $NO_x$ emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

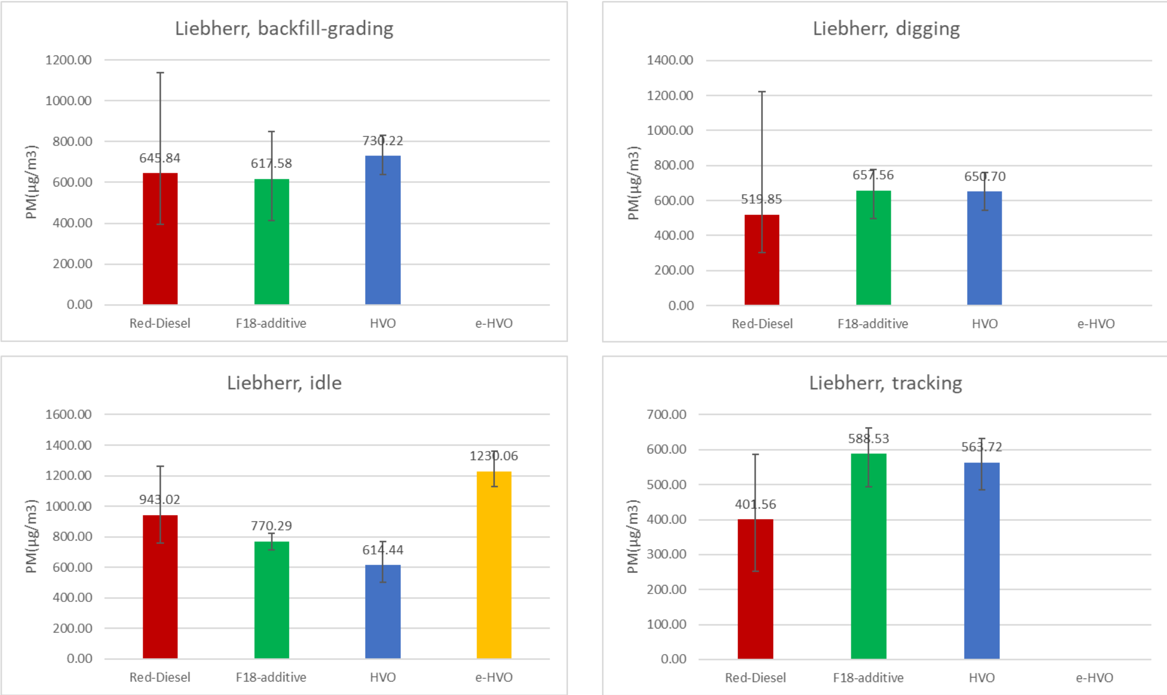


**Figure 5 Bar charts of PM emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

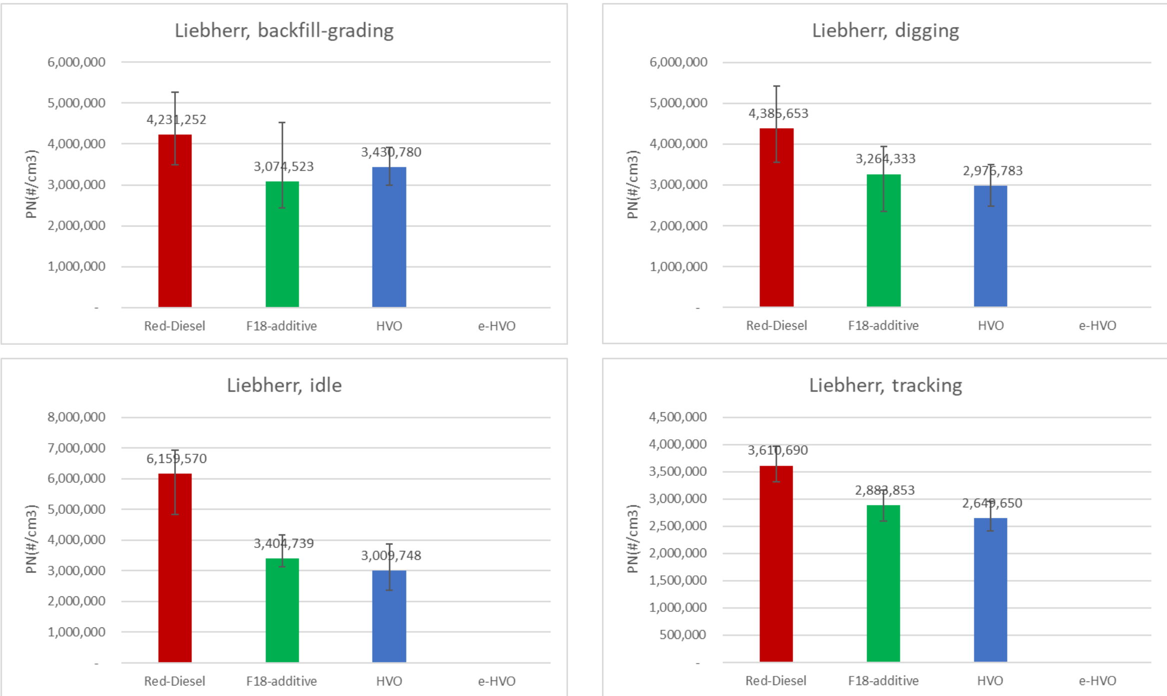


**Figure 6 Bar charts of PN emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

### 3.1.2 ENGINE PARAMETERS

Engine speed (rpm) and engine torque (Nm) were logged from the machine's Engine Control Module (ECM), using proprietary CANbus loggers and Liebherr's software tools. These parameters were used to calculate engine power (kW). The aim of the engine log was to demonstrate that the machine used the same power across activities when performing the same task. The calculated engine power (kW) was used to calculate 'mass-power based emissions' (g/kWh), to compare with the emission standards. Engine log data was time aligned with the emissions data, using proprietary emission quality assurance software.

The engine power data is shown in Figure 7 and Figure 27. On Day2, there were issues noted with the engine data logging software, and only a single test run on machine digging and machine backfill-grading was successfully performed. During idle, significantly lower power was recorded for both HVO and enhanced HVO, when compared with Red-Diesel respectively. This has implications for mass-based emission calculations since lower power translates to higher emissions and vice-versa. Similar engine power was recorded for all fuel types when the machine was tracking. When digging, the F18 additive showed comparative engine power as Red-Diesel, but HVO and enhanced-HVO showed lower engine power when compared to Red-Diesel, respectively. For backfill-grading, all three fuel types showed lower engine power when compared with Red-Diesel, respectively.

Fuel injection (mg/stroke) was also logged, by the engine data logger. The issue on Day2 translated to engine fuel injection data being available only for a single test cycle run on machine digging and backfill-grading, shown in Figure 8 and Figure 28. When idling, the machine showed lower fuel injection on HVO and enhanced HVO, when compared with Red-Diesel, respectively. During tracking, HVO showed lower fuel injection while enhanced HVO showed an increase in the fuel injection, when compared with Red-Diesel. For both digging and backfill-grading, all three fuel types showed a decrease in fuel injection, when compared with Red-Diesel, respectively. An increase in fuel injection equates to higher fuel consumption and a decrease in fuel injection equates to lower fuel consumption.

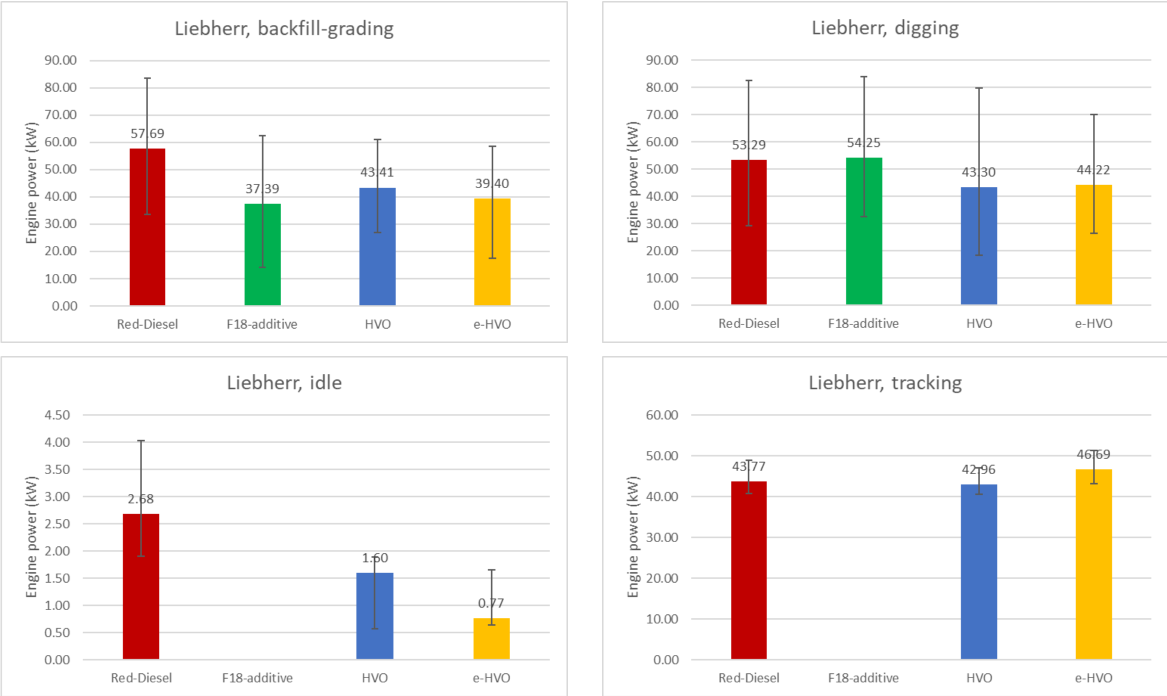


**Figure 7 Bar charts of engine power (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

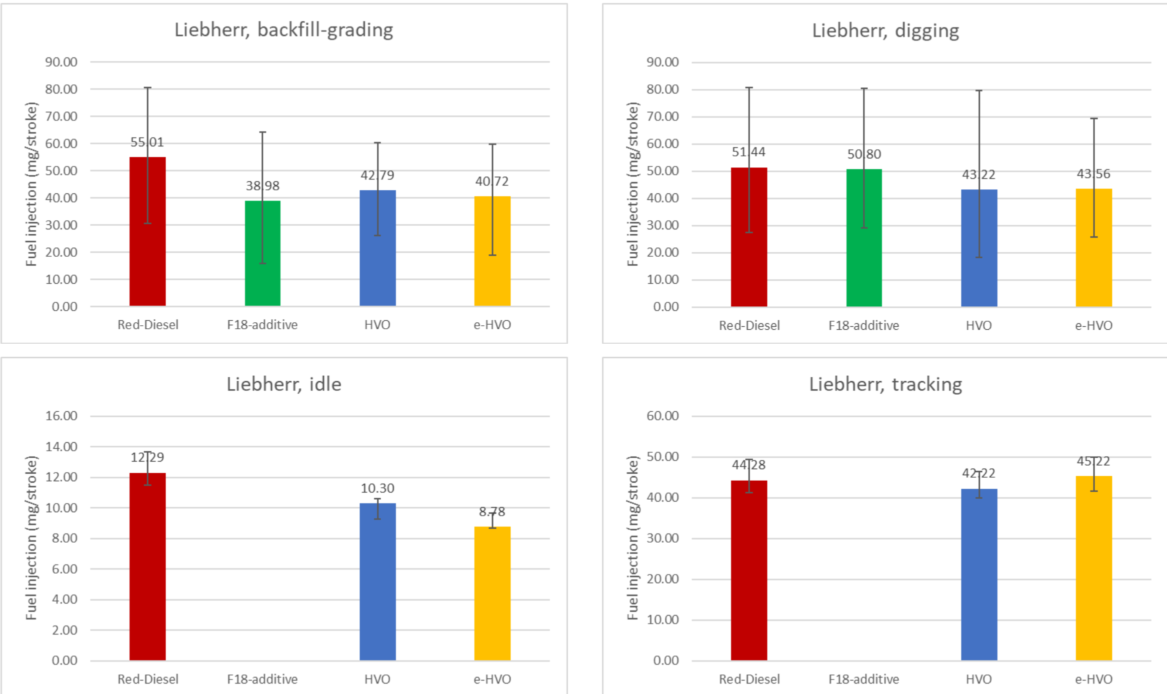


**Figure 8 Bar charts of engine fuel injection (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

### 3.1.3 EMISSION STANDARDS

In order to compare with EU emission standards, the measured emissions were coupled with engine logged data. Currently, CO, HC, $NO_X$, and PM are regulated for Stage III-B and Stage IV machines. In this test, HC was not measured, but PN was measured, hence a comparison was made for CO, $NO_X$, and PM with the respective emission standard, while PN was compared with the future Stage V emission standard.

Figure 9 and Figure 29 shows CO emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The current EU emission standard for this Stage IV excavator for CO is 3.5g/kWh, shown by the dotted line across the y-axis (only in boxplots). For all activities, the emissions measured are below the EU Stage IV emission standard. Since, no engine data log was available for F18 additive during idle and tracking, there is no ‘mass-based emissions’ calculated.

Figure 10 and Figure 30 show the $NO_X$ (g/kwh) emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The current EU emission standard for this Stage IV excavator for $NO_X$ is 0.4 g/kWh, shown by the dotted line across the y-axis (only in boxplots). When idling, both Red-Diesel and HVO were above the emission standards. When working, all fuels were within the emission standards for all activities.

Figure 11 and Figure 31 show the PM (g/kwh) emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The current EU emission standard for this Stage IV excavator for PM is 0.025 g/kWh, shown by the dotted line across the y-axis (only in boxplots). For all activities, the emissions measured are below the EU Stage IV emission standard.

Figure 12 and Figure 32 show the PN (#/kwh) emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The future EU emission standard for a Stage V NRMM for PN is $1\times10^{12}$ #/kWh, shown by the dotted line across the y-axis (only in boxplots). For all activities, the emissions measured are below the future EU Stage V emission standard.

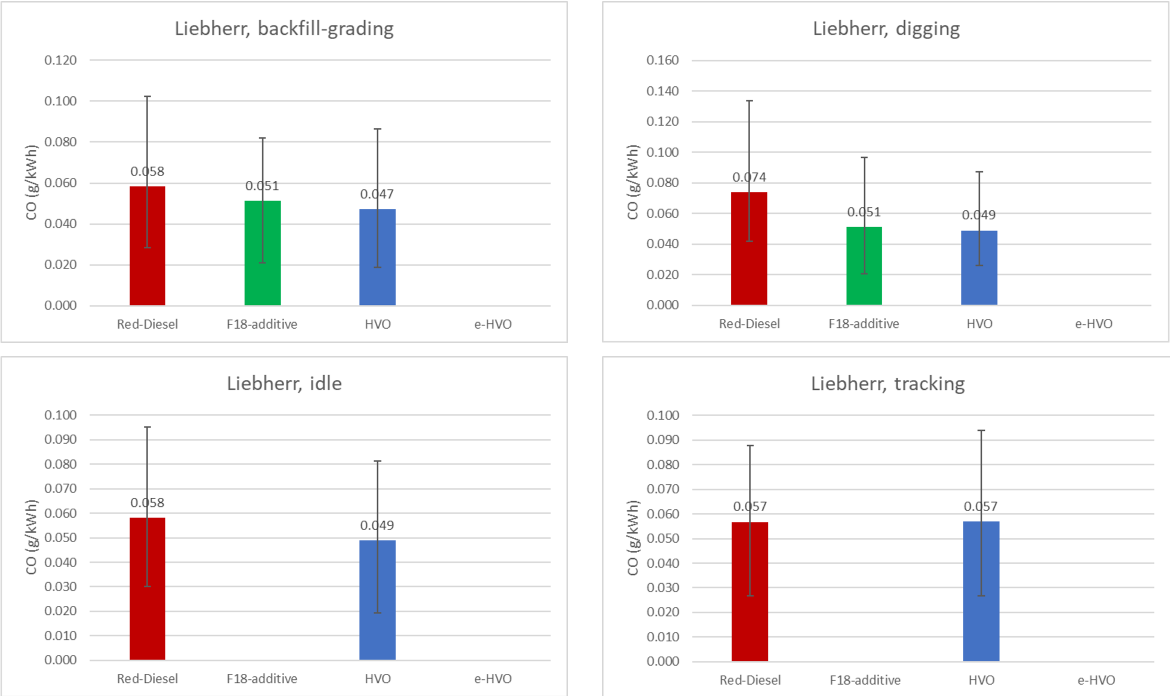


**Figure 9 Bar charts of CO emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

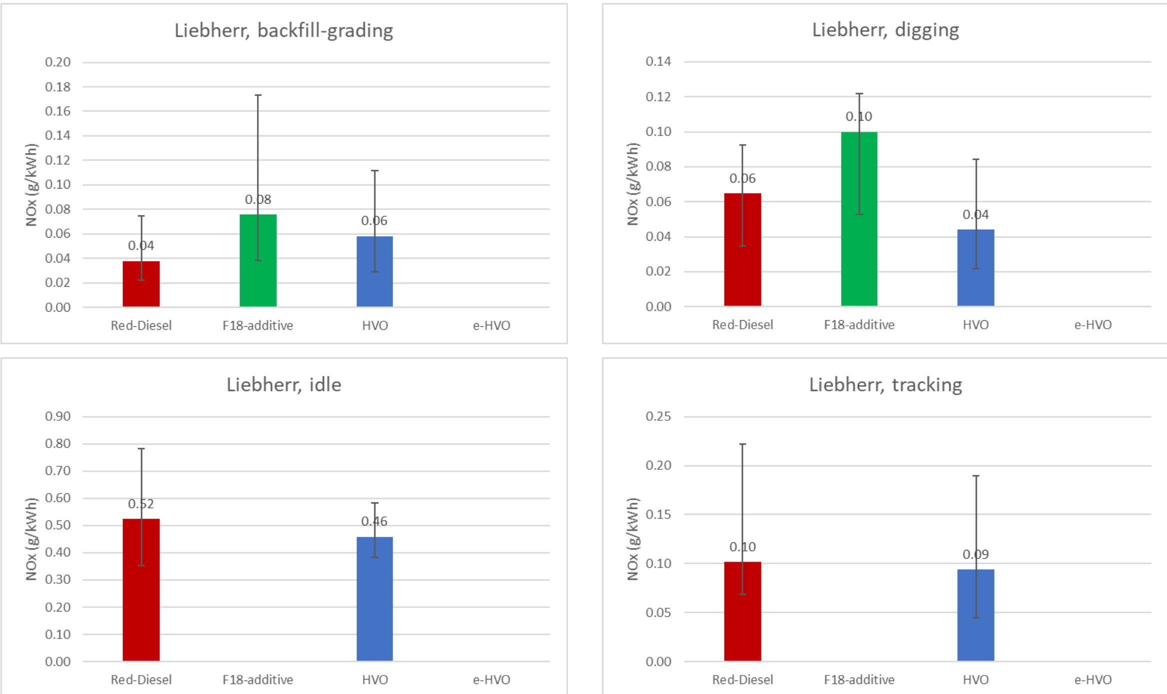


**Figure 10 Bar charts of $NO_X$ emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

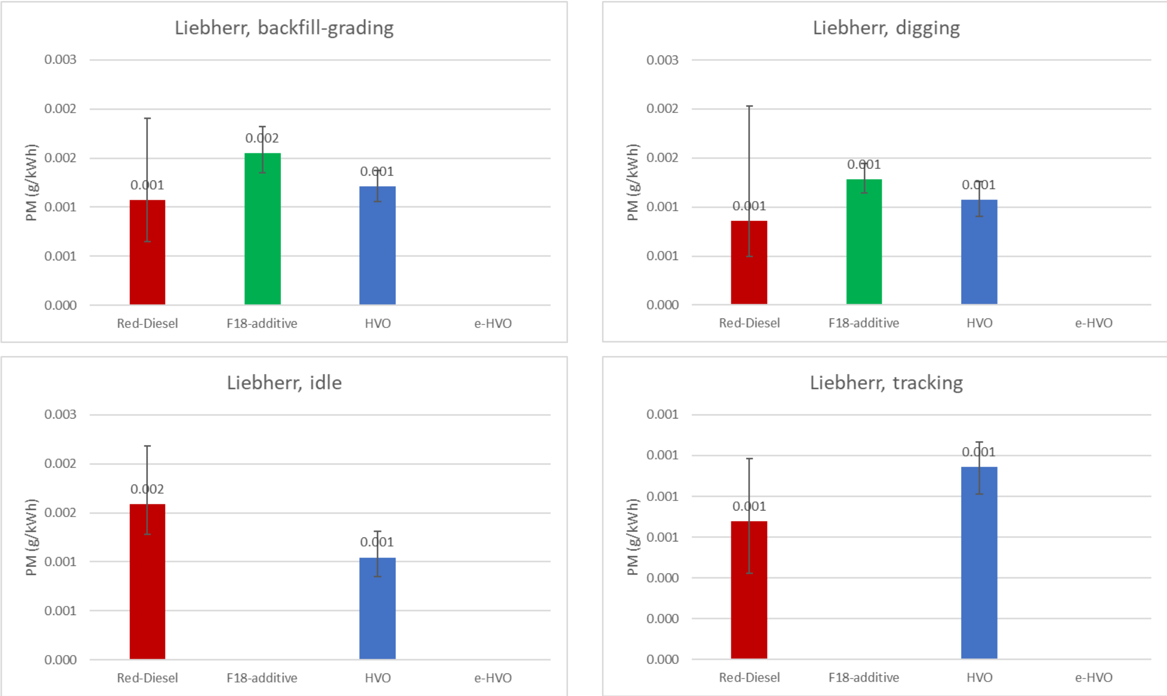


**Figure 11 Bar charts of PM emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

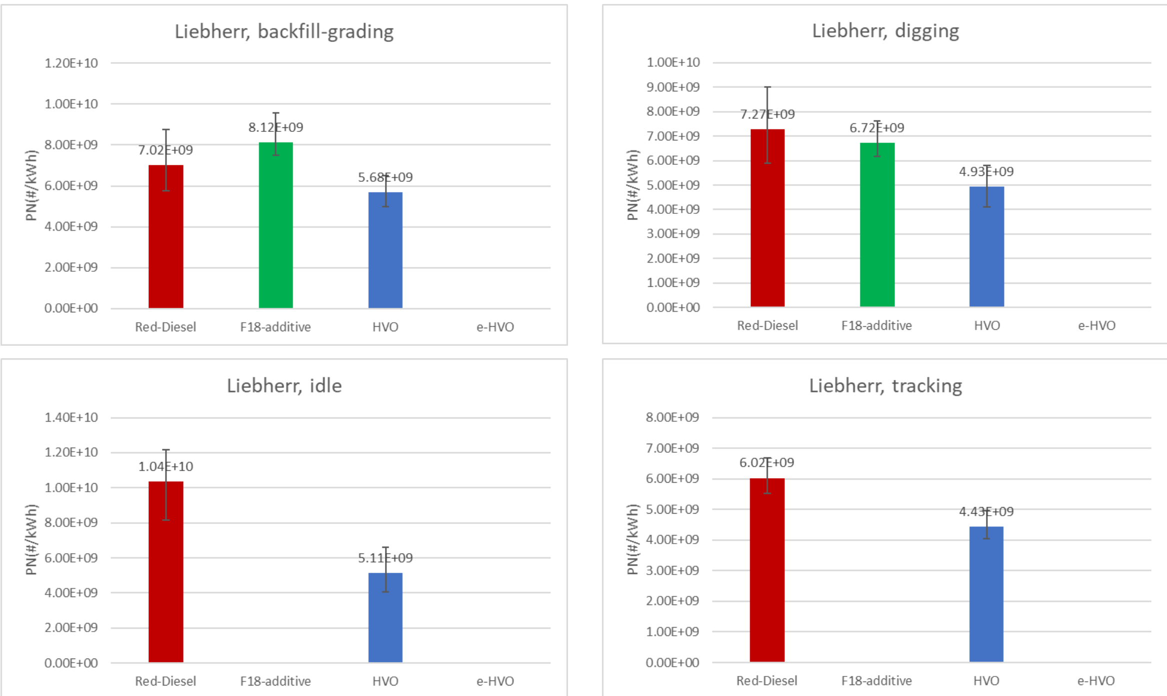


**Figure 12 Bar charts of PN emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

## 3.2 KOMATSU EXCAVATOR

The data is presented with each fuel type having a unique bar chart colour and disaggregated by the activity performed. Boxplots are plotted in Appendix for the emissions, with the median instead of the mean, to eliminate the influence of any outliers. The median value is then plotted as a bar chart, and the error bars are calculated from the difference to the inter-quartile range ($25^{th}$ and $75^{th}$ percentile) of the boxplots.

### 3.2.1 EMISSION CONCENTRATIONS

$CO_2$ emissions are shown in Figure 13 and Figure 33. When working (tracking, digging, and backfill-grading), the excavator emitted more emissions than machine-idle, which is consistent with normal engine emissions. This difference is noted for all fuel types used. For idle emissions, the excavator emitted the lowest $CO_2$ when working on HVO fuel. However, the difference in emissions for all fuel types, when compared with standard Red-Diesel is minimal. The same difference is noted for working activity, a minimal change in $CO_2$ emissions on all fuel types, when compared with Red-Diesel, respectively.

$NO_X$ emissions are shown in Figure 14 and Figure 34. The highest $NO_X$ emissions were noted when the machine was idling, which is caused due to the after-treatment not functioning effectively at this exhaust temperature range. This is common across all diesel engines, which use SCR to reduce $NO_X$ emissions. When working, the excavator emitted lower $NO_X$, when compared to idle, for all respective fuel types. All fuel types emitted higher $NO_X$ concentrations when compared with Red-Diesel, respectively.

PM emissions are shown in Figure 15 and Figure 35. When idling, all fuel types showed a decreasing difference, when compared to Red-Diesel, respectively. A similar difference was also noted during all working activities, for all fuels, with the exception of enhanced-HVO during backfill-grading, which showed an increase in PM emissions, when compared with Red-Diesel.

PN emissions are shown in Figure 16 and Figure 36. During machine idle, an increase in PN was noted for F18 additive, but a decrease in PN was noted for both HVO fuels, when compared with Red-Diesel, respectively. When working, all fuel types showed a decrease in PN for all activities, when compared with Red-Diesel, respectively.

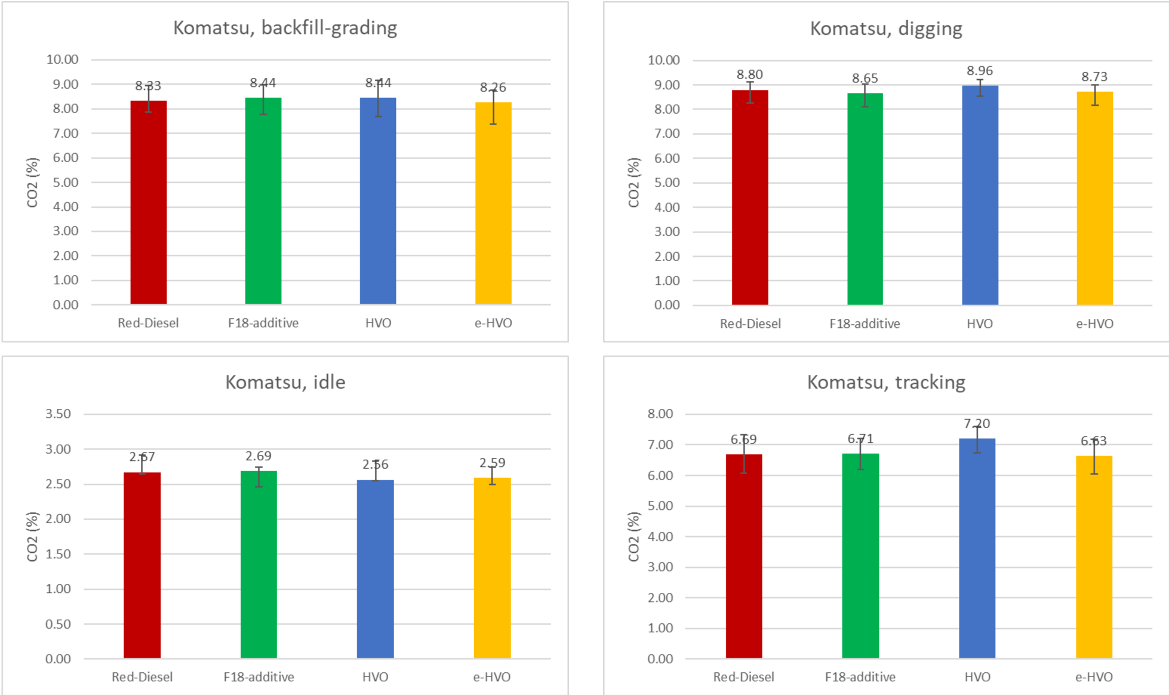


**Figure 13 Bar charts of $CO_2$ emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

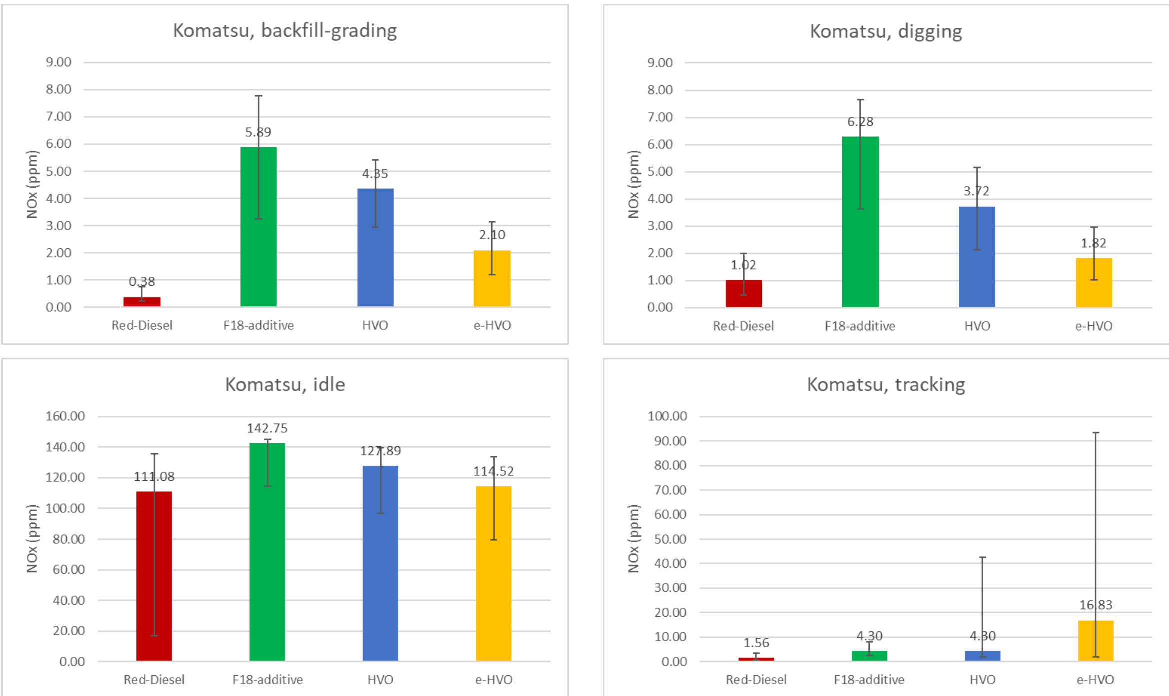


**Figure 14 Bar charts of $NO_x$ emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

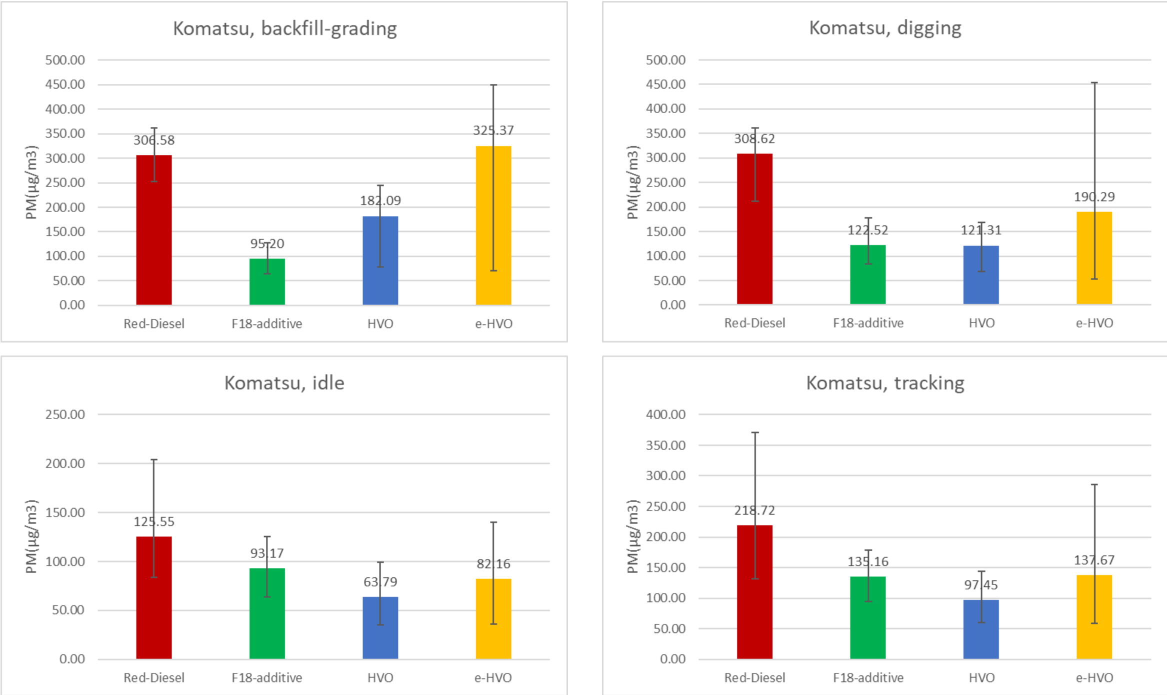


**Figure 15 Bar charts of PM emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

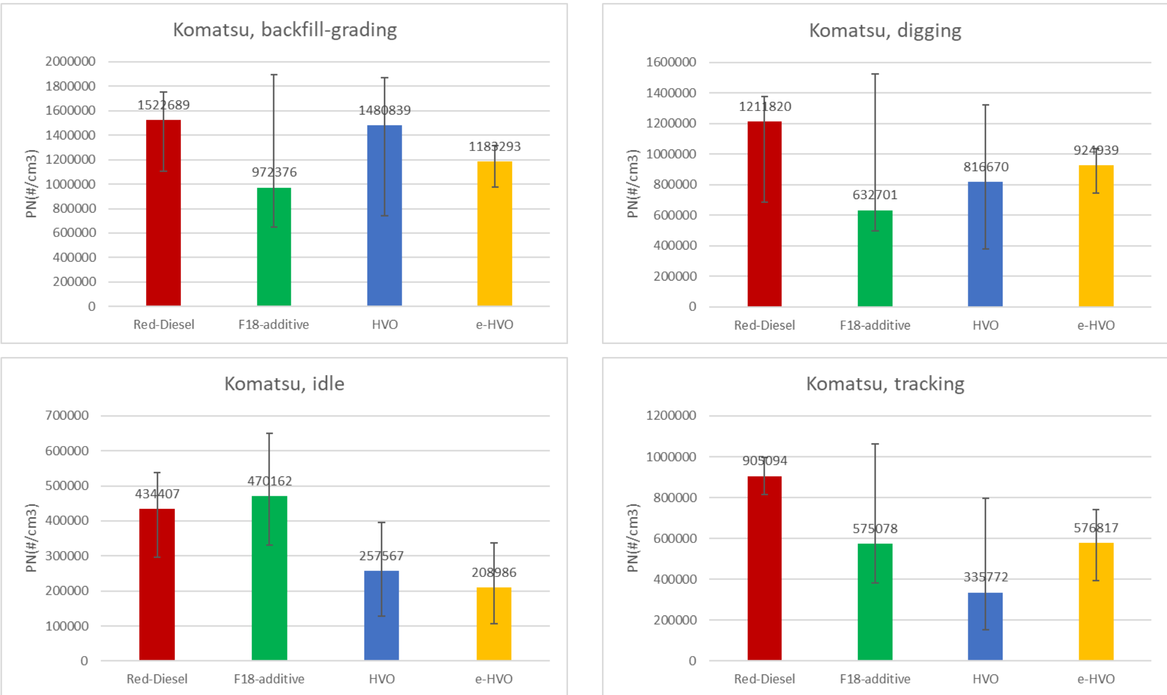


**Figure 16 Bar charts of PN emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

#### 3.2.2 ENGINE PARAMETERS

Engine speed (rpm) and engine torque (Nm) were logged from the machine's Engine Control Module (ECM), using proprietary CANbus loggers and Komatsu's software tools. These parameters were used to calculate engine power (kW). The aim of the engine log was to show that the machine used the same power across activities when performing the same task. The calculated engine power (kW) was used to calculate 'mass-power based emissions' (g/kWh), to compare with the emission standards. Engine log data was time aligned with the emissions data, using proprietary emission quality assurance software.

The engine power data is shown in Figure 17 and Figure 37. Similar engine power was noted for all fuel types, during the different activities performed by the machine. When digging, the machine showed slightly higher engine power for both HVO fuel types, when compared with Red-Diesel.

Fuel rate (litres per hour) was logged by the engine data logger and is shown in Figure 18 and Figure 38. When idling, all fuel types showed an increase in fuel rate, as compared with Red-Diesel, respectively. A similar increasing difference was also noted when the machine was working, for all activities, for all fuel types, when compared with Red-Diesel. An increase in fuel rate equates to higher fuel consumption, which could have implications on overall operational cost.

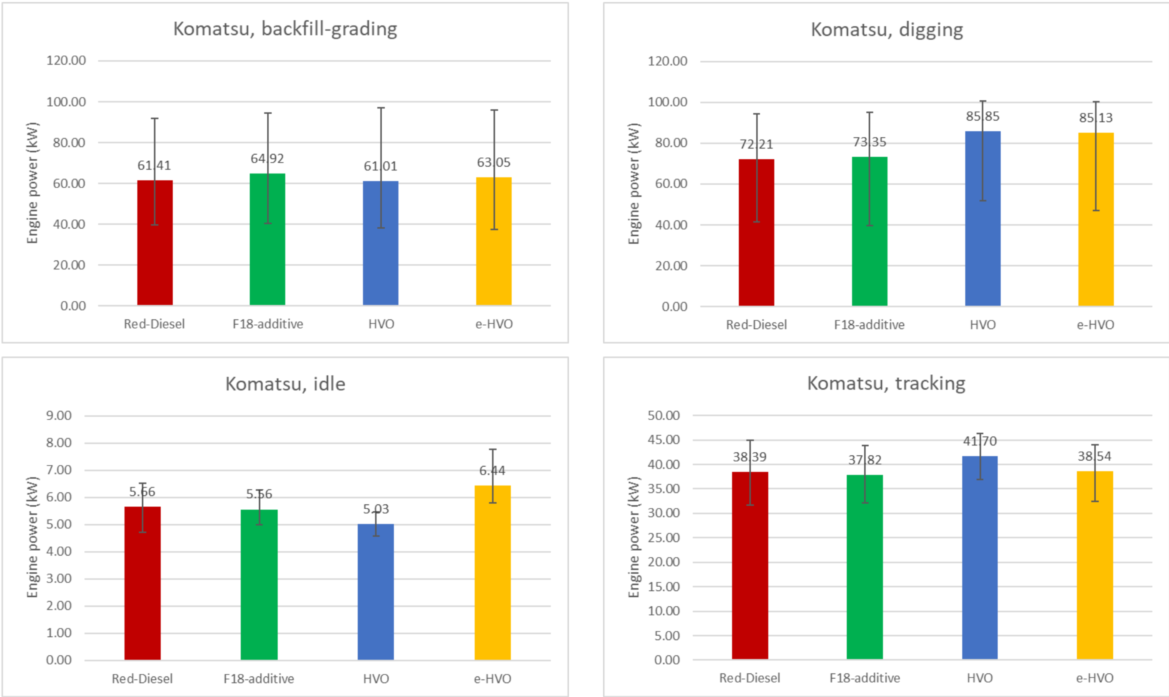


**Figure 17 Bar charts of engine power (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

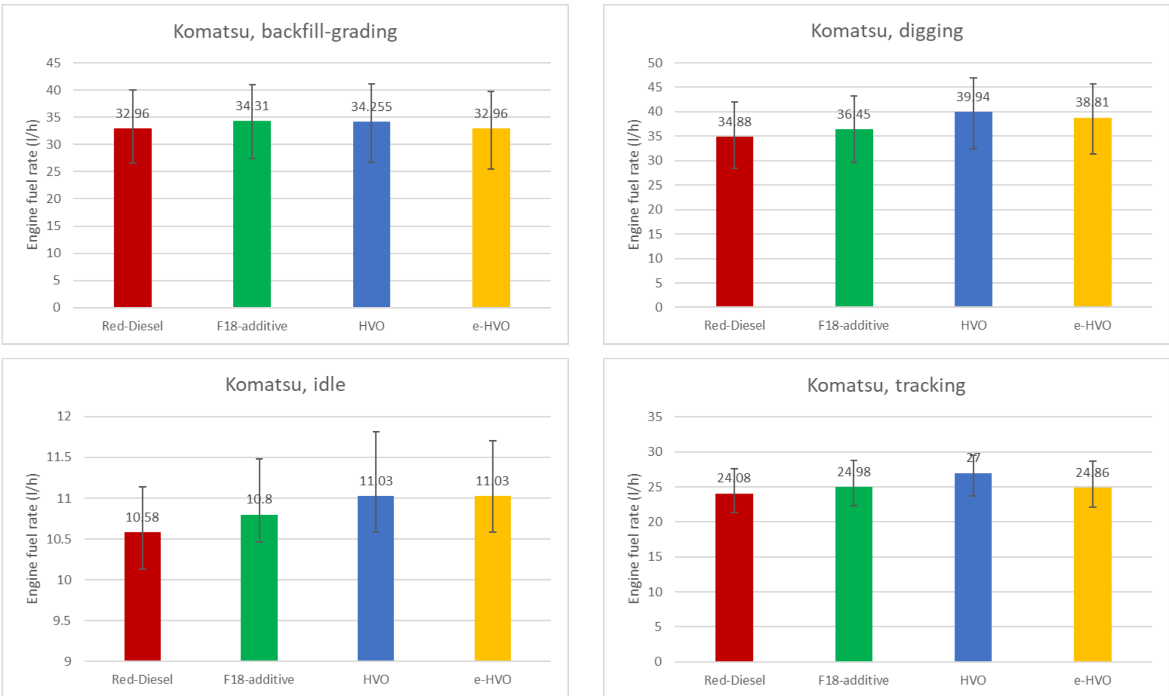


**Figure 18 Bar charts of engine fuel rate (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

### 3.2.3 EMISSION STANDARDS

In order to compare with EU emission standards, the measured emissions were coupled with engine logged data. Currently, CO, HC, $NO_X$, and PM are regulated for Stage III-B and Stage IV machines. In this test, HC was not measured, but PN was measured, hence a comparison was made for CO, $NO_X$, and PM with the respective emission standard, while PN was compared with the future Stage V emission standard.

Figure 19 and Figure 39 show the CO (g/kwh) emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The current EU emission standard for this Stage IV excavator for CO is 3.5 g/kWh, shown by the dotted line across the y-axis (only in boxplots). For all activities, the emissions measured are below the EU Stage IV emission standard.

Figure 20 and Figure 40 show the $NO_X$ (g/kwh) emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The current EU emission standard for this Stage IV excavator for $NO_X$ is 0.4 g/kWh, shown by the dotted line across the y-axis (only in boxplots). When idling, all fuel types were above the emission standards. When tracking, Red-Diesel was within the emission standards, but all other fuel types were above the emission standards; when digging and backfill-grading, Red-Diesel and enhanced-HVO were within the emission standards, but F18 additive and HVO were above the emission standards.

Figure 21 and Figure 41 show the PM (g/kwh) emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The current EU emission standard for this Stage IV excavator for PM is 0.025 g/kWh, shown by the dotted line across the y-axis (only in boxplots). When idling, all fuel types were above the emission standards. When tracking and digging, PM emissions were within the emission standards for all fuel types except Red-Diesel; when backfill-grading, PM emissions were within the emission standards for F18 additive and HVO fuel but not for Red-Diesel and enhanced-HVO.

Figure 22 and Figure 42 show the PN (#/kwh) emissions in comparison with the EU emission standard, for the different activities performed for the different fuels. The future EU emission standard for a Stage V NRMM for PN is $1 \times 10^{12}$ #/kWh, shown by the dotted line across the y-axis (only in boxplots). For all activities, the emissions measured are below the future EU Stage V emission standard.

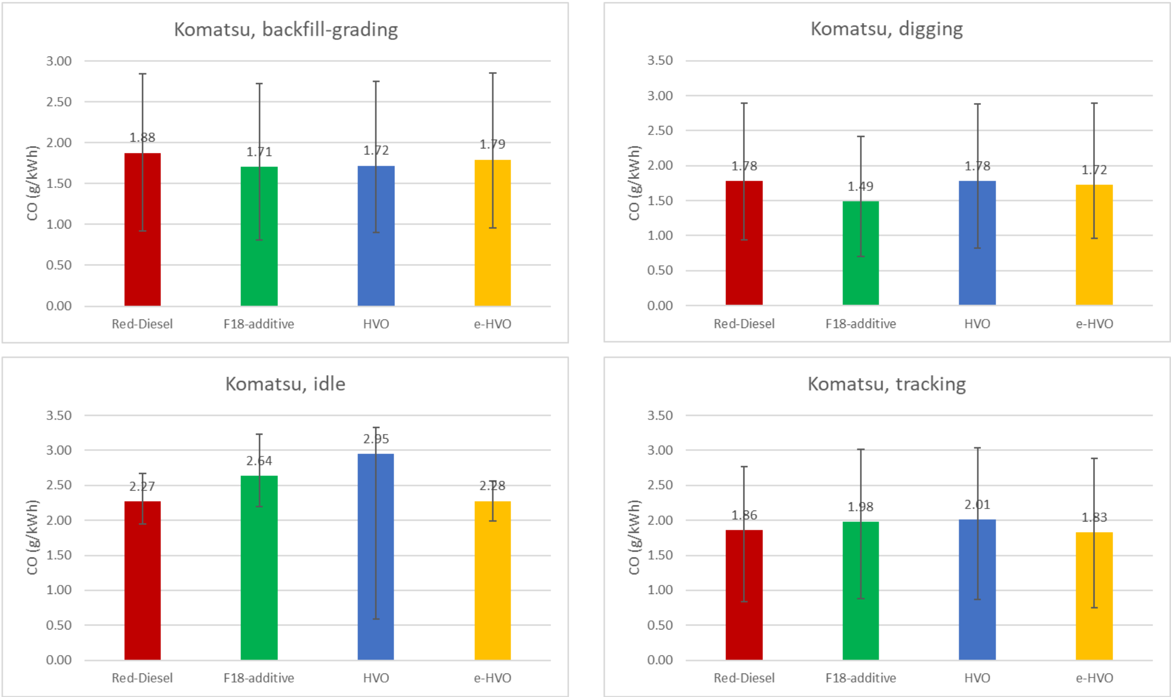


**Figure 19 Bar charts of CO emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

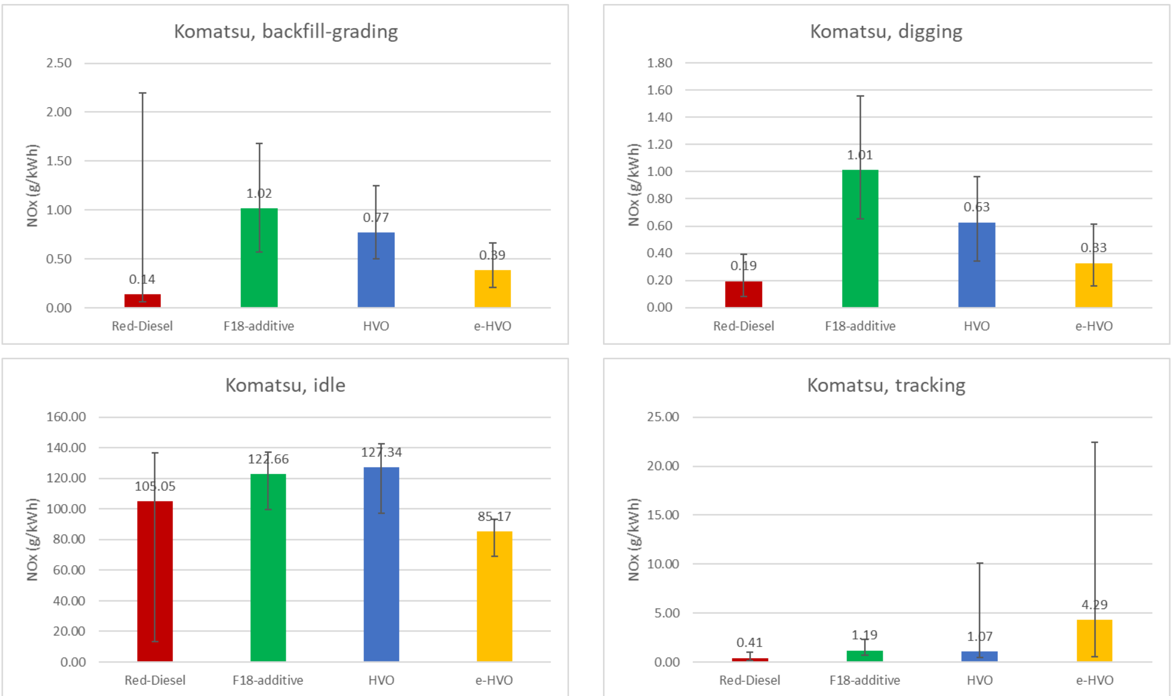


**Figure 20 Bar charts of $NO_X$ emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

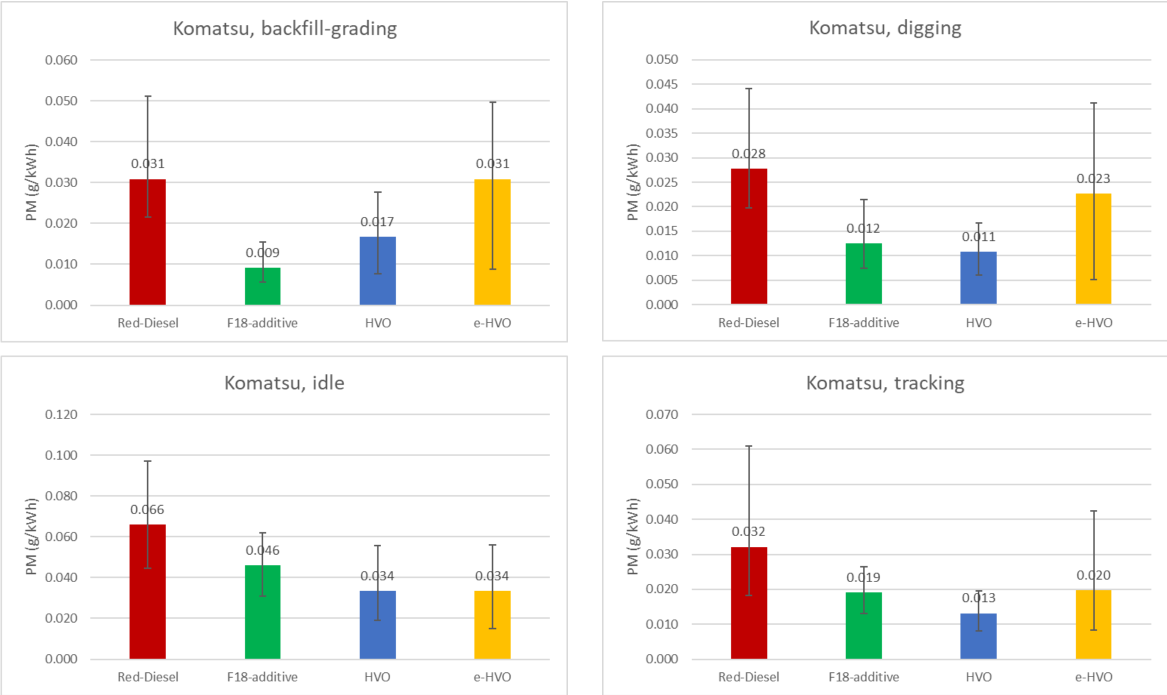


**Figure 21 Bar charts of PM emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

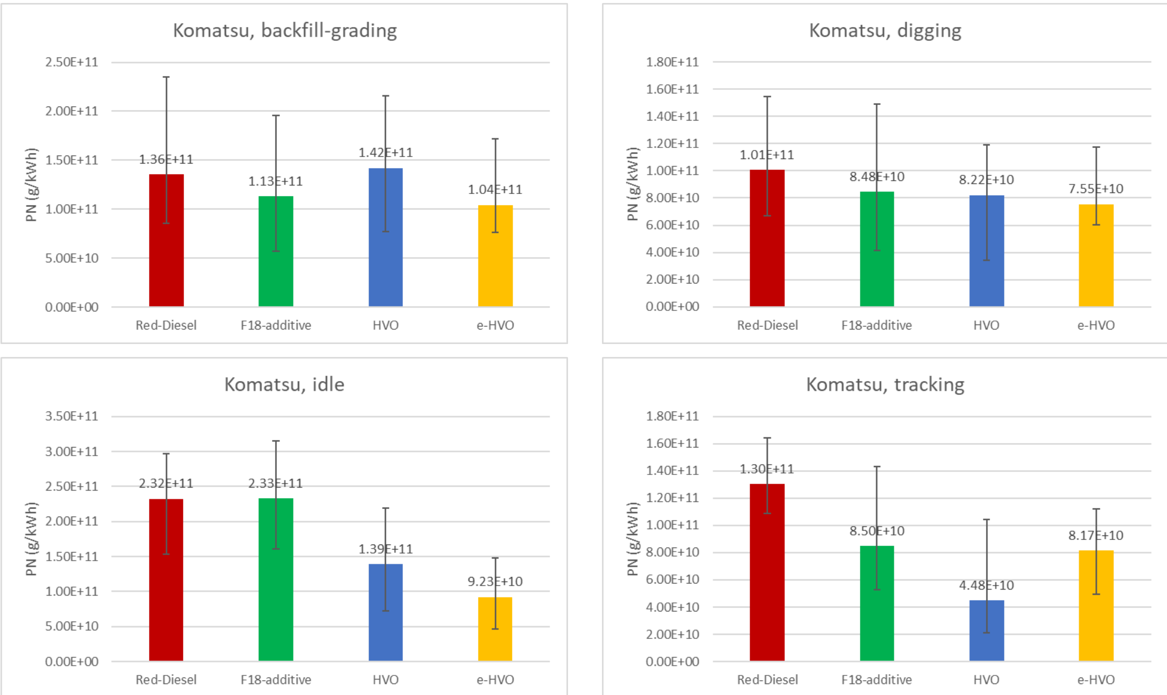


**Figure 22 Bar charts of PN emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

# 4 CONCLUSIONS

The Liebherr excavator tested during week 1 showed slight decrease in $CO_2$ emissions, for all fuel types, when compared with Red-Diesel. However, these reductions were minimal, since they were within the inter-quartile ranges of each other. $NO_X$ emissions followed a downward difference for the alternative fuels tested during machine idle but increased during machine operation. Again, the change in these emissions were minimal, since they were within the inter-quartile ranges of each other. PM emissions showed a similar difference to $NO_X$ emissions, both during machine idle (decreasing difference) and machine working activities (increasing difference). Like gaseous emissions, the changes in the PM emissions were minimal, apart from enhanced HVO measured during machine idle. The lack of emissions data for this fuel due to loss of engine activity data coupled with issues noted during post-processing of the emissions data meant that stronger conclusions cannot be made. PN emissions showed a decreasing difference; these emissions were of the same order of magnitude as Red-Diesel. A few issues were encountered, both during testing, as well as during post-processing, which were used to facilitate ease of operations during week 2.

The Komatsu excavator tested during week 2 showed minimal change in $CO_2$ emissions, for all fuel types, when compared with Red-Diesel. A similar difference was also noted for $NO_X$ emissions, across all fuel types. A slight decrease in emissions were noted for PM emissions, when compared with Red-Diesel, which were within the inter-quartile ranges of each other. However, during digging, all fuel types showed significant decrease in PM emissions, when compared with Red-Diesel. No significant differences in PN emissions were noted for any of the fuel types, when compared with Red-Diesel.

Both machines selected for the trial had exhaust gas after-treatment technology (SCR and DPF) installed to reduce $NO_X$ and particle emissions; hence, an older machine with no after-treatment technology could be tested to see if alternative fuels could have a greater potential for reducing emissions. However, with the current emission standard regulations for HS2, older machines would require special exemption status to be granted, for use on-site. Since, alternative fuels do not have the same potential to reduce tailpipe emissions as exhaust gas after-treatment technology, the use of such fuels in areas with high emissions regulations (for example HS2 or London's NRMM Clean Air Zone), would not be a viable option to reduce tail-pipe emissions.

The Liebherr excavator (week 1) showed a larger decrease in fuel injection (mg/stroke), as recorded by the engine data logger, when the machine was idling, digging, and backfill-grading; the same reduction was not seen when the machine was tracking, when compared with Red-Diesel. The Komatsu excavator (week 2) showed an increase in fuel rate (litres/hour), as recorded by the engine data logger, for all fuel types and across all activities. An increase in fuel injection or fuel rate translates to an increase in fuel consumption, which could have significant implications for the overall operational costs of a project.

# 5 ACKNOWLEDGEMENTS

The authors would like to thank Jake Walker and Lyndon Trinder at Balfour Beatty Vinci for organising and managing the trial and providing the machines to test on-site HS2; Chris Purvis at Balfour Beatty Plant and Fleet for maintaining the machines on both weeks; Douglas Mehrer for operating both machines; Simon Shipley at Liebherr for logging engine parameters, changing fuel and filters on Week 1; Peter Bell at Komatsu for logging engine parameters, changing fuel and filters on Week 2.

# 6 APPENDIX

When performing 'real-world' emission measurements on variable speed engines, it is not possible to exactly replicate the machine activity across each test cycle. In a laboratory or test-cell facility, a direct comparison can be made since the engine traces a specific load cycle. To overcome any anomalies and outliers that may occur due to operator behaviour or other variables, instead of bar charts, we use boxplots to depict groups of numerical data through their quartiles (an inter-quartile range on the measured data).

The inter-quartile range (IQR) is a measure of where the "middle fifty" is in a data set. It is a measure of where the bulk of the values lie – the 25$^{th}$ to 75$^{th}$ quartile. The median is denoted by the 50$^{th}$ quartile, while the entire range is covered between the 0$^{th}$ to 100$^{th}$ quartile.

## 6.1 LIEBHERR EXCAVATOR

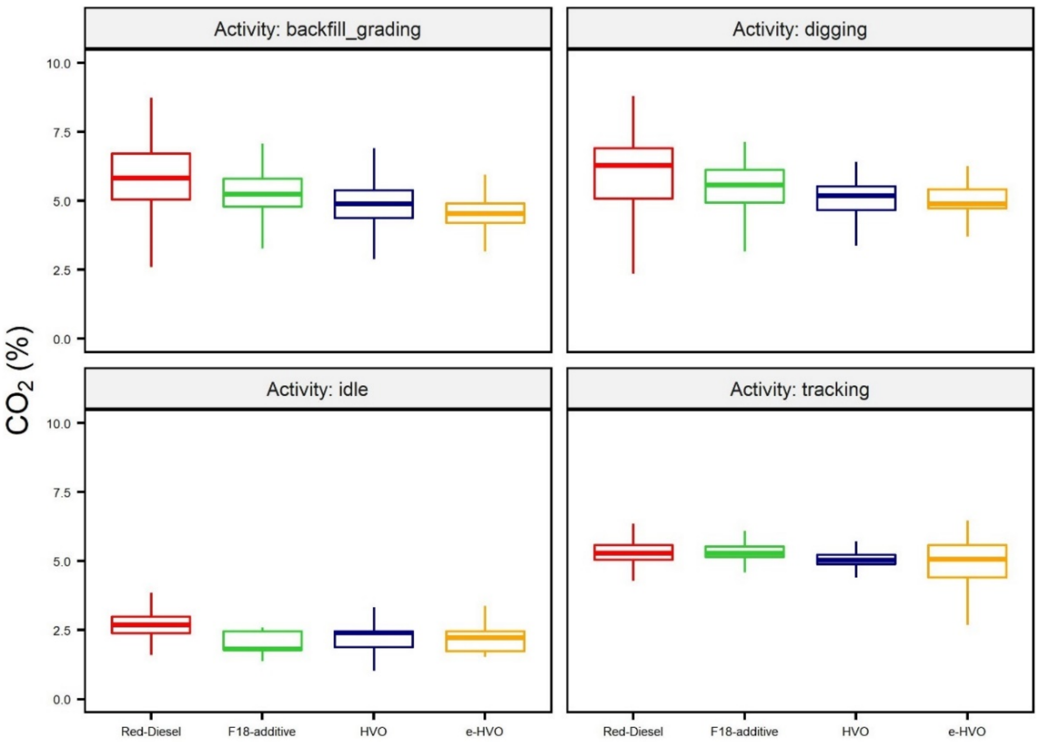


**Figure 23 Box plots of $CO_2$ emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

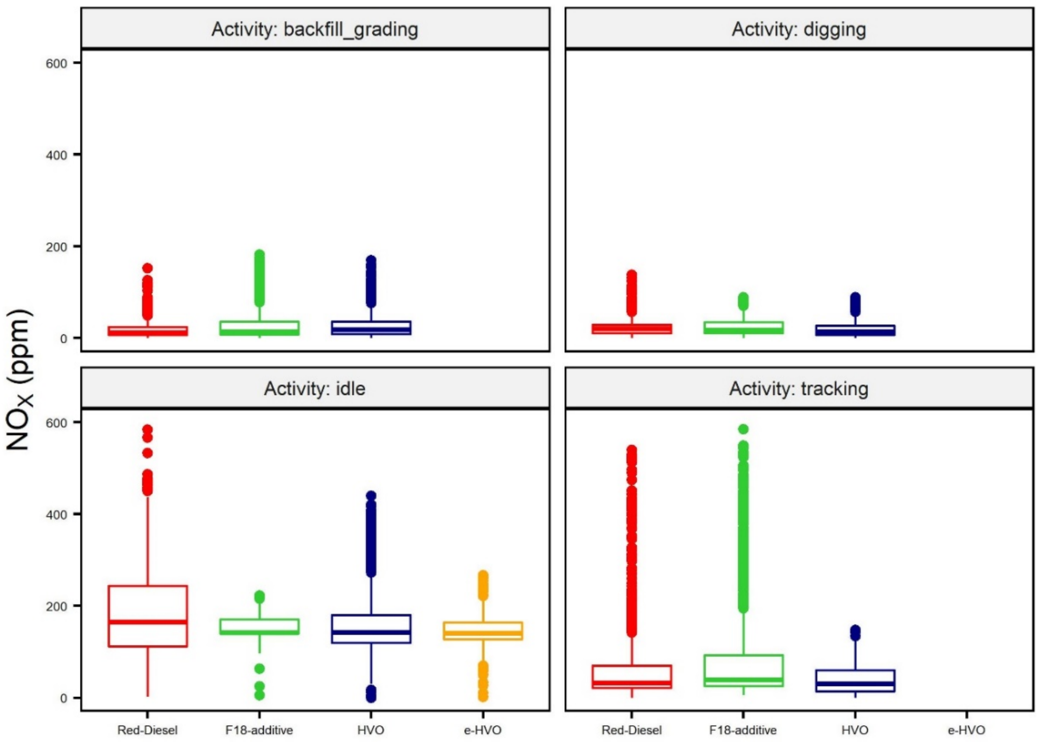


**Figure 24 Box plots of $NO_X$ emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

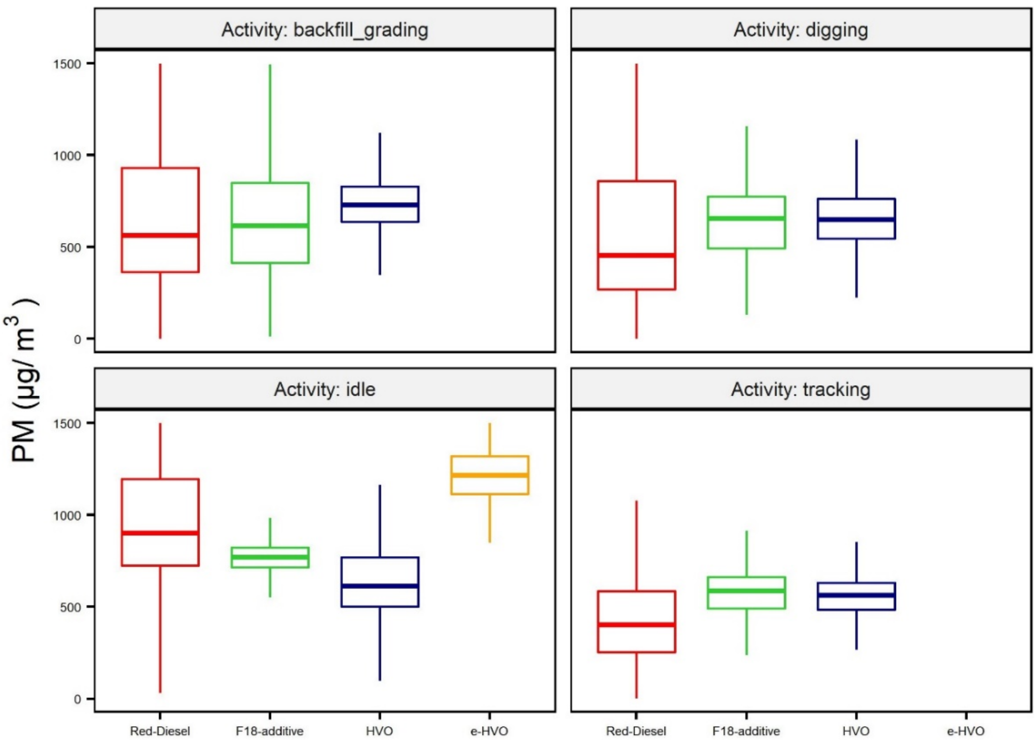


**Figure 25 Box plots of PM emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

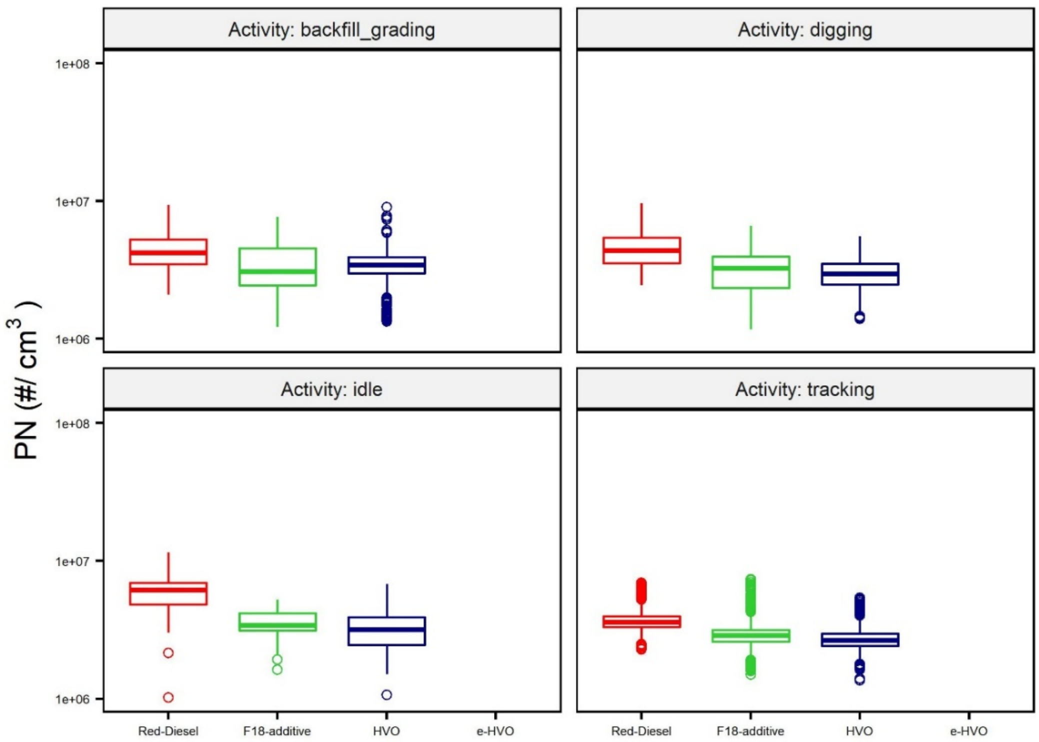


**Figure 26 Box plots of PN emissions (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

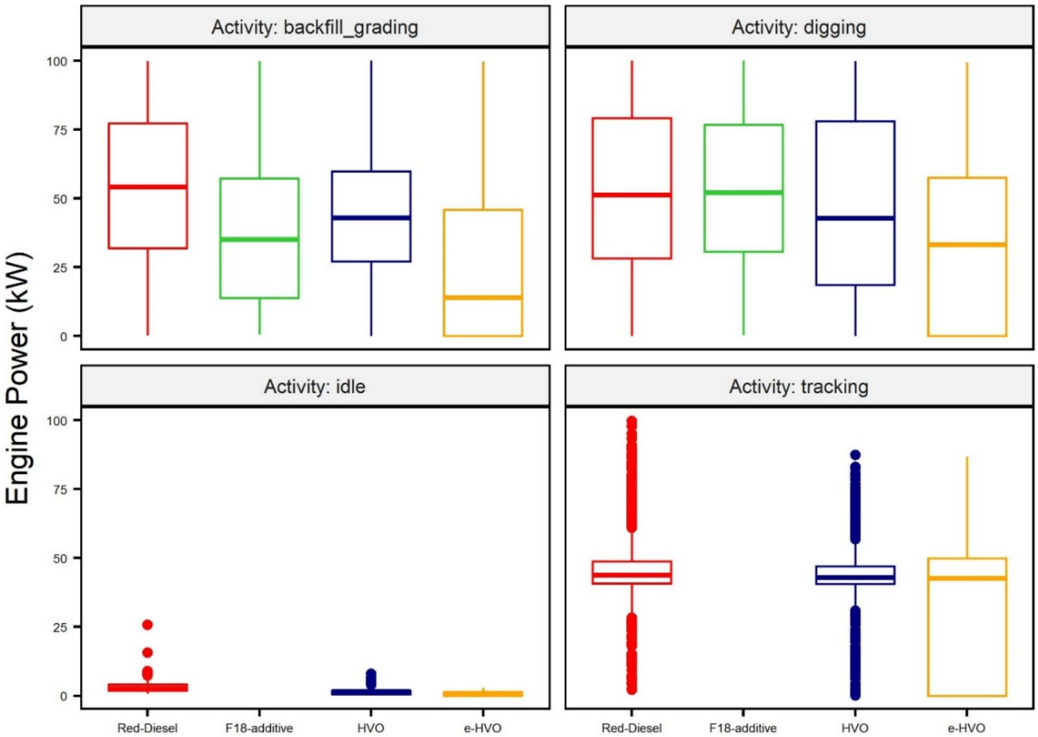


**Figure 27 Box plots of engine power (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

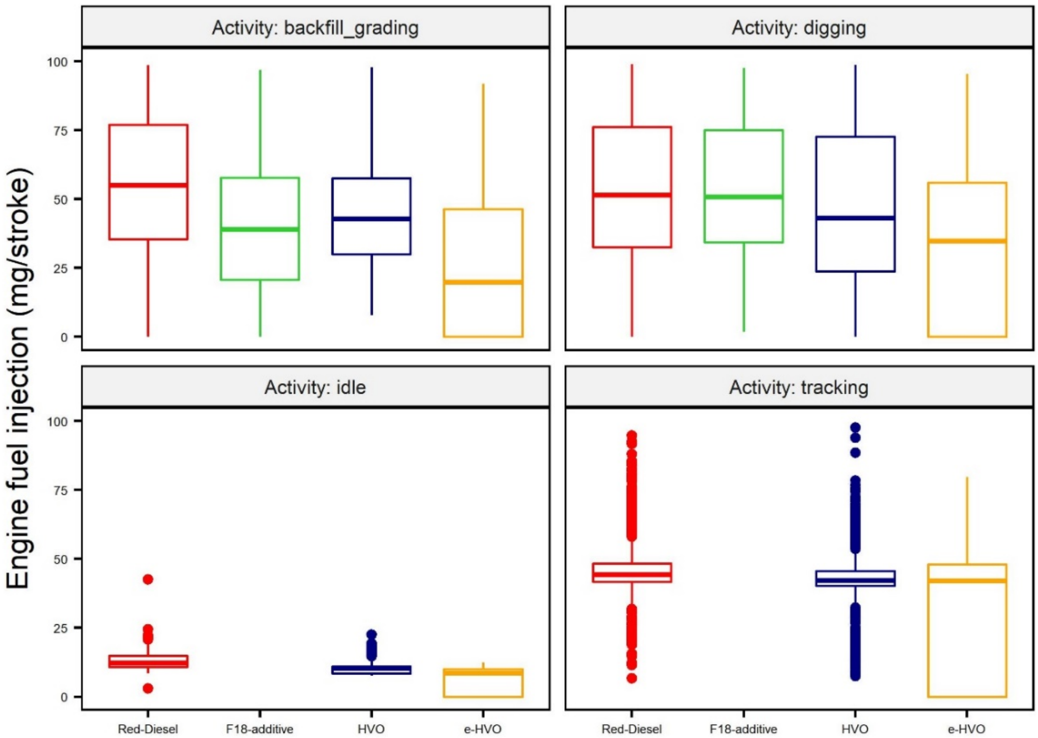


**Figure 28 Box plots of engine fuel injection (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

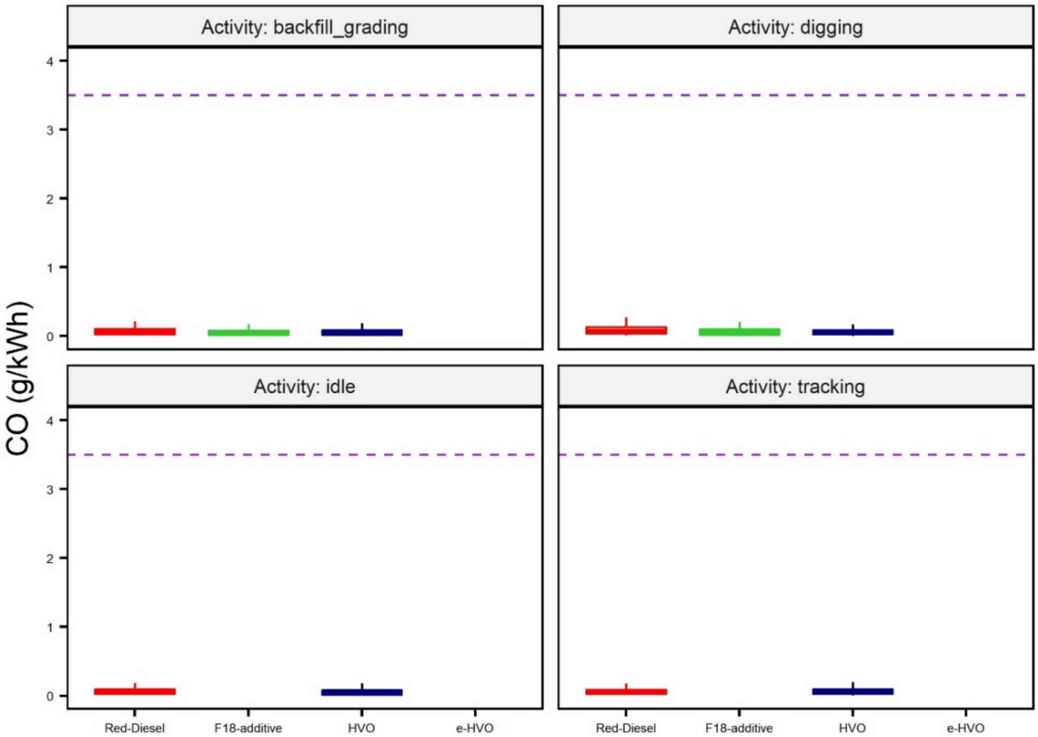


**Figure 29 Box plots of CO emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

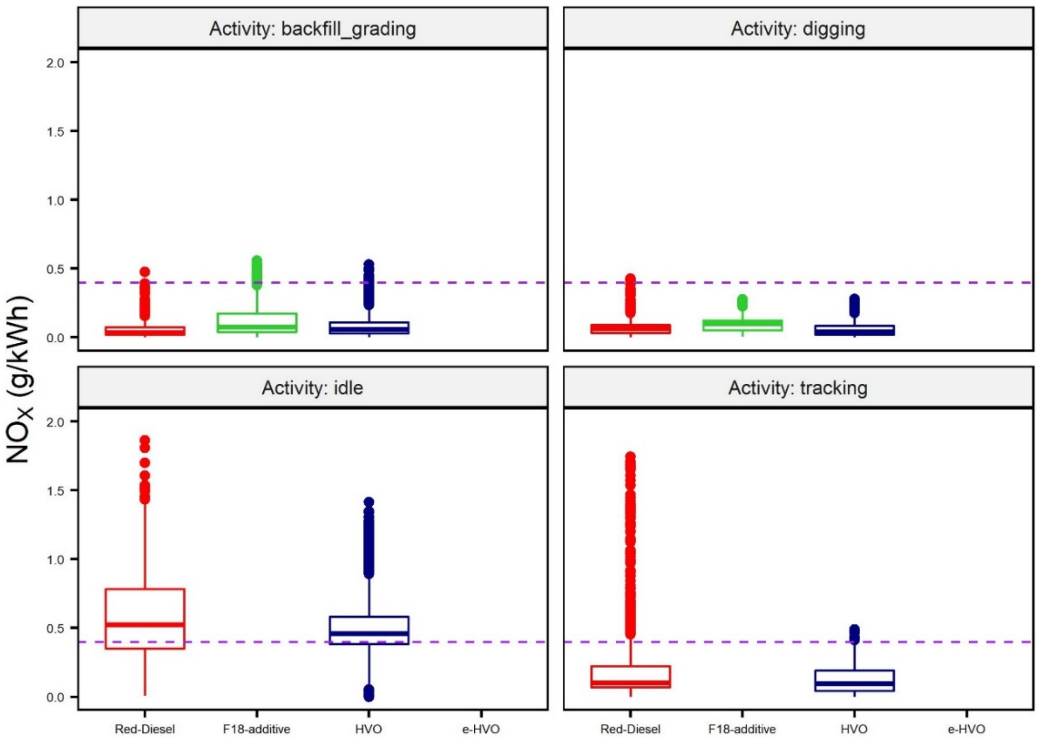


**Figure 30 Box plots of $NO_X$ emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

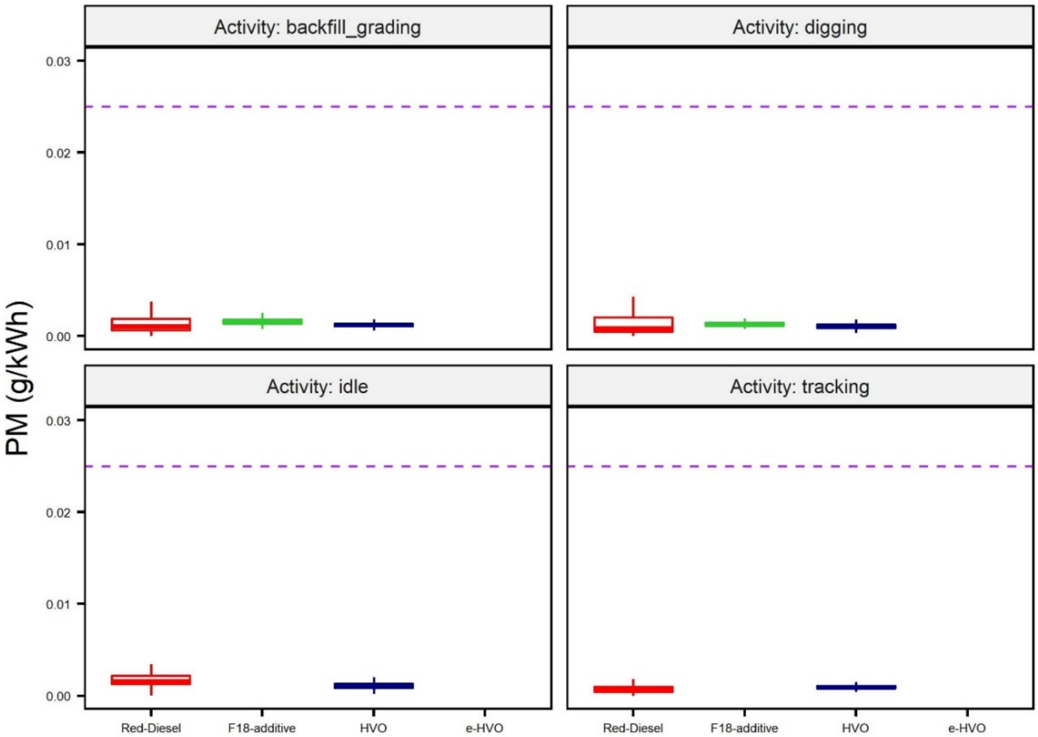


**Figure 31 Box plots of PM emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

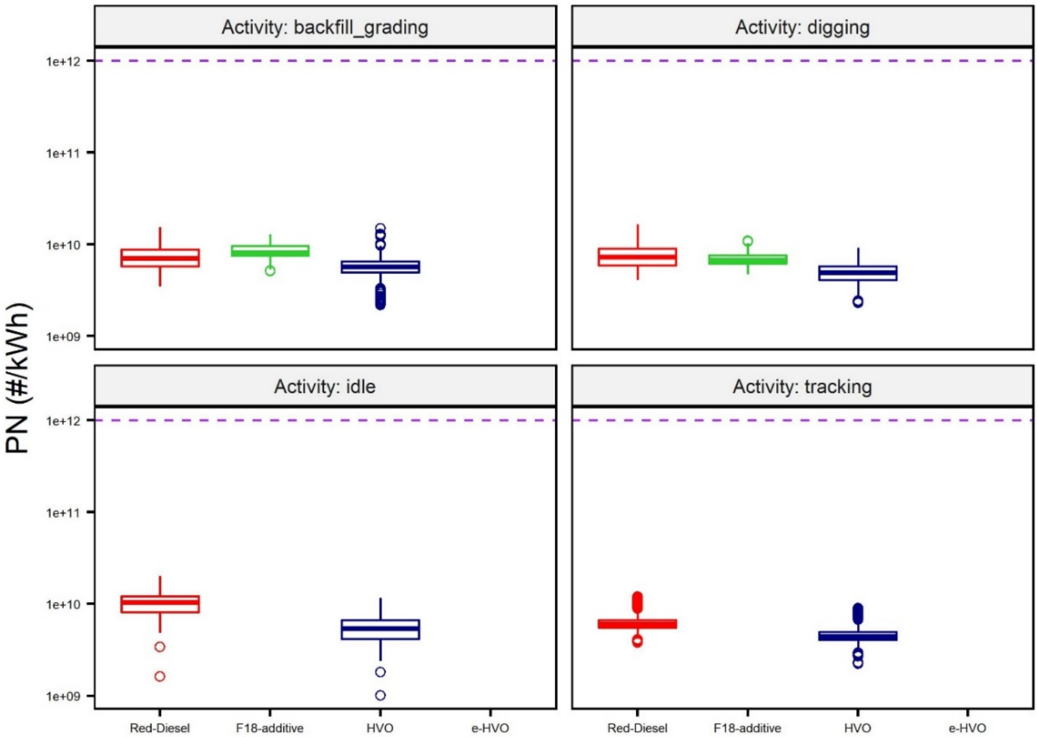


**Figure 32 Box plots of PN emission standards (Liebherr) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

## 6.2 KOMATSU EXCAVATOR

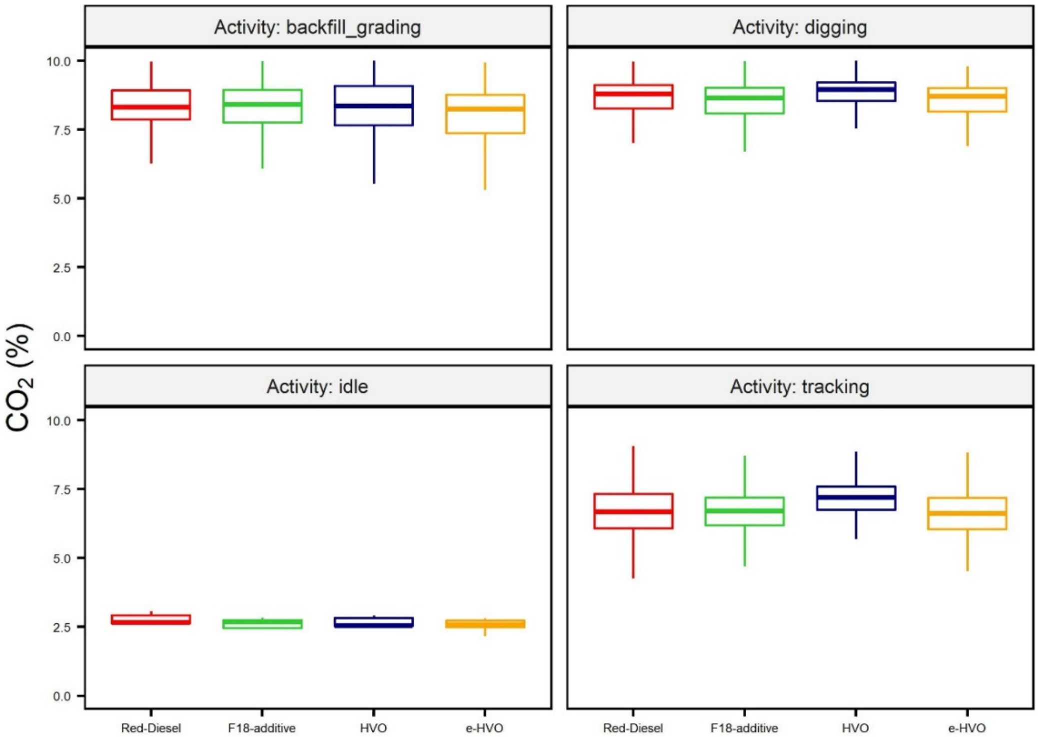


**Figure 33 Box plots of $CO_2$ emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

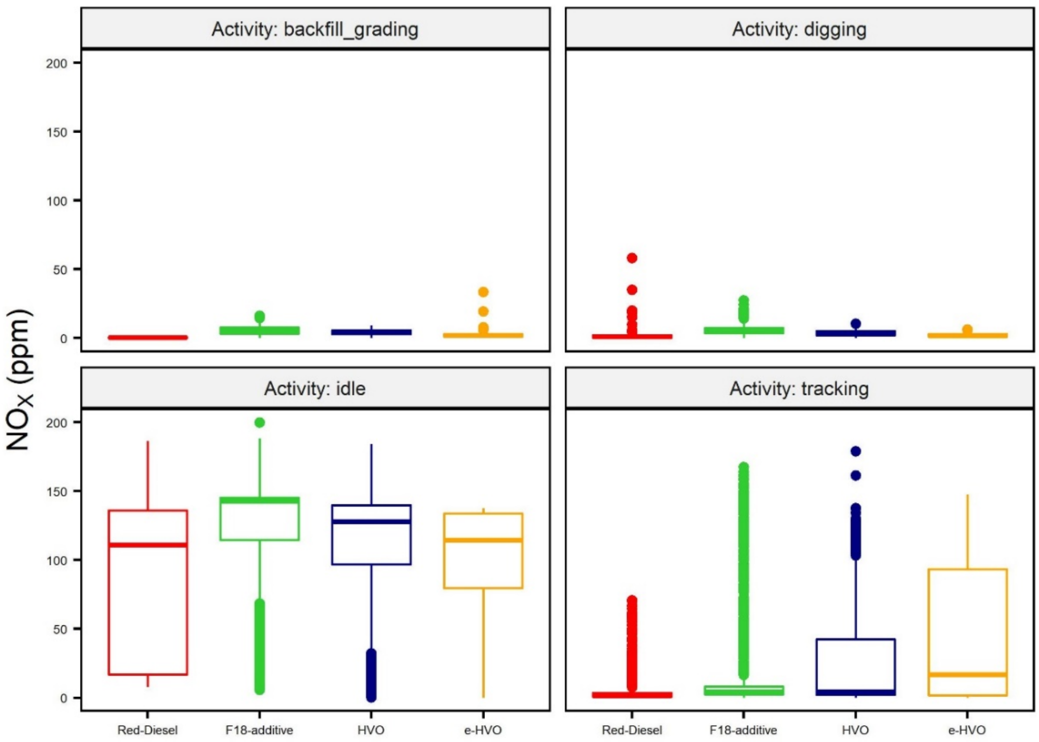


**Figure 34 Box plots of NOx emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

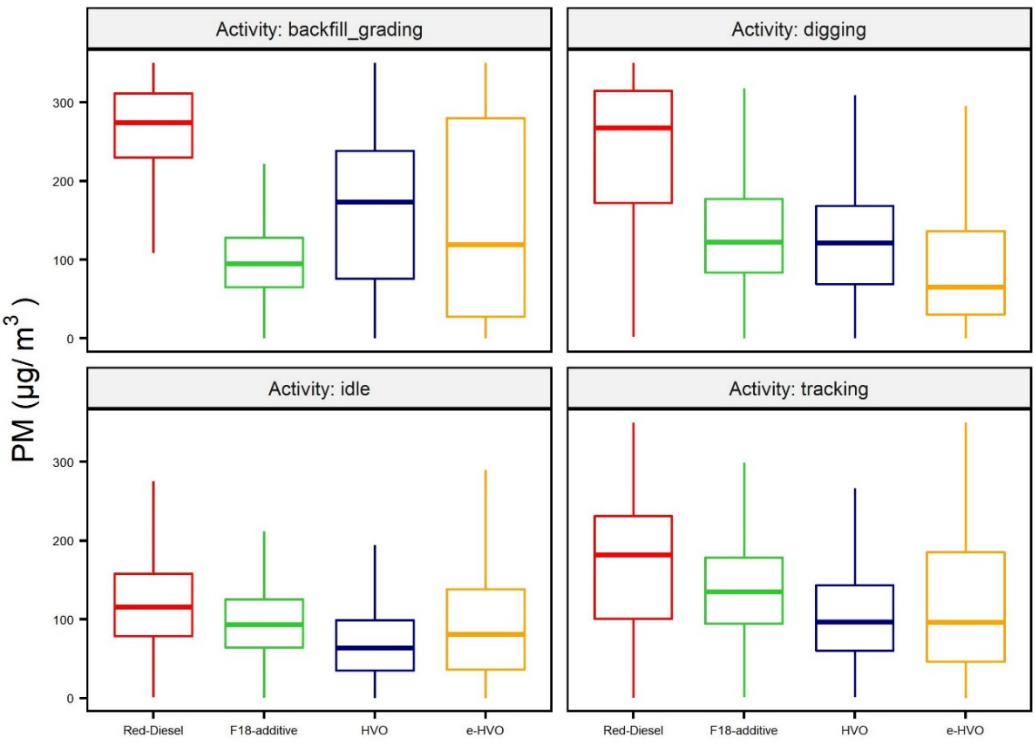


**Figure 35 Box plots of PM emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

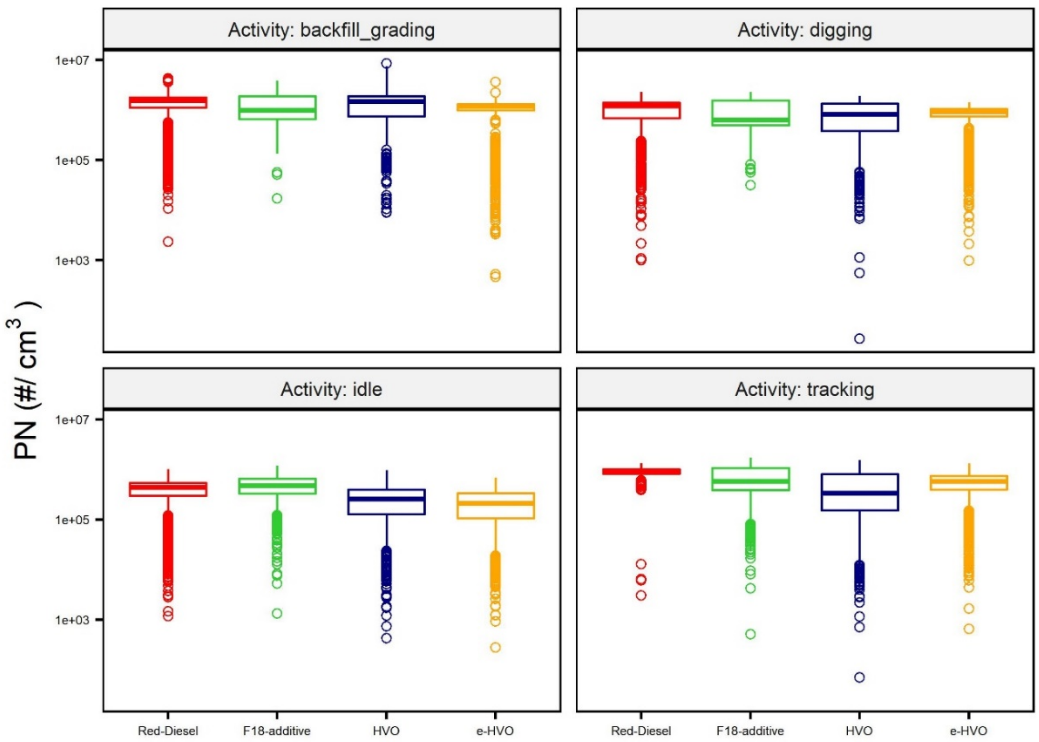


**Figure 36 Box plots of PN emissions (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

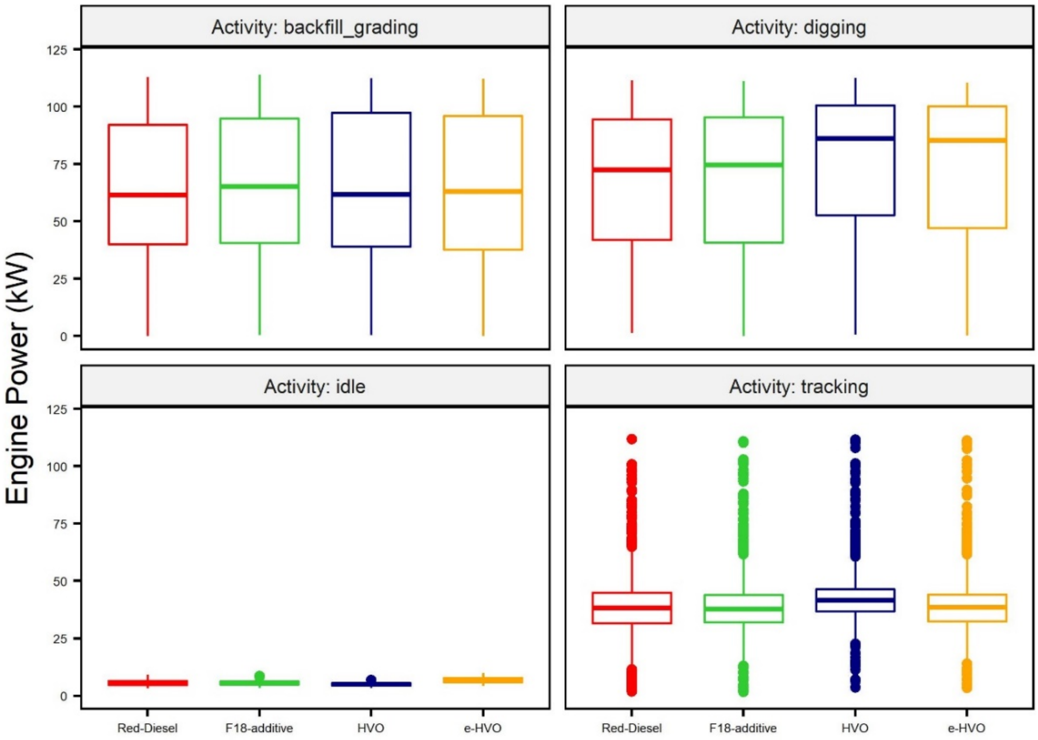


**Figure 37 Box plots of engine power (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

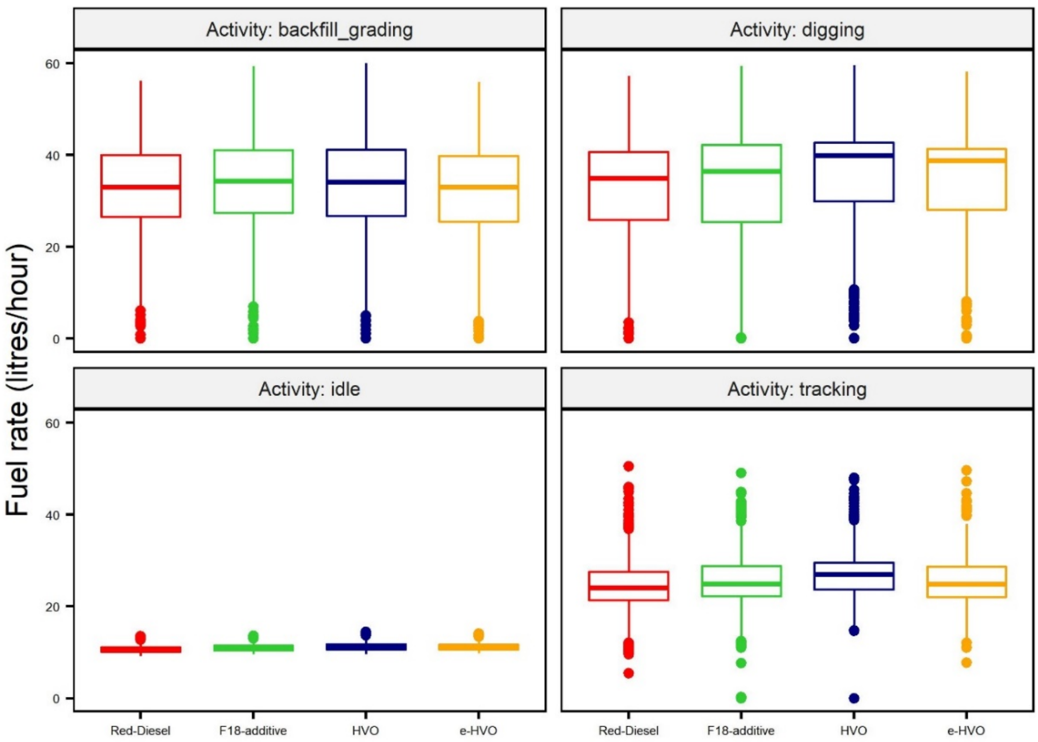


**Figure 38 Box plots of engine fuel rate (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

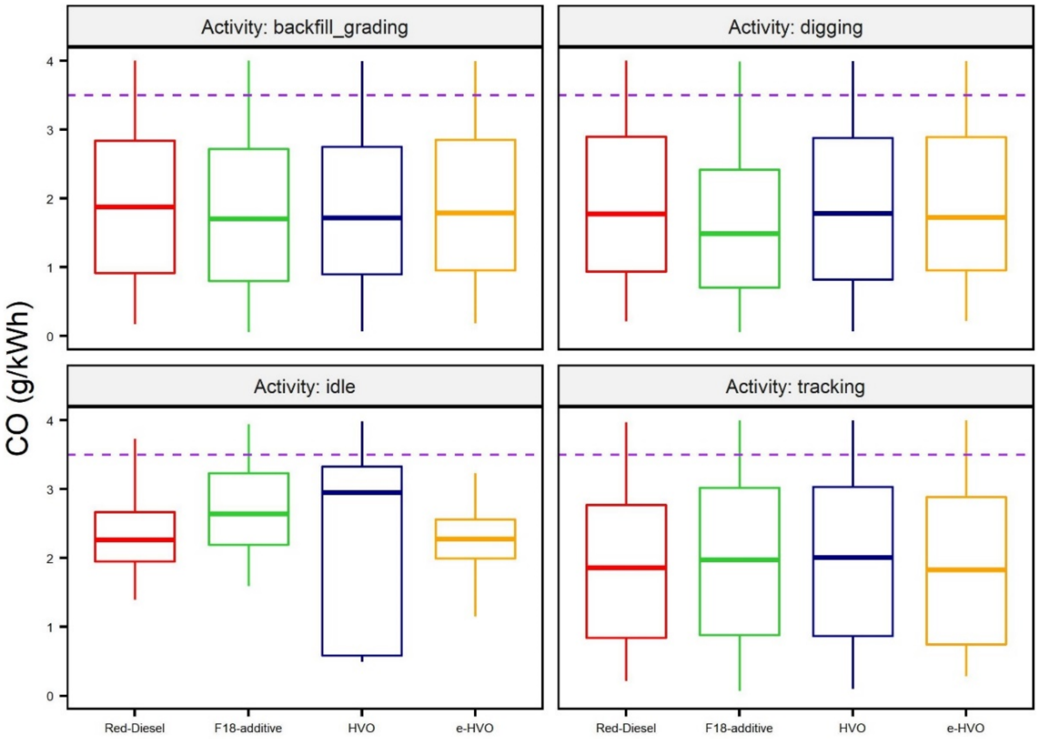


**Figure 39 Box plots of CO emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

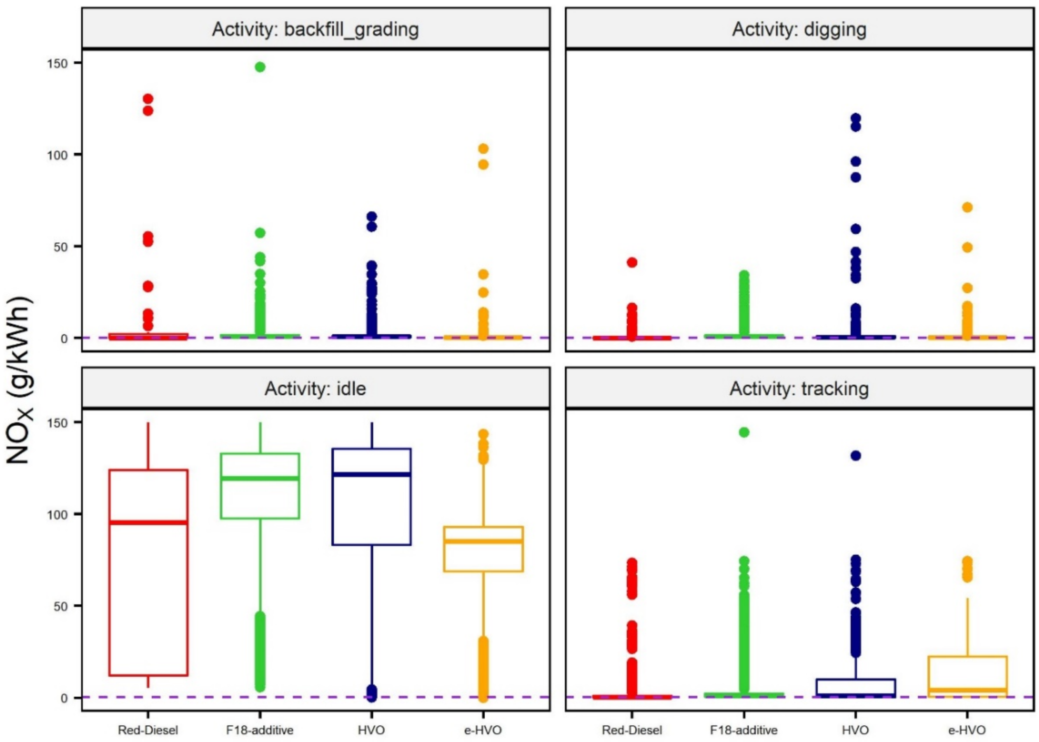


**Figure 40 Box plots of $NO_X$ emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

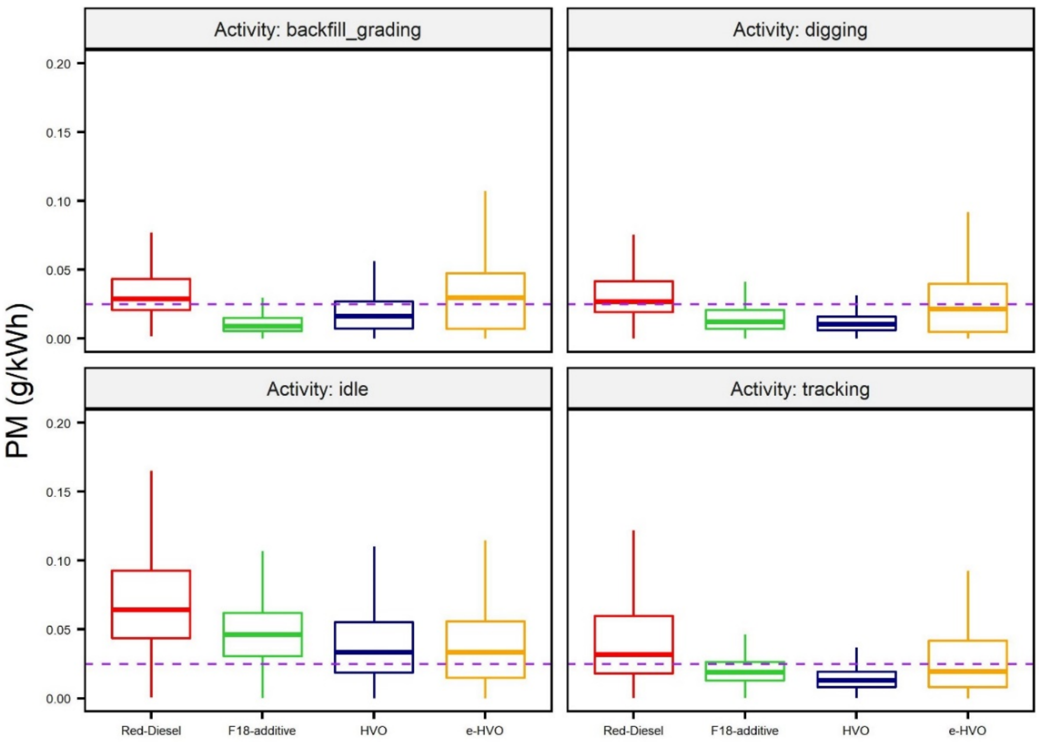


**Figure 41 Box plots of PM emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

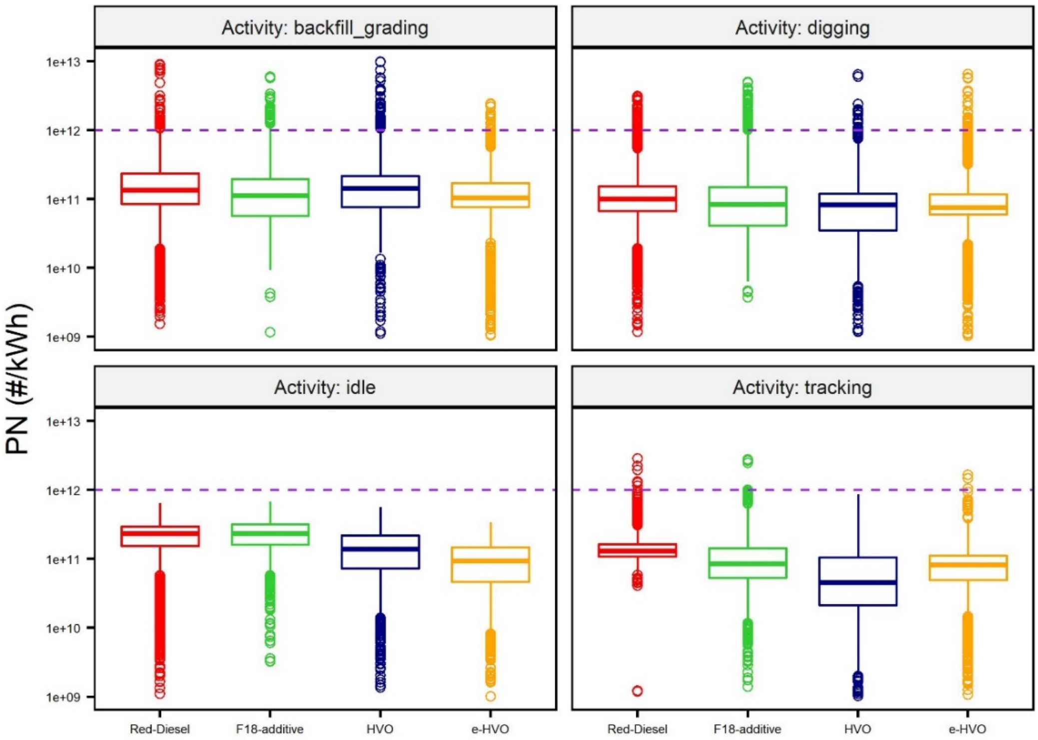


**Figure 42 Box plots of PN emission standards (Komatsu) comparing Red-Diesel with F18-additive, HVO, and enhanced HVO (e-HVO). Red-Diesel is plotted in red, F18 additive in green, HVO in blue and enhanced HVO (e-HVO) in yellow.**

Imperial College London
Projects

Environmental Research Group

## Contact us:

Daniel Marsh - Programme Manager
Email: daniel.marsh@imperial.ac.uk

Natasha Ahuja - Imperial Projects
Email: n.ahuja@imperial.ac.uk

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