Zemo Partnership
Accelerating Transport to Zero Emissions

HGV Auxiliary Engines:

Baseline auxTRU testing and modelling of UK impacts

The results of a DfT funded programme to measure the baseline energy consumption and emissions performance of diesel auxiliary transport refrigeration units (auxTRUs) and model their UK environmental impacts

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Contents

Contents

Executive Summary

With tailpipe pollutant emissions from heavy vehicles falling rapidly as the latest Euro VI regulations take effect, the scope of air quality improvement is widening towards other sources such as ancillary engines used for purposes other than vehicle propulsion. These engines include auxiliary transport refrigeration units (auxTRUs) fitted to many of the heavy goods vehicles (HGVs) used in cold chain distribution systems. These fall under the general term "non-road mobile machinery" (NRMM) but in the case of auxTRUs, the emissions are on the road in real terms.

This new research is largely designed to take forward the recommendations for further research we made in our report for Transport Scotland[1]. Crucially, however, the research aims to expand the scope beyond transport refrigeration units and technologies, to cover other commonly used forms of auxiliary HGV engines – i.e. those permanently fitted and used to perform functions separate from vehicle propulsion, e.g. road sweepers, cranes etc. Such engines are regulated as Non-Road Mobile Machinery.

The DfT funded research programme began towards the end of 2022 and is scheduled to complete in November 2024. This report covers the results from the first phase of the research, namely further emissions testing of conventional diesel auxiliary TRUs and a comprehensive aux engine market review. It also combines the test and survey results to provide some initial UK-wide estimates as to the overall fuel consumption and environmental impacts of diesel auxTRUs.

A major new programme of baseline testing of diesel auxTRU systems has been completed. Combined with data from earlier tests, we now have a much stronger evidence base as to their overall environmental impacts under different usage conditions (chilled, frozen and multi-temperature), at different ambient temperatures (from 5 to 30 °C) and how those emissions vary between pre-2019 and post-2019 units – the Non-Road Mobile Machinery (NRMM) regulations started to impose limits on some auxTRU emissions from January 2019.

[1] Emissions Testing of Two Auxiliary Transport Refrigeration Units, Zemo Partnership 2021.

A market survey has also been conducted and its results used to more robustly characterise the operational duties of the UK's auxTRU fleet, including their use across the three operational modes and their typical annual hours of use.

National data sources and published literature have been used to estimate the overall numbers of diesel auxTRU in use in the UK (reckoned to be in the range 40,000-55,000) and combined with the survey and test programme results to produce the following overall estimates for UK environmental impacts:

- UK diesel auxTRU consume around 235 million litres of fuel per annum (range 132-364 Ml).
- They contribute about 590 kilo-tonnes of tailpipe GHG emissions (range 330-910 kt). Note this does not include other GHG emissions, e.g. from loss of refrigerant.
- They produce around 4.4 kt of NOx emissions (range 2.5-6.8 kt).
- They emit about 126 tonnes of $PM_{2.5}$ particulate mass emissions (range 71-195 t).
- And they emit about 330 x 10^{21} particle number (PN) emissions (range 185-510 x 10^{21}).

The test results indicate that in comparison to the vehicle's Euro VI compliant propulsion engine, a single diesel auxTRU fitted to a Euro VI HGV would (in a city/urban environment during periods of reasonably average ambient temperatures):

- Consume about **1/9th the fuel if manufactured prior to 2019 or about 1/10th if after 2019.**
- Produce about **1/9th or 1/10th the GHG emissions respectively.**
- Produce at least **double (2x) the NOx if pre-2019 and at least 50% more (1.5x) if post-2019.**
- Emit at least **five times (5x) the Particle Mass ($PM_{2.5}$) if pre-2019 and around triple (3x) if post-2019.**
- Emit about **400 times (400x) the number of particles if pre-2019 and around 300 times (300x) if post-2019.**

1. Introduction

1.1 Background

With tailpipe pollutant emissions from heavy vehicles falling rapidly as the latest Euro VI regulations take full effect, the scope of air quality improvement efforts is widening towards other sources such as brake and tyre wear, construction equipment and ancillary engines used for purposes other than vehicle propulsion. These engines include auxiliary transport refrigeration units (auxTRUs) fitted to many heavy goods vehicles, and other engines commonly fitted to HGVs (in addition to and separate from the propulsion engine). These fall under the general term "non-road mobile machinery" (NRMM) but in many cases, the emissions are generated on the road in real terms.

Greenhouse gas (GHG) emissions are also, of course, a major concern. Most existing auxiliary engine applications use the combustion of fossil diesel fuel to provide the power and energy needed, with commensurate emissions of carbon dioxide and other GHGs.

As well as the long-standing environmental prerogative to find lower and zero emission solutions, recent changes to the tax treatment of this diesel fuel (predominantly gas oil or "red diesel"), and fuel price increases brought about in large part by the conflict in Ukraine, have brought into sharp focus commercial issues and the desirability to operators of finding lower cost solutions.

Furthermore, while there are now clear timelines in place for the full decarbonisation of all road vehicles, through the ramping up of renewable energy generation and phase-out dates for the sale of non-zero emission vehicles (including HGVs up to 26t by 2035 and over 26t by 2040), there are as yet no such dates set for NRMM. Without clear policy direction, this situation could result in emissions from this sector remaining relatively high and increasingly threatening to undermine cross-economy moves towards net zero.

To further complicate the issue, there is currently a lack of robust information on exactly how many engines are in use, what duties they perform, how much fuel they burn or what emissions they collectively or individually produce.

In 2018, Cenex, supported by Zemo Partnership, attempted to quantify the scale of the emissions challenge from Transport Refrigeration Units (TRUs) in London via desktop analysis of the TRU market and use, combined with estimated emission performance. Amongst that study's conclusions was "…a clear need to develop an emissions evidence base from real-world emissions testing."

With this identified need to improve the TRU emissions evidence base, in 2019 Zemo Partnership was funded by Innovate UK to develop and validate an initial emissions test protocol for auxiliary transport refrigeration units (auxTRUs). As part of that preparatory work, pilot testing of a single diesel auxTRU was carried out[2]. This largely validated the proposed test procedures as being broadly representative of typical in-service conditions but also indicated that pollutant emissions such as oxides of nitrogen and particulates from an auxTRU could be many (up to two hundred) times higher, per hour or per kilometre driven, than a Euro VI vehicle to which it might be fitted.

This was, however, based on just one set of tests on one unit, therefore it could not be stated with high confidence that these emissions levels are representative of the wider auxTRU fleet. The 2019 report clearly identified the need for a more comprehensive series of baseline tests to establish if the pilot test results were indeed representative or in some way atypical.

In 2021, Transport Scotland provided funding for Zemo Partnership to carry out further emissions testing on two more conventional diesel auxTRUs, one fitted to a full-size semitrailer and the other to a (smaller) three-axle rigid HGV (26 tonne gross weight), each at two separate ambient temperatures (selected to be broadly representative of typical daytime summer and winter temperatures in Scotland). Chilled tests were at a target of 2 °C, frozen at -15 °C (rigid HGV) or -20 °C (semitrailer). The units tested date from 2014 and 2016 and are considered likely to be broadly representative of the current in-service fleet. It cannot, however, be assumed the results obtained would be representative of the very latest auxTRU products (produced since regulatory changes took effect in January 2019).

Our report for Transport Scotland concluded by making various next step recommendations to further strengthen the evidence regarding current refrigerated transport technologies, the various alternative technologies and the retrofit solutions that could potentially be deployed to reduce the sector's environmental impacts.

This new research is largely designed to take forward the recommendations for further research we made in our report for Transport Scotland. Crucially, however, the research aims to expand the scope beyond transport refrigeration units and technologies, to cover other commonly used forms of auxiliary HGV engines – i.e. those permanently fitted and used to perform functions separate from vehicle propulsion, e.g. road sweepers, cranes etc. Such engines are regulated as Non-Road Mobile Machinery (NRMM).

The DfT funded research programme began towards the end of 2022 and is scheduled to complete in November 2024. This report covers the results from the first phase of the research, namely further emissions testing of conventional diesel auxiliary TRUs, combined with a comprehensive aux engine market review to model their UK-wide emissions impacts.

[2] Development of Emissions Testing Procedures for Transport Refrigeration Units (TRUs), LowCVP June 2019.

1.2 Objectives

The objectives of this first research phase were:

Emissions testing of conventional diesel auxiliary TRUs

- Test new auxTRUs, certified as being compliant with NRMM Stage V, which came into effect for all units entering the market after 1st January 2019, to provide evidence as to whether such units have demonstrably lower emissions impacts than the pre-2019 models tested to date.
- Extend baseline auxTRU testing to include other manufacturers (all three units tested to date have been from the same supplier), to ensure the baseline evidence base is more fully representative of the in-service fleet.

Extend baseline testing

- Develop the test procedures to include assessment of multi-temperature operations typical of normal cold-chain distribution systems. This will help to strengthen the emissions testing protocols by being more fully representative of normal in-service conditions.

Market Review

- Gather comprehensive and nationally/regionally representative data on typical aux engine operations and duty cycles to inform future test process development and provide confidence in making overall fleet environmental impact estimates.

1.3 Methodology

The basic test methodology followed the protocols developed by Zemo Partnership, as first reported in 2019 and then used again for the Transport Scotland research reported in 2021.

This involves loading a refrigerated vehicle with a combination of pre-conditioned water-filled containers and empty cardboard boxes in such a way as to realistically simulate real-world air flow and temperature conditions within the load space.

The vehicle is then placed into a temperature-controlled test chamber at a defined ambient temperature and the auxTRU is run for several hours, maintaining the desired internal load space temperature(s); chilled, frozen or a multi-temp combination of the two. During the tests, the vehicle's doors are periodically opened for a defined amount of time to simulate delivery/drop-off events.

Throughout the tests, measurements are taken of diesel auxTRU fuel consumption (from which CO_2 emissions can be calculated), internal and external temperatures and the emissions of oxides of Nitrogen (NOx) and particulates (both their mass, $PM_{2.5}$, and number, PN).

A survey to better characterise the temperature-controlled HGV fleet was developed in collaboration with the University of Birmingham (who are contracted separately by DESNZ to carry out research into cold chain decarbonisation). The survey was targeted at four specific sectors:

- Transport Operators including Supermarkets.
- Rental and Leasing Companies.
- Transport Refrigeration manufactures and dealers.
- Commercial body builders.

Companies in each sector had around 20-30 questions to answer and the companies surveyed were identified via desktop research and industry knowledge using published company activity data. The survey was designed to not be burdensome on the companies completing it and uses transport industry specific terminology. The survey responses, coupled with the test results and other relevant data sources have then been used to model/estimate the overall environmental impacts of diesel auxTRUs across the UK.

A less formal market review has also been carried out to identify non-TRU auxiliary engine types commonly used on-road by HGVs.

1.4 Report structure

Chapter 2 fully describes the test procedures and measurement systems. Chapter 3 presents the fuel consumption and emissions results and compares them to those from the previous tested reported in 2019 and 2021. Chapter 4 presents the survey results and combines them with the emissions data to provide UK-wide emissions estimates for TRUs. Chapter 5 summarizes the initial findings from a review of the market for non-TRU HGV auxiliary engines. Chapter 6 summarises our conclusions and makes a series of recommendations for the second phase of this research.

1.5 Commentary on particulate emissions

Particulate Matter (PM) is highly varied in size, chemical composition, and origin, all of which influence particle behaviour and their impacts on human health. Typically, particulates are characterized by their aerodynamic diameter, and range from 'ultrafine' to 'coarse'. 'Ultrafine' particles have an aerodynamic diameter of less than 0.1 µm, 'fine' particles have a diameter of less than 2.5 µm (commonly known as $PM_{2.5}$) and 'coarse' particles have a diameter between 2.5 to 10 µm ($PM_{2.5-10}$).

Finer particles are much more effective at permeating deep into the human respiratory and cardiovascular systems, as they are less likely to be filtered out by the nasal passage during inhalation. $PM_{2.5}$ has been linked to a vast array of adverse health effects, such as asthma, lung cancer, strokes, chronic obstructive pulmonary disease (COPD) and heart disease. The extent to which particulates impact our health is still not yet fully understood, as seen with emerging concerns that ultrafine particles can breach and consequently impact the central nervous system.

When measuring the levels of particulates, ultrafine and fine particulates will influence particulate number more than they will particulate mass as a result of being lighter and smaller, with the inverse being true for coarser particulates.

Historically, vehicle emissions tests have measured PM based on particulate mass concentrations, achieved by measuring a weight increase on a particulate filter. Unfortunately, the omission of regulation around particulate number means that ultrafine particulate emissions may have flown somewhat under the radar. Furthermore, particulate number concentrations may be the more significant indicator for any consequent human health impacts. To tackle this, the EU introduced regulatory amendments in 2016 for NRMM engines, commonly known as the Stage V regulations. This widened the regulatory scope to include particle number, as well as the particulate mass-based approach, specifically to introduce the regulation of ultrafine particle emissions. It is important to note, however, that the particle number requirements do not apply to engines of less than 19 kW rated power, which will include auxiliary transport refrigeration units.

For the remainder of this report, particle mass measurements are referred to interchangeably as either PM or $PM_{2.5}$ and particle number measurements as PN. A more detailed analysis of the exact distribution of the particles emitted by size is beyond the scope of this report but it is likely that the results presented cover the mass and number of particles emitted in the size range 0.01-0.50 µm and that there would have been very few if any particles emitted of sizes outside of this range.

2. Test procedures

The test programme was carried during 2023 under the supervision of Cambridge Refrigeration Technology (CRT), an independent research and test organisation. CRT provides expertise for industry within the areas of environmental testing, refrigerated systems and cargo care.

Pollutant emissions monitoring was carried out by Cambustion Ltd, an independent, privately owned company with headquarters also in Cambridge and world-class expertise in fast response measurement of gaseous and particulate emissions.

CRT and Cambustion were similarly contracted by Zemo Partnership to run the pilot auxTRU testing programme in 2019 and the testing for Transport Scotland in 2021, thus providing continuity and consistency with all the earlier research.

2.1 Vehicle and auxTRU details

All testing was on auxTRUs fitted to full-size semitrailers - testing carried out in 2021 indicated little difference between otherwise similar systems fitted to rigid HGVs or semitrailers and as semitrailer systems are more common, they were chosen to be the focus of this new research.

Of the six units tested:

- One was a pre-2019 unit manufactured by Thermo King (TK).
- Three were post-2019 units also manufactured by Thermo King.
- Two were post-2019 units manufactured by Carrier.

For reference, the three auxTRUs tested in earlier research were all pre-2019 units manufactured by Carrier.

Full details of all the units tested are provided in Table 1. Results from the post-2019 units (i.e. those in current production) have been anonymized in this report. The purpose of this research was to develop a representative evidence base for auxTRU emissions across the UK fleet, not to assess any differences between individual makes or models.

Table 1. Details of auxTRUs tested

Manufacturer	Model	Capacity at 0 °C	Age	Refrigerant
Carrier	Vector HE19 MT	17.6 kW	Post-2019	R452A
Carrier	Vector HE19 MT	17.6 kW	Post-2019	R452A
Thermo King	Advancer 400	16.2 kW	Post-2019	R452A
Thermo King	Advancer 400	16.2 kW	Post-2019	R452A
Thermo King	Advancer 500	18.6 kW	Post-2019	R452A
Thermo King	SLXe 300	14.7 kW	Pre-2019	R404A

Prior to testing, CRT checked each auxTRU was operating correctly.

2.2 Instrumentation

Tests were carried out in CRT's environmental test chamber with an external airflow of 1-2 m/s and the necessary extraction of exhaust fumes.

2.2.1 Temperature measurement & control

Average temperatures inside and outside the load box were measured at a frequency of 1 Hz using more than twenty Type 'T' thermocouples, placed in various locations in accordance with CRT's standard test set-ups. The chilled or frozen load was simulated using a combination of six pre-cooled Intermediate Bulk Containers (IBCs) and pallets loaded with empty cardboard boxes. Each IBC was filled with approximately 600 litres of water and 25kg of sodium chloride salt, cooled to (and stabilised at) the required test target temperatures in separate refrigeration chambers beforehand. The load was arranged as shown below in Figure 1.

Figure 1. Boxes and IBC locations

2.2.2 Fuel and emissions measurement

Cambustion used their rapid response engine particulate analyser and fast NOx analyser to measure (also at 1 Hz) the gases coming from the refrigeration unit's exhaust pipe. These measured:

- Nitric oxide (NO) and nitrogen dioxide (NO_2)
- Oxides of nitrogen (NOx = NO + NO_2)
- Particle size distributions from 5nm-1μm
- Particle number (PN, measured in ways equivalent to Euro 6 protocols)
- Particle mass ($PM_{2.5}$, estimated based on measured distribution of particle sizes)

Fuel consumption was measured once every 20 seconds via a container placed on weighing scales.

2.3 Test protocol

Tests on all six auxTRU generally involved two modes and one ambient temperature (15 °C):

- Chilled (setpoint 2 °C, 4-5 hours total duration)
- Frozen (setpoint -20 °C, 6-7 hours)

For operational reasons at CRT at the time, one of the units could only be tested in frozen mode. For this unit, an additional test at 5 °C ambient temperature was carried out to provide a further direct comparison with the 2021 test programme results. As part of the same issue, another of the units could only be tested in chilled mode; for this unit, a re-test at 15 °C ambient temperature was carried out to check test-to-test repeatability.

The sixth unit was in addition used for a series of multi-temperature tests and tested under a broader range of ambient temperatures (5, 15 and 30 °C). The multi-temperature tests were configured with a 50:50 split between chilled and frozen compartments.

Six phases were used for each mode, with the total duration varying, dependent largely on how long the auxTRUs took to achieve the setpoint temperatures (longer for frozen mode tests than chilled):

1. Stabilise empty trailer/vehicle in test chamber at target ambient temperature.
2. Remove from test chamber and load with pre-chilled/frozen, water-filled IBCs and empty cardboard boxes.
3. Close doors, install into chamber again, and run auxTRU to pull down to setpoint(s).
4. Run auxTRU in continuous mode (chilled) or stop/start mode (frozen and multi-temp) for 3 hours.
5. 30-minute door opening (with auxTRU running).
6. Close doors and auxTRU pulls down again to setpoint(s), at which stage test ends.

Note that due to logistical constraints at the test site, the trailer and vehicle had to be removed from the chamber for loading. The TRU was switched off while this loading took place. The cardboard boxes and IBCs were stored in separate chambers prior to loading to ensure they were uniformly at the setpoint temperatures, so the pull-down (in the third phase) would serve to reduce the temperature of the air above the load but not, to any appreciable degree, the load itself. This approach was adopted to replicate normal practice by temperature-controlled transport (TCT) vehicle operators.

3. Test results

3.1 Chilled mode

The following sections present the main results from the chilled tests at 2 °C; the temperatures, fuel consumption, NOx and particle emissions data taken from the tests on each auxTRU.

3.1.1 Temperatures & fuel consumption

Table 2 summarises the internal temperatures achieved, and fuel consumed during each phase.

A quite significant improvement in fuel consumption is suggested for the post-2019 units, compared to the pre-2019 unit tested here, of the order of 20-40%.

On average, fuel consumption for the semitrailer auxTRUs varied between 1.05 and 1.75 litres per hour (l/h) at 15 °C. While there were small variations in fuel consumption rates between the two tests on one of the post-2019 units, these were within +/- 5%, indicating good test repeatability.

There were generally only quite small differences in fuel consumption rates between the pull-down and steady state phases, suggesting that under these chilled conditions (and at relatively modest ambient temperatures) the units ran at a fairly constant speed throughout the tests. At 30 °C ambient temperature, however, the rate of fuel consumption during the initial pull-down was notably higher than (more than three times) that measured during the steady-state phase.

The unit tested at 5, 15 and 30 °C ambient temperatures consumed fuel at roughly double the rate at the highest ambient temperature compared to the lowest, but the increase in consumption in moving from 5 to 15 °C ambient was less marked and under steady-state conditions was almost identical.

Table 2. Chilled mode temperatures and fuel results

Phase	Ambient °C	Duration mins	Internal °C Max	Internal °C Mean	Internal °C Min	Fuel used litres	Fuel consumption litres per hour
Unit 1: pre-2019							
3 Pull-Down 1	15	30	4	2	0	0.93	1.86
4 Steady State	15	180	3	2	1	5.11	1.70
5 Doors Open	15	30	11	5	2	0.95	1.90
6 Pull-Down 2	15	7	5	2	1	0.23	1.97
All	**15**	**247**				**7.22**	**1.75**
Unit 2: post-2019							
3 Pull-Down 1	15	30	9	4	1	0.58	1.16
4 Steady State	15	180	6	3	1	3.05	1.02
5 Doors Open	15	30	12	6	2	0.58	1.16
6 Pull-Down 2	15	22	8	4	2	0.37	1.01
All	**15**	**262**				**4.58**	**1.05**
Unit 3: post-2019							
3 Pull-Down 1	15	28	7	4	1	0.54	1.16
4 Steady State	15	180	6	3	1	3.16	1.05
5 Doors Open	15	30	12	6	2	0.59	1.18
6 Pull-Down 2	15	11	7	4	1	0.19	1.04
All	**15**	**249**				**4.48**	**1.08**
Unit 4: post-2019							
3 Pull-Down 1	15	21	14	4	-2	0.58	1.66
4 Steady State	15	180	5	2	-1	3.89	1.30
5 Doors Open	15	30	13	7	1	0.69	1.38
6 Pull-Down 2	15	5	8	3	0	0.13	1.56
All	**15**	**236**				**5.29**	**1.34**

Phase	Ambient °C	Duration mins	Internal °C Max	Internal °C Mean	Internal °C Min	Fuel used litres	Fuel consumption litres per hour
Unit 4: post-2019 (re-test)							
3 Pull-Down 1	15	36	7	2	-1	1.05	1.75
4 Steady State	15	180	10	2	0	4.20	1.40
5 Doors Open	15	30	12	5	0	0.74	1.48
6 Pull-Down 2	15	7	9	3	1	0.17	1.46
All	**15**	**253**				**6.16**	**1.46**
Unit 6: post-2019							
3 Pull-Down 1	30	101	17	7	2	6.72	4.01
4 Steady State	30	180	8	4	1	3.76	1.25
5 Doors Open	30	30	24	11	1	0.88	1.77
6 Pull-Down 2	30	43	14	5	2	1.00	1.38
All	**30**	**354**				**12.36**	**2.10**
3 Pull-Down 1	15	61	12	5	1	1.48	1.46
4 Steady State	15	180	6	3	0	3.10	1.03
5 Doors Open	15	30	13	6	2	0.63	1.26
6 Pull-Down 2	15	15	12	3	1	0.30	1.18
All	**15**	**286**				**5.51**	**1.16**
3 Pull-Down 1	5	51	9	5	2	1.09	1.29
4 Steady State	5	180	6	3	1	3.06	1.02
5 Doors Open	5	30	4	3	2	0.53	1.07
6 Pull-Down 2	5	7	5	5	5	0.12	0.96
All	**5**	**268**				**4.80**	**1.07**

3.1.2 NOx emissions

Table 3 shows the total cumulative emissions of oxides of Nitrogen (NOx) in each phase, along with the primary NO_2 percentages. In line with the improvements in fuel consumption, NOx emissions also appear to be somewhat lower for the post-2019 units, by around 25-50%.

There was again good repeatability (within +/- 5%) between the two tests on one post-2019 unit.

The test at 30 °C ambient temperature produced only modest increases in NOx production rates compared to the lower temperature tests on that unit, but still well within the range of the other post-2019 units at 15 °C ambient.

Table 3. Chilled mode NOx emissions results

Phase	Ambient °C	Duration mins	NOx grammes	NOx rate grammes per hour	Primary NO_2 %
Unit 1: pre-2019					
3 Pull-Down 1	15	30	22	44	20
4 Steady State	15	180	117	39	22
5 Doors Open	15	30	22	44	19
6 Pull-Down 2	15	7	5	41	21
All	**15**	**247**	**166**	**40**	**22**
Unit 2: post-2019					
3 Pull-Down 1	15	30	15	30	18
4 Steady State	15	180	64	21	23
5 Doors Open	15	30	12	24	21
6 Pull-Down 2	15	22	8	22	22
All	**15**	**262**	**99**	**23**	**22**
Unit 3: post-2019					
3 Pull-Down 1	15	28	19	41	16
4 Steady State	15	180	83	28	19
5 Doors Open	15	30	15	29	19
6 Pull-Down 2	15	11	5	27	20
All	**15**	**249**	**122**	**29**	**19**

Phase	Ambient °C	Duration mins	NOx grammes	NOx rate grammes per hour	Primary NO_2 %
Unit 4: post-2019					
3 Pull-Down 1	15	21	13	38	13
4 Steady State	15	180	73	24	14
5 Doors Open	15	30	17	34	14
6 Pull-Down 2	15	5	3	35	10
All	**15**	**236**	**107**	**27**	**14**
Unit 4: post-2019 (re-test)					
3 Pull-Down 1	15	36	20	33	15
4 Steady State	15	180	81	27	16
5 Doors Open	15	30	15	30	14
6 Pull-Down 2	15	7	3	30	14
All	**15**	**253**	**119**	**28**	**15**
Unit 6: post-2019					
3 Pull-Down 1	30	101	50	30	15
4 Steady State	30	180	64	21	22
5 Doors Open	30	30	15	31	10
6 Pull-Down 2	30	43	17	24	16
All	**30**	**354**	**147**	**25**	**18**
3 Pull-Down 1	15	61	24	24	20
4 Steady State	15	180	53	18	25
5 Doors Open	15	30	10	21	20
6 Pull-Down 2	15	15	5	19	22
All	**15**	**286**	**93**	**19**	**23**
3 Pull-Down 1	5	51	21	25	20
4 Steady State	5	180	55	18	24
5 Doors Open	5	30	9	17	24
6 Pull-Down 2	5	7	2	17	24
All	**5**	**268**	**86**	**19**	**23**

3.1.3 Particle emissions

Table 4 shows the total cumulative particulate emissions in each phase, in both mass ($PM_{2.5}$) and number (PN) form.

Table 4. Chilled mode particle emissions results

Phase	Ambient °C	Duration mins	Particle Mass mg	PM rate g per hour	Particle Number x 10^{14}	PN rate x 10^{14} per hour
Unit 1: pre-2019						
3 Pull-Down 1	15	30	121	0.24	3	7
4 Steady State	15	180	888	0.30	22	7
5 Doors Open	15	30	147	0.29	4	7
6 Pull-Down 2	15	7	30	0.26	1	7
All	**15**	**247**	**1186**	**0.29**	**30**	**7**
Unit 2: post-2019						
3 Pull-Down 1	15	30	191	0.38	6	12
4 Steady State	15	180	1102	0.37	36	12
5 Doors Open	15	30	257	0.51	7	14
6 Pull-Down 2	15	22	136	0.37	4	12
All	**15**	**262**	**1686**	**0.39**	**53**	**12**
Unit 3: post-2019						
3 Pull-Down 1	15	28	156	0.33	4	9
4 Steady State	15	180	897	0.30	29	10
5 Doors Open	15	30	178	0.36	5	11
6 Pull-Down 2	15	11	60	0.33	2	11
All	**15**	**249**	**1291**	**0.31**	**41**	**10**
Unit 4: post-2019						
3 Pull-Down 1	15	21	128	0.37	7	20
4 Steady State	15	180	695	0.23	31	10
5 Doors Open	15	30	174	0.35	8	17
6 Pull-Down 2	15	5	30	0.36	1	16
All	**15**	**236**	**1027**	**0.26**	**48**	**12**

Phase	Ambient °C	Duration mins	Particle Mass mg	PM rate g per hour	Particle Number x 10^{14}	PN rate x 10^{14} per hour
Unit 4: post-2019 (re-test)						
3 Pull-Down 1	15	36	172	0.29	8	14
4 Steady State	15	180	830	0.28	37	12
5 Doors Open	15	30	150	0.30	6	13
6 Pull-Down 2	15	7	37	0.32	2	13
All	**15**	**253**	**1189**	**0.28**	**53**	**13**
Unit 6: post-2019						
3 Pull-Down 1	30	101	1817	1.08	19	11
4 Steady State	30	180	3622	1.21	35	11
5 Doors Open	30	30	897	1.79	7	14
6 Pull-Down 2	30	43	902	1.25	9	12
All	**30**	**354**	**7238**	**1.23**	**69**	**12**
3 Pull-Down 1	15	61	680	0.67	9	9
4 Steady State	15	180	1886	0.63	27	9
5 Doors Open	15	30	562	1.12	6	12
6 Pull-Down 2	15	15	222	0.87	3	10
All	**15**	**286**	**3350**	**0.70**	**44**	**9**
3 Pull-Down 1	5	51	524	0.62	7	8
4 Steady State	5	180	1899	0.63	28	9
5 Doors Open	5	30	395	0.79	5	11
6 Pull-Down 2	5	7	115	0.95	1	11
All	**5**	**268**	**2933**	**0.66**	**41**	**9**

Both the pre-2019 unit and most of the post-2019 units produced broadly similar PM emissions but one of the post-2019 units tested here produced notably higher PM emissions. At the same ambient temperature (15 °C), this unit's PM production rate was about double that of any of the other units tested here. At 30 °C ambient, it was producing PM emissions at around four times the rate of the other units did at 15 °C.

PN emission rates were, however, very similar across all the units tested and only rose slightly from their 15 °C levels when one of the units was tested at 30 °C.

Section 1.5 above provides further commentary on the distinction between PM and PN emissions.

3.2 Frozen mode

The following sections present the main results from the frozen setpoint tests at -20 °C; they show the temperatures, fuel consumption, NOx and particle emissions data taken from the tests on each auxTRU.

3.2.1 Temperatures & fuel consumption

Table 5 summarises the temperatures achieved, and fuel consumed during each phase of the frozen mode tests, mostly at 15 °C ambient temperature, for each of the auxTRUs tested.

At 15 °C , some of the post-2019 units showed a 20-35% improvement in fuel consumption compared to the older unit tested here but the other post-2019 units consumed fuel at roughly a 20% higher rate (2.3 l/h cf. 1.9 l/h), at the same ambient temperature.

As with the chilled mode tests, average fuel consumption increased with increasing ambient temperatures, with again more significant increases seen when moving from 15 °C to 30 °C than from 5 °C to 15 °C.

Table 5. Frozen mode temperatures and fuel results

Phase	Ambient °C	Duration mins	Internal °C Max	Internal °C Mean	Internal °C Min	Fuel used litres	Fuel consumption litres per hour
Unit 1: pre-2019							
3 Pull-Down 1	15	119	1	-14	-20	5.72	2.88
4 Steady State	15	180	-8	-13	-19	2.90	0.97
5 Doors Open	15	30	3	-7	-12	1.31	2.62
6 Pull-Down 2	15	25	-5	-14	-19	1.19	2.86
All	**15**	**354**				**11.12**	**1.88**
Unit 2: post-2019							
3 Pull-Down 1	15	107	7	-13	-21	4.26	2.39
4 Steady State	15	180	-9	-15	-22	2.74	0.91
5 Doors Open	15	30	10	-5	-15	0.77	1.54
6 Pull-Down 2	15	27	-1	-14	-23	0.84	1.87
All	**15**	**344**				**8.61**	**1.50**

Phase	Ambient °C	Duration mins	Internal °C Max	Internal °C Mean	Internal °C Min	Fuel used litres	Fuel consumption litres per hour
Unit 3: post-2019							
3 Pull-Down 1	15	86	6	-13	-21	3.58	2.50
4 Steady State	15	180	-10	-16	-21	2.27	0.76
5 Doors Open	15	30	9	-4	-18	0.80	1.60
6 Pull-Down 2	15	29	-2	-14	-21	0.90	1.86
All	**15**	**325**				**7.55**	**1.39**

Phase	Ambient °C	Duration mins	Internal °C Max	Internal °C Mean	Internal °C Min	Fuel used litres	Fuel consumption litres per hour
Unit 5: post-2019							
3 Pull-Down 1	15	80	5	-13	-22	5.42	4.07
4 Steady State	15	180	-11	-17	-22	4.60	1.53
5 Doors Open	15	30	10	-1	-16	0.85	1.70
6 Pull-Down 2	15	74	4	-12	-12	3.26	2.64
All	**15**	**364**				**14.13**	**2.33**
3 Pull-Down 1	5	52	-3	-15	-22	3.79	4.37
4 Steady State	5	180	-13	-17	-22	2.43	0.81
5 Doors Open	5	30	2	-6	-20	0.97	1.94
6 Pull-Down 2	5	28	-7	-17	-22	1.32	2.83
All	**5**	**290**				**8.51**	**1.76**

Phase	Ambient °C	Duration mins	Internal °C Max	Internal °C Mean	Internal °C Min	Fuel used litres	Fuel consumption litres per hour
Unit 6: post-2019							
3 Pull-Down 1	30	327	10	-13	-21	18.43	3.38
4 Steady State	30	180	-4	-14	-21	5.80	1.94
5 Doors Open	30	30	21	0	-15	1.56	3.10
6 Pull-Down 2	30	46	19	-12	-21	2.28	2.97
All	**30**	**584**				**28.07**	**2.89**
3 Pull-Down 1	15	123	10	-12	-21	6.69	3.26
4 Steady State	15	180	-8	-15	-22	4.22	1.40
5 Doors Open	15	30	11	-4	-17	1.28	2.56
6 Pull-Down 2	15	35	11	-11	-21	1.66	2.87
All	**15**	**368**				**13.85**	**2.26**
3 Pull-Down 1	5	111	4	-13	-21	5.95	3.23
4 Steady State	5	180	-8	-14	-22	3.78	1.26
5 Doors Open	5	30	4	-11	-21	1.35	2.70
6 Pull-Down 2	5	6	5	-12	-22	0.27	2.62
All	**5**	**327**				**11.35**	**2.08**

3.2.2 NOx emissions

Table 6 shows the total cumulative emissions of oxides of Nitrogen (NOx) in each phase, along with the primary NO_2 percentages.

The post-2019 units showed a 15-25% reduction in NOx emission rates compared to the pre-2019 unit tested here, at 15 °C ambient. NOx production rates were found to increase only modestly when raising the ambient temperature (from 30 g/h at 5 °C to 36 g/h at 30 °C).

Table 6. Frozen mode NOx emissions results

Phase	Ambient °C	Duration mins	NOx grammes	NOx rate grammes per hour	Primary NO_2 %
Unit 1: pre-2019					
3 Pull-Down 1	15	119	114	57	11
4 Steady State	15	180	60	20	13
5 Doors Open	15	30	26	52	10
6 Pull-Down 2	15	25	23	55	10
All	**15**	**354**	**223**	**38**	**11**
Unit 2: post-2019					
3 Pull-Down 1	15	107	79	44	15
4 Steady State	15	180	53	18	20
5 Doors Open	15	30	18	36	17
6 Pull-Down 2	15	27	16	36	19
All	**15**	**344**	**166**	**29**	**17**
Unit 3: post-2019					
3 Pull-Down 1	15	86	73	51	14
4 Steady State	15	180	53	18	19
5 Doors Open	15	30	20	41	15
6 Pull-Down 2	15	29	19	39	19
All	**15**	**325**	**165**	**30**	**16**

Phase	Ambient °C	Duration mins	NOx grammes	NOx rate grammes per hour	Primary NO_2 %
Unit 5: post-2019					
3 Pull-Down 1	15	80	60	45	11
4 Steady State	15	180	53	18	12
5 Doors Open	15	30	15	30	13
6 Pull-Down 2	15	74	50	40	12
All	**15**	**364**	**177**	**29**	**12**
3 Pull-Down 1	5	52	37	43	14
4 Steady State	5	180	55	18	15
5 Doors Open	5	30	6	12	15
6 Pull-Down 2	5	28	12	26	14
All	**5**	**290**	**110**	**23**	**14**
Unit 6: post-2019					
3 Pull-Down 1	30	327	233	43	8
4 Steady State	30	180	72	24	9
5 Doors Open	30	30	18	36	2
6 Pull-Down 2	30	46	25	33	3
All	**30**	**584**	**349**	**36**	**8**
3 Pull-Down 1	15	123	92	45	14
4 Steady State	15	180	62	21	18
5 Doors Open	15	30	20	41	13
6 Pull-Down 2	15	35	23	40	16
All	**15**	**368**	**198**	**32**	**16**
3 Pull-Down 1	5	111	84	45	14
4 Steady State	5	180	54	18	18
5 Doors Open	5	30	20	39	17
6 Pull-Down 2	5	6	4	38	17
All	**5**	**327**	**161**	**30**	**16**

3.2.3 Particle emissions

Table 7 shows the total cumulative particulate emissions in each phase, in both mass ($PM_{2.5}$) and number (PN) form.

At the same ambient temperature, the post-2019 units produced PM and/or PN emissions at substantially higher rates than the pre-2019 unit tested here. In the most extreme case, by factors of five times the PM and nine times the PN.

Table 7. Frozen mode particle emissions results

Phase	Ambient °C	Duration mins	Particle Mass mg	PM rate g per hour	Particle Number x 10^{14}	PN rate x 10^{14} per hour
Unit 1: pre-2019						
3 Pull-Down 1	15	119	783	0.39	21	11
4 Steady State	15	180	777	0.26	15	5
5 Doors Open	15	30	248	0.50	6	11
6 Pull-Down 2	15	25	248	0.60	6	13
All	**15**	**354**	**2056**	**0.35**	**47**	**8**
Unit 2: post-2019						
3 Pull-Down 1	15	107	1840	1.03	65	37
4 Steady State	15	180	1291	0.43	43	14
5 Doors Open	15	30	357	0.71	10	21
6 Pull-Down 2	15	27	362	0.80	13	28
All	**15**	**344**	**3850**	**0.67**	**131**	**23**
Unit 3: post-2019						
3 Pull-Down 1	15	86	1488	1.04	52	36
4 Steady State	15	180	1084	0.36	35	12
5 Doors Open	15	30	358	0.72	10	19
6 Pull-Down 2	15	29	434	0.90	14	28
All	**15**	**325**	**3364**	**0.62**	**111**	**20**

Phase	Ambient °C	Duration mins	Particle Mass mg	PM rate g per hour	Particle Number x 10^{14}	PN rate x 10^{14} per hour
Unit 5: post-2019						
3 Pull-Down 1	15	80	860	0.65	47	35
4 Steady State	15	180	565	0.19	34	11
5 Doors Open	15	30	145	0.29	8	16
6 Pull-Down 2	15	74	791	0.64	42	34
All	**15**	**364**	**2361**	**0.39**	**132**	**22**
3 Pull-Down 1	5	52	430	0.50	29	33
4 Steady State	5	180	604	0.20	37	12
5 Doors Open	5	30	62	0.12	4	7
6 Pull-Down 2	5	28	135	0.29	7	15
All	**5**	**290**	**1231**	**0.25**	**76**	**16**
Unit 6: post-2019						
3 Pull-Down 1	30	327	19621	3.60	580	110
4 Steady State	30	180	6223	2.08	180	60
5 Doors Open	30	30	2343	4.66	56	110
6 Pull-Down 2	30	46	3240	4.22	84	110
All	**30**	**584**	**31427**	**3.23**	**900**	**92**
3 Pull-Down 1	15	123	5796	2.83	220	110
4 Steady State	15	180	3296	1.10	140	46
5 Doors Open	15	30	1055	2.11	36	71
6 Pull-Down 2	15	35	1316	2.27	54	94
All	**15**	**368**	**11464**	**1.87**	**450**	**73**
3 Pull-Down 1	5	111	5571	3.02	130	72
4 Steady State	5	180	3159	1.05	83	28
5 Doors Open	5	30	1103	2.21	32	63
6 Pull-Down 2	5	6	225	2.20	7	64
All	**5**	**327**	**10059**	**1.85**	**250**	**47**

The unit tested at three separate ambient temperatures appears to be especially prone to high particle emission rates under frozen mode conditions (as it was, though to a lesser extent, in the chilled mode tests). Its PM and PN rates were also found to increase markedly as ambient temperatures rose, almost doubling in moving from 5 °C to 30 °C.

3.3 Multi-temperature mode

The following sections present the main results from the multi-temperature tests at three different ambient temperatures; they show the temperatures, fuel consumption, NOx and particle emissions data taken from the tests on the one auxTRU tested under this condition.

3.3.1 Temperatures & fuel consumption

Table 8 summarises the temperatures achieved, and fuel consumed during each phase.

Table 8. Multi-temp mode temperatures and fuel results

Phase	Ambient °C	Duration mins	Internal °C Max	Internal °C Mean	Internal °C Min	Fuel used litres	Fuel consumption litres per hour
Unit 6: post-2019							
3 Pull-Down 1	30	256	8/16	-15/5	-21/-1	14.43	3.38
4 Steady State	30	180	-5/7	-18/6	-22/-2	4.92	1.64
5 Doors Open	30	30	10/24	2/13	-12/6	1.55	3.08
6 Pull-Down 2	30	57	1/9	-12/3	-20/-1	3.06	3.21
All	**30**	**523**				**23.95**	**2.75**
3 Pull-Down 1	15	73	10/16	-12/5	-21/-1	4.33	3.55
4 Steady State	15	180	-10/7	-17/5	-22/-2	3.03	1.01
5 Doors Open	15	30	-1/13	-8/6	-16/-4	1.65	3.32
6 Pull-Down 2	15	21	-10/4	-17/2	-22/-2	0.77	2.19
All	**15**	**304**				**9.78**	**1.93**
3 Pull-Down 1	5	40	2/6	-14/4	-21/-1	2.16	3.27
4 Steady State	5	180	-12/5	-17/4	-23/3	2.44	0.81
5 Doors Open	5	30	-11/4	-15/-2	-22/-10	1.40	2.78
6 Pull-Down 2	5	11	-18/0	-21/-1	-23/-2	0.21	1.14
All	**5**	**261**				**6.21**	**1.43**

The results indicate a clear trend in, not surprisingly, fuel consumption increasing with ambient temperature. And, as for the chilled and frozen mode tests, more of an increase in moving from 15 °C to 30 °C and relatively modest increases when moving from 5 °C to 15 °C.

3.3.2 NOx emissions

Table 9 shows the total cumulative emissions of oxides of Nitrogen (NOx) in each phase, along with the primary NO_2 percentages.

NOx production rates were also found (and estimated in the case of the 30 °C tests) to increase with increasing ambient temperature, from 19 g/h at 5 °C to 35 g/h at 30 °C.

Table 9. Multi-temp mode NOx emissions results

Phase	Ambient °C	Duration mins	NOx grammes	NOx rate grammes per hour	Primary NO_2 %
Unit 6: post-2019					
3 Pull-Down 1	30	256	183	43	14
4 Steady State	30	180	66	22	19
5 Doors Open	30	30	21	42	14
6 Pull-Down 2	30	57	36	38	17
All	**30**	**523**	**306***	**35***	**16***
3 Pull-Down 1	15	73	58	47	10
4 Steady State	15	180	44	15	18
5 Doors Open	15	30	22	44	10
6 Pull-Down 2	15	21	11	31	15
All	**15**	**304**	**134**	**26**	**13**
3 Pull-Down 1	5	40	30	45	12
4 Steady State	5	180	34	11	20
5 Doors Open	5	30	18	35	17
6 Pull-Down 2	5	11	3	15	19
All	**5**	**261**	**84**	**19**	**17**

* NO_2 logger malfunction, results estimated based on measured NO and average NO_2 %'s from other tests

3.3.3 Particle emissions

Table 10 shows the total cumulative particulate emissions in each phase, in both mass ($PM_{2.5}$) and number (PN) form.

Table 10. Multi-temp mode particle emissions results

Phase	Ambient °C	Duration mins	Particle Mass mg	PM rate g per hour	Particle Number x 10^{14}	PN rate x 10^{14} per hour
Unit 6: post-2019						
3 Pull-Down 1	30	256	17149	4.02	300	70
4 Steady State	30	180	5601	1.87	95	32
5 Doors Open	30	30	2348	4.67	21	41
6 Pull-Down 2	30	57	5147	5.39	66	69
All	**30**	**523**	**30245**	**3.47**	**480**	**55**
3 Pull-Down 1	15	73	3677	3.01	79	65
4 Steady State	15	180	2321	0.77	57	19
5 Doors Open	15	30	1472	2.96	32	64
6 Pull-Down 2	15	21	576	1.65	15	42
All	**15**	**304**	**8046**	**1.59**	**180**	**36**
3 Pull-Down 1	5	40	1862	2.81	43	64
4 Steady State	5	180	1795	0.60	46	15
5 Doors Open	5	30	1128	2.25	31	62
6 Pull-Down 2	5	11	190	1.04	5	26
All	**5**	**261**	**4976**	**1.14**	**120**	**29**

Here again, a clear relationship between production rates and ambient temperature is evident, with the PM rate more than doubling in moving from 15 °C to 30 °C and the PN rate increasing by 50%.

3.4 Comparisons between multi-temp, chilled and frozen mode tests

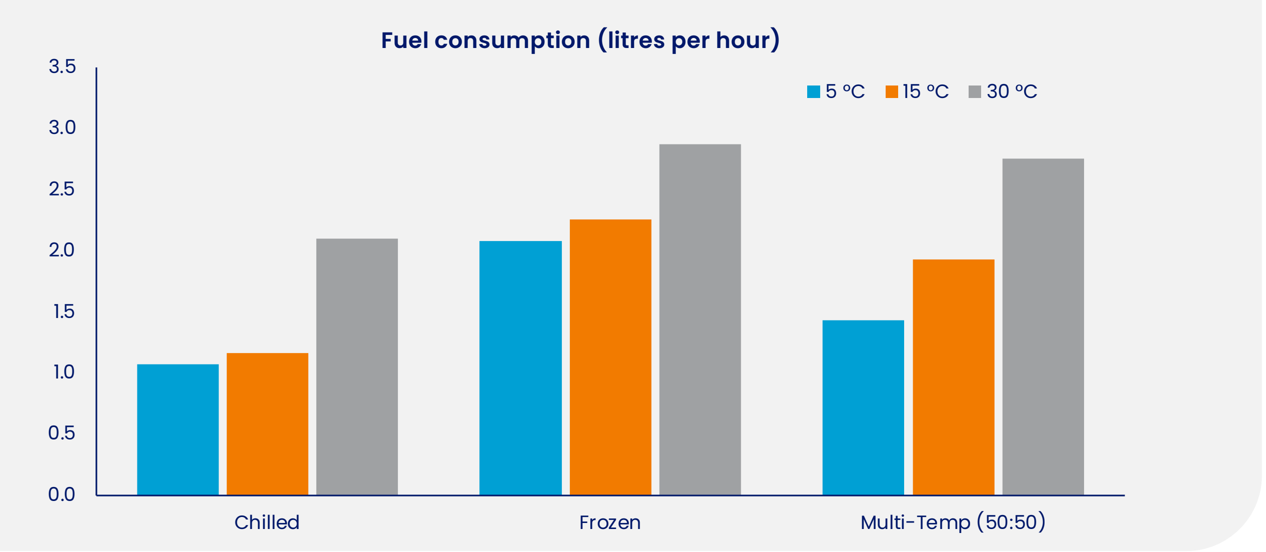
A primary objective the multi-temperature testing was to better understand how fuel and emissions varied in comparison to simply averaging the results from separate chilled and frozen mode tests. Industry experts had suggested that the units would need to work harder in multi-temp mode than such a simplistic averaging approach would indicate. The results described above generally confirm their basic premise, but the following sections explore the relationships in greater depth.

3.4.1 Fuel consumption

Figure 2 presents the measured fuel consumption rates across the nine test conditions combining variations in loading condition and ambient temperature. At the lowest ambient temperature, the fuel consumption in multi-temp conditions was slightly lower than the average of chilled and frozen at the same temperature but as ambient temperature increased, so did the multi-temp fuel consumption and the measured rates got progressively closer to those from the frozen mode tests. These results tend to confirm the basic premise that multi-temp applications are usually more energy intensive than simply averaging between chilled and frozen mode tests would indicate, but

- at low ambient temperatures the premise is less valid, simply averaging suffices
- at high ambient temperatures there is very little difference between the multi-temp and frozen mode results
- the frozen mode results seem to represent a reasonable "worst-case" estimate for multi-temp operations at such high ambient temperatures.

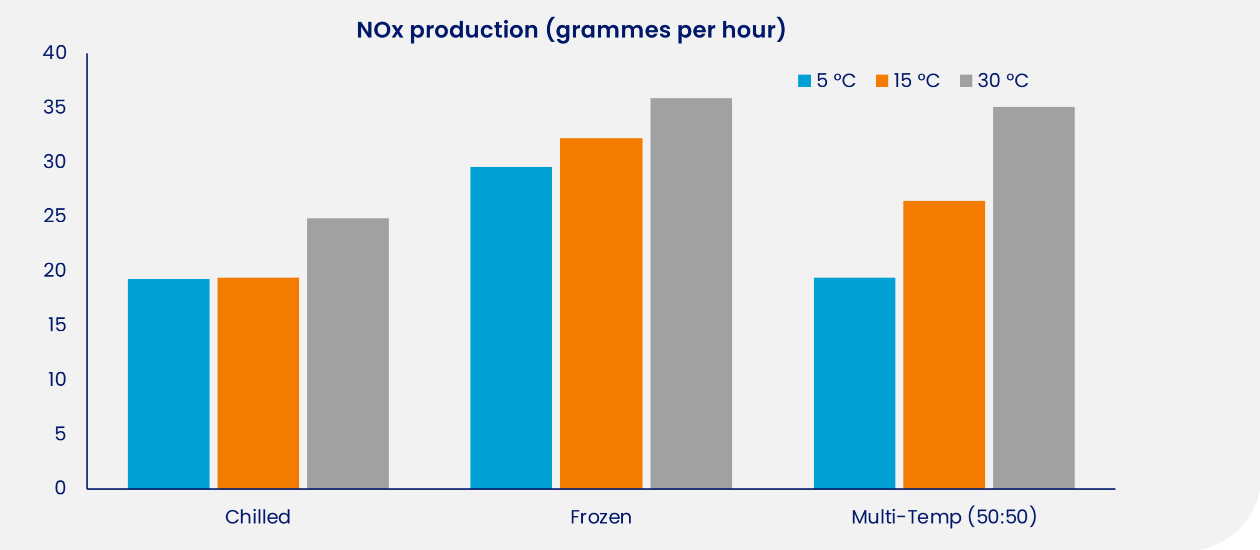
Figure 2. Fuel consumption at different load conditions and ambient temps



3.4.2 NOx emissions

Figure 3 shows how loading condition and ambient temperature influenced NOx production. A similar pattern is evident, with NOx rates being very close to the chilled mode condition in multi-temp mode at 5 °C ambient, but progressively rising and getting closer to the results from frozen mode conditions at the higher ambient temperatures.

Figure 3. NOx production at different load conditions and ambient temps



3.4.3 Particulate emissions

Figure 4 shows how particle mass emission rates varied across the nine tests. The pattern is evident once again, with the multi-temp results being this time being close to the average of the chilled and frozen mode tests at the lowest ambient temperature but rising to very close to the frozen mode results at the higher temperatures (and even exceeding them at 30 °C).

Figure 4. $PM_{2.5}$ production at different load conditions and ambient temps

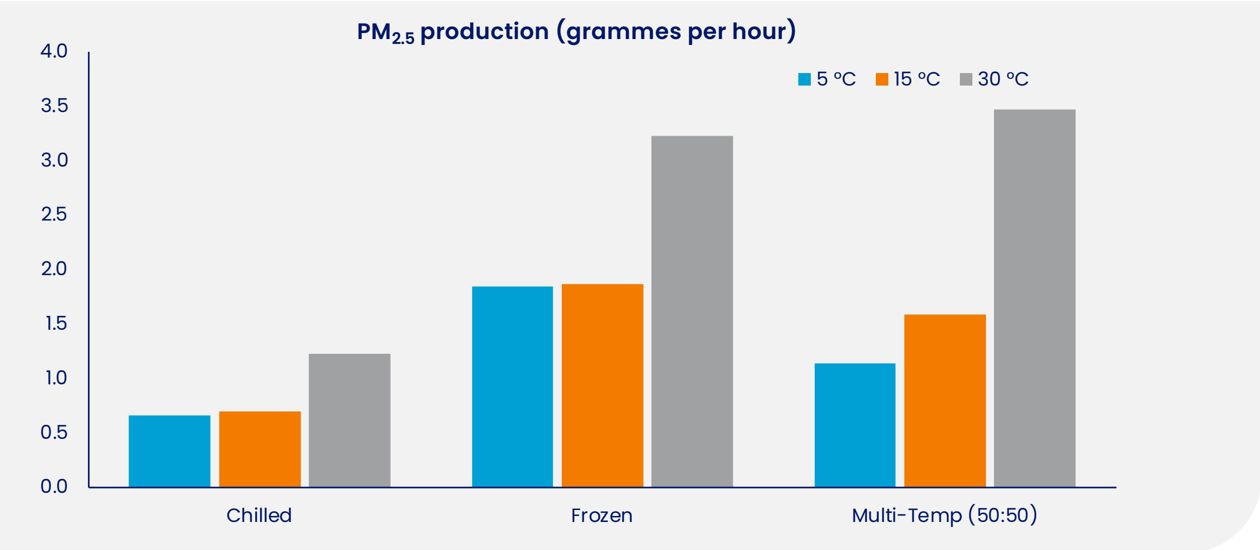
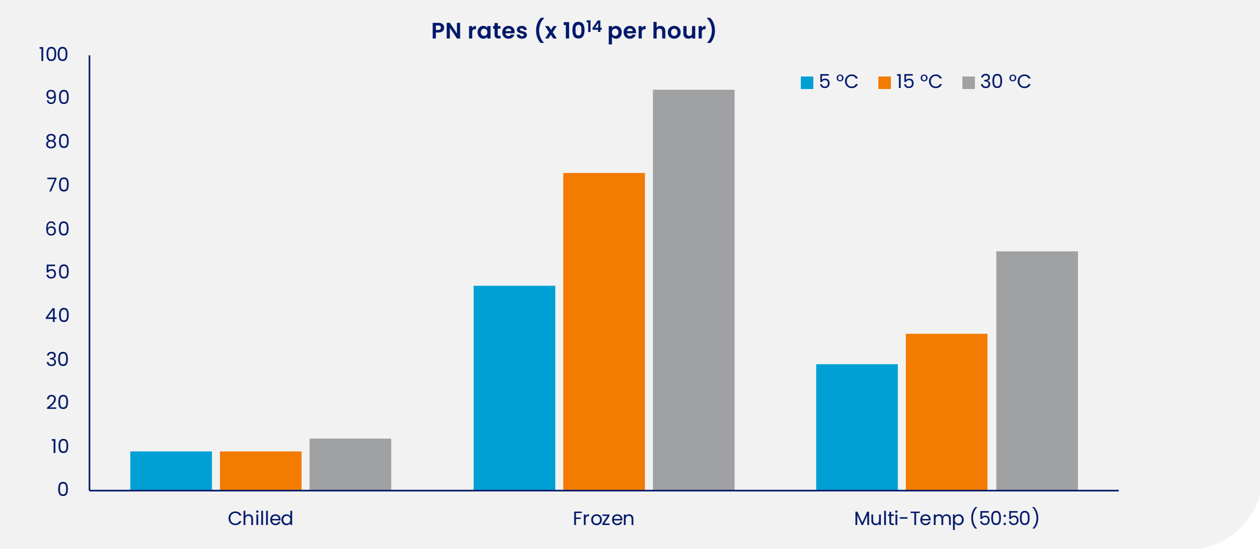


Figure 5 shows the particle number emissions rates. The pattern is slightly different in this case, with the multi-temp results being quite consistently close to the average of the chilled and frozen mode tests regardless of ambient temperature.

Figure 5. PN production at different load conditions and ambient temps



3.5 Comparisons to 2019 and 2021 test results

This section compares the main fuel consumption and emissions results from the auxTRU with those obtained from similar units (but under slightly different test conditions) during the pilot testing programme reported in 2019 and the additional baseline testing (identical test conditions) carried out for Transport Scotland in 2021.

In total, nine different diesel auxTRU have now been tested; four manufactured before 2019 and five since. The tested units vary in rated capacity from 11-19 kW and come from the two main suppliers operating in the UK market (five from Carrier and four from Thermo King).

In the following sections, tests of statistical significance are based on one-tailed students t-tests with equal or unequal variances as appropriate and with 95% confidence. This is testing the hypothesis that the post-2019 units have statistically significantly lower (or higher) emissions or fuel consumption than their pre-2019 counterparts. Note, however, that while the latest batch of tests substantially increases the evidence base for emissions from auxTRU and fills the key gaps identified in 2021, the sample size is still very small, limiting the power of statistical analyses.

Credit: Caetano

The results for pre-2019 and post-2019 units are presented in the form of box plots. These show the following pieces of information about each set of results:

- The top and bottom horizontal lines represent the maximum and minimum values recorded.
- The top and bottom of the box represents the third (Q3) and first quartile (Q1) values, i.e. the value that only 25% of the test results exceeded and the value that only 25% were below.
- The line across the box represents the median value (Q2), i.e. half the recorded values were above this, half below.
- The cross represents the mean of the results, i.e. the numerical average.

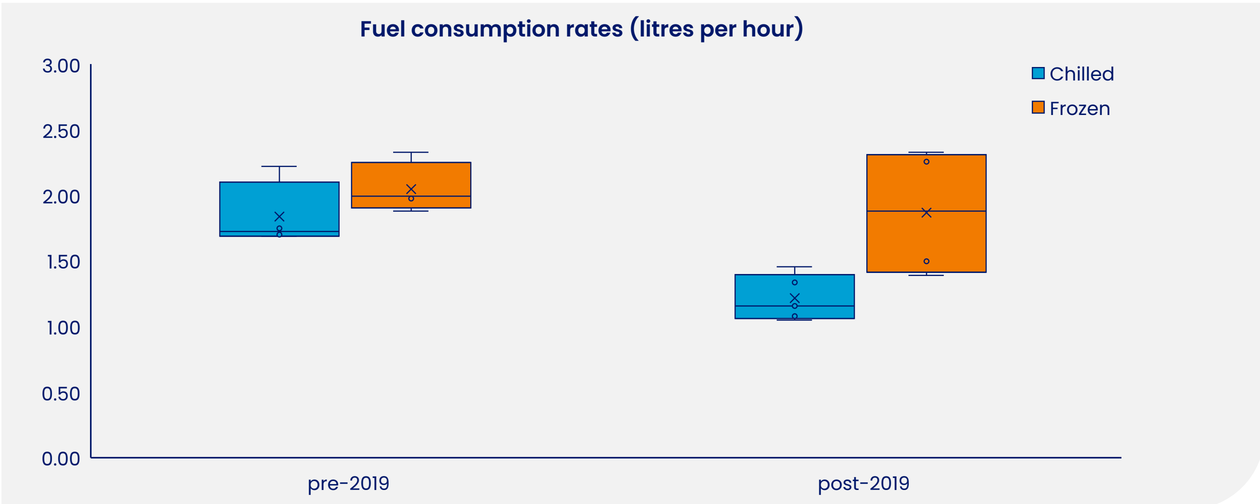
While the box plots do not perfectly correlate to the tests for statistical significance, they can be used as an indicator. Generally speaking, where the two boxes overlap, a statistically significant difference between the samples is unlikely but where they do not overlap, a statistically significant difference is more likely. In either case, the t-test is used to confirm any significant differences.

3.5.1 Fuel consumption rates

The average fuel consumption rates for all the chilled and frozen mode tests at 15-20 °C ambient are shown in Figure 6. While a general (and statistically significant) reduction in fuel consumption (and thus, in direct proportion, CO_2 emissions) is evident for the chilled mode tests, there is no such consistent reduction apparent for the frozen mode tests.

On average, the post-2019 units consumed 34% less fuel than the pre-2019 units tested in chilled mode tests but only 9% less in frozen mode. Averaging between the two modes, the pre-2019 units consumed fuel at a rate of 1.9 l/h and the post-2019 units did so at 1.5 l/h (22% reduction).

Figure 6. Comparison of fuel consumption rates

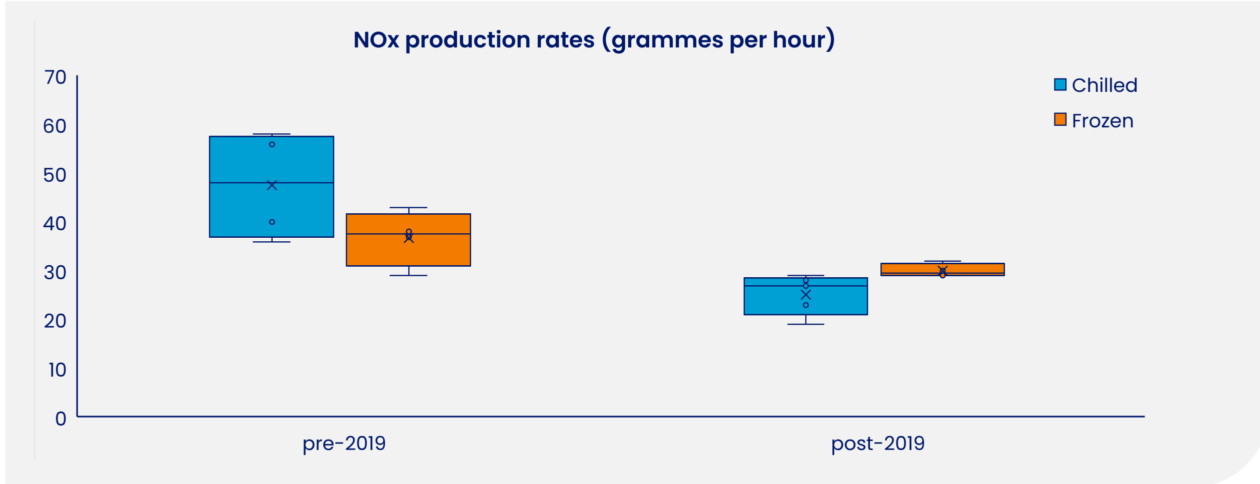


3.5.2 NOx production rates

The average NOx emissions production rates for all the chilled and frozen mode tests are shown in Figure 7. As with fuel, there is a general (and statistically significant) reduction in NOx emissions evident from the chilled tests (of 47% on average) but a smaller (though also statistically significant) reduction of 18% on average for the frozen mode tests.

Averaging across both test modes, the pre-2019 units produced NOx at a rate of 42 g/h and the post-2019 units did so at 27 g/h (35% lower).

Figure 7. Comparison of NOx emission production rates

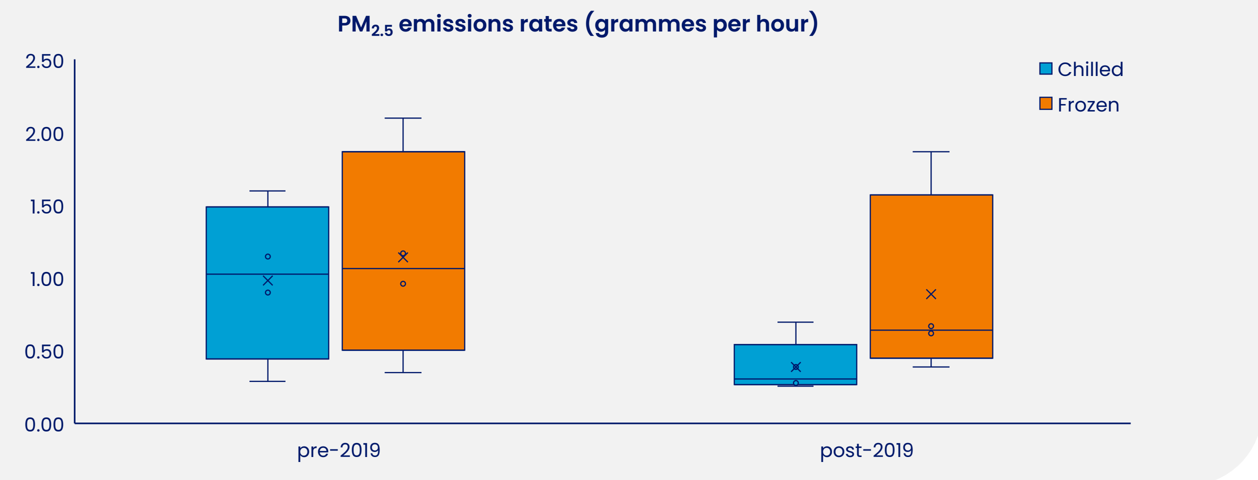


3.5.3 Particulate emissions rates

The average $PM_{2.5}$ and PN emissions rates are shown in Figure 8 and Figure 9 respectively.

Particle Mass measurements show a high degree of variation amongst the pre-2019 units tested. Overall, however, there is a reduction (but, in relation to this wide variation, not statistically significant) for the post-2019 units in the chilled mode tests (of 61% on average). For the frozen tests the corresponding reduction is lower, at 22%, and this is also not statistically significant. Overall, averaging across both test modes, PM emissions were 1.1 g/h for the pre-2019 units and 0.6 g/h for the post-2019 units (43% lower).

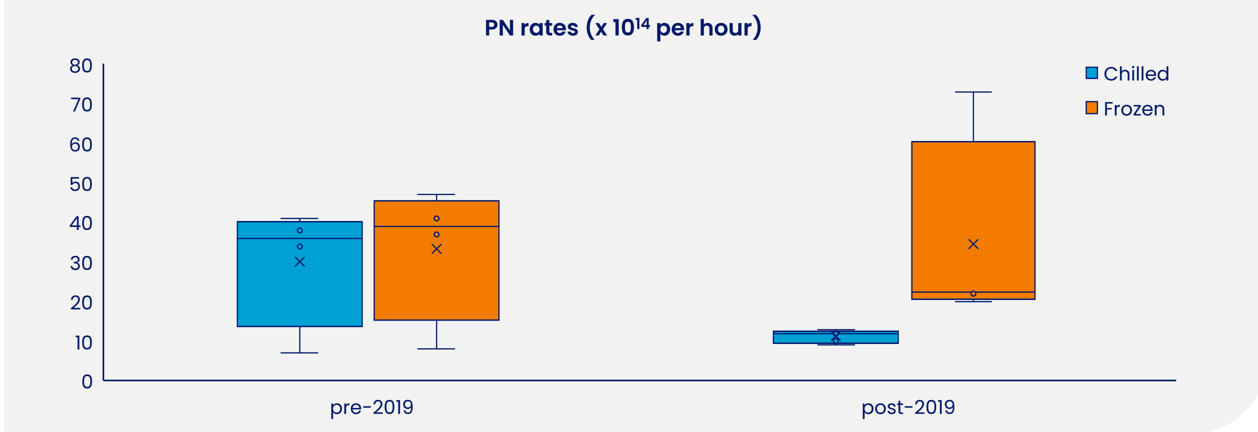
Figure 8. Comparison of Particle Mass emissions rates



A slightly different situation applies, however, for Particle Number emissions. Here again there is quite a high degree of variation amongst the pre-2019 units tested but there is this time a statistically significant reduction evident for the post-2019 units in the chilled mode tests (of 63% on average). For the frozen tests there is no reduction (4% increase on average), but this is not statistically significant.

Overall, averaging across both test modes and despite one of the post-2019 units producing particulates at a notably higher rate than any other units, and one of the pre-2019 units doing so at a notably lower rate than other such units, PN emissions were $32x10^{14}$/h on average for the pre-2019 units and $22x10^{14}$/h for the post-2019 units (32% lower).

Figure 9. Comparison of Particle Number rates



3.6 Ambient temperature effects

To strengthen potential confidence in any UK-wide emissions estimates based on the programme of lab-based tests, it is useful to be able to quantify the effects of ambient temperature and thus the sensitivities of those estimates to climatic changes and regional temperature differences. The test programme reported in 2021 involved tests of two diesel auxTRU at two different ambient temperatures (5 °C and 15 °C), in both chilled and frozen mode. The results, however, were somewhat inconsistent, with fuel consumption and emissions rates not always falling as the ambient temperature was reduced – as one might reasonably expect given the reduced energy requirement to maintain target temperatures.

The programme of new (2023) tests described above provided an opportunity to add more evidence on ambient temperature effects. One of the units was tested in frozen mode only but at the same two ambient temperatures as used in 2021, while another unit was tested in both chilled and frozen mode (and multi-temperature mode), at both these temperatures and at a much higher ambient temperature of 30 °C, representing conditions on a hot summer's day.

As can be seen from the preceding data tables, the 2023 tests showed consistent reductions in fuel consumption, NOx production and particulate emissions as ambient temperatures reduced. Furthermore, the unit tested at all three ambient temperatures generally demonstrated that moving from 15 °C to 30 °C increased fuel consumption and emissions rates by more than was found when moving from 5 °C to 15 °C.

The following sections explore the measured relationships between fuel and emissions rates and ambient temperatures in more detail.

3.6.1 Fuel consumption

Averaging across all three of the semitrailer auxTRU systems that have been tested since 2019 (two post-2019 and one pre-2019) at both 5 °C and 15 °C, in chilled, frozen and/or multi-temp mode, the increase in fuel consumption in moving from the lower to the higher temperature was 18% (range 4-35%). Tests on one unit indicate that increasing the temperature to 30 °C leads to fuel consumption rising by a further 50% on average (range 27-81%).

In absolute terms, these percentage increases translate into approximately a 0.3 l/h increase in fuel consumption in moving from 5 °C to 15 °C, and a further increase of 0.8 l/h when the ambient temperature rises to 30 °C.

3.6.2 NOx emissions

Averaging across all three of the semitrailer auxTRU systems that have been tested since 2019 at both 5 °C and 15 °C, the increase in NOx production rates in moving from the lower to the higher temperature was 23% (range -6-75%). Tests on one unit indicate that increasing the temperature to 30 °C leads to NOx rates rising by a further 24% on average (range 11-33%).

In absolute terms, these percentage increases translate into approximately a 6 g/h increase in NOx production rates in moving from 5 °C to 15 °C, and a further increase of 6 g/h when the ambient temperature rises to 30 °C.

3.6.3 Particulate emissions

Averaging across all three of the semitrailer auxTRU systems that have been tested since 2019 at both 5 °C and 15 °C, the increase in $PM_{2.5}$ production rates in moving from the lower to the higher temperature was 21% (range -7-56%). Particle number emissions rose on average by 17% (range -16-55%). Tests on one unit indicate that increasing the temperature to 30 °C leads to particle mass rates rising by a further 89% on average (range 73-118%) and PN rates by a further 37% on average (range 26-53%).

In absolute terms, these percentage increases translate into approximately a 0.1 g/h increase in $PM_{2.5}$ production rates in moving from 5 °C to 15 °C, and a further increase of 1.3 g/h when the ambient temperature rises to 30 °C. Particle number rates increase by roughly 5 x 10^{14} per hour and 14 x 10^{14} per hour respectively.

3.6.4 Overall summary of ambient temperature effects

The measured effects of increasing ambient temperature on fuel consumption and emissions rates can be combined with the preceding analysis of the differences between pre and post-2019 units and summarized as follows:

- Fuel consumption increases from an average of around 1.5 l/h at 5 °C ambient to 1.8 l/h at 15 °C and 2.7 l/h at 30 °C. Pre and post-2019 units could typically be expected to consume fuel at rates of around 0.2 l/h higher/lower than these figures respectively (averaging across all modes).
- NOx emission production rates increase from an average of around 29 g/h at 5 °C ambient to 35 g/h at 15 °C and 41 g/h at 30 °C. Pre and post-2019 units could typically be expected to produce NOx at rates of around 7 g/h higher/lower than these figures respectively (averaging across all modes).
- Particle Mass emission production rates increase from an average of around 0.7 g/h at 5 °C ambient to 0.8 g/h at 15 °C and 2.1 g/h at 30 °C. Statistically significant differences between pre and post-2019 units have not been demonstrated but, on average, production rates for pre-2019 units were around 0.2 g/h higher than these figures and the post-2019 units were around 0.2 g/h lower on average.
- Particle Number emission production rates increase from an average of around 21 x 10^{14} per hour at 5 °C ambient to 26 x 10^{14} per hour at 15 °C and 40 x 10^{14} per hour at 30 °C. Pre and post-2019 units could typically be expected to produce PN emissions rates of around 5 x 10^{14} per hour higher/lower than these figures respectively (averaging across all modes).

4. Estimates of environmental impact of TRUs

The following sections describe how a market survey and published data have been used to estimate the number of diesel auxTRUs in daily use, their operational characteristics and, when combined with the preceding evidence on emissions production rates, their overall likely contribution to emissions of greenhouse gases and air pollutants in the UK.

The basic approach to modelling these overall impacts involves the same equation as was used in our work for Transport Scotland:

I = N x H x R

Where I is the annual total impact being estimated, N is the number of auxTRUs in use, H the hours of use per annum and R the relevant annual average per hour fuel consumption or emission production rate (from the test programmes described above).

4.1 Market survey

In conjunction with the University of Birmingham, as part of a separate cold-chain project of theirs funded by DESNZ, an on-line survey was developed and promoted widely across various sections of the industry, including equipment suppliers, body builders, operators and rental/leasing companies.

In all, 139 companies were approached to complete the survey and 26 did so, a response rate of 19%. While this response rate probably reflects the complexity and thus time-burden on individuals to complete it, the overall market coverage obtained is likely to be substantially greater than 19% and as a much higher proportion (15 out of 22 approached, 68%) of the supermarket and food distribution companies responded. Between them, these companies are thought to operate a very significant share of the overall UK diesel auxTRU fleet.

The survey gathered detailed information on various aspects of temperature-controlled transport, not all of which is directly relevant to this research. The topics it covered that are useful include:

- Average age of auxTRU (allowing us to estimate the split between pre and post-2019 units across the UK fleet).
- Trailer configuration (allowing us to estimate the split between single and multi-temperature operations).
- Hours use per annum (allowing us to refine the annual hours numbers used in the Transport Scotland research, which were themselves based on earlier estimates by Cenex).
- Split between chilled and frozen for single-temperature and multi-temp operations.

The detailed survey results in these areas, and their subsequent usage in our environmental impact modelling, are described in the following sections.

4.2 Number of auxTRUs

A survey of this nature cannot provide robust data on the total size of the auxTRU population across the UK, because to do so it would need to achieve a 100% response rate across the entire industry – a wholly unrealistic objective. As we reported in 2021, there are currently no official sources of data on the exact numbers of auxTRU in use in the UK (or elsewhere), so other data sources and techniques must be used to make reasonable estimates.

According to official UK statistics (from DVSA), in the year between April 2022 and March 2023, a total of just under 289,000 trailer inspections were carried out across the UK (excluding any re-tests). Although this figure excludes trailers less than one year old (which do not yet need to be inspected), it is likely that a broadly similar number of older trailers were or will be retired from service in the twelve months since their last inspection. Overall, therefore, this figure of 289,000 is considered a reasonable first estimate as to the size of the UK trailer fleet.

There are also no official data sources on what proportion of the trailer fleet are used in temperature-controlled transport operations. However, various other data sources can be used to estimate this. The first comes from research carried out by the International Council on Clean Transportation (ICCT) and published in 2018[3]. Between 2009 and 2016, this research reported that 15% of EU trailers were refrigerated and, furthermore, that this proportion was projected to remain within one percent of this number out to 2021.

[3] Market Analysis of Heavy-Duty Commercial Trailers in Europe, ICCT, September 2018.

The paper does not provide a breakdown of if or how that proportion varied by country but it seems reasonable to speculate that this proportion would not vary significantly. This research would therefore lead us to estimate that 15% of the UK's 289,000 trailers are likely to be refrigerated, i.e. 43,350.

Further supporting evidence for this comes from the UK's official freight transport statistics. The latest statistics (for 2022) suggest that about 20% of all goods lifted (tonnes) in the UK by articulated vehicles were in the category "food products, including beverages and tobacco". For goods moved (tonne-kilometres), the equivalent figure was 21%. While the proportion of these goods such as beverages, tobacco, tinned food etc that would not necessarily be transported in refrigerated trailers is not known, reducing those overall percentages to something like 15% to account for this does not seem unreasonable.

The Trailer Registration Act 2018, as amended in 2021, requires certain trailers used for the international transport of goods to be registered. Data on the trailers registered by UK hauliers has been obtained from DVLA via a freedom of Information request and includes information on the trailer type. This data indicates that about 20% of the heavy goods vehicle trailers registered are refrigerated. For international movements, however, there is likely to be a slight bias towards such trailer types, because perishable foods need to be moved quite quickly, favouring road transport over long-distance rail or maritime journeys. Overall, therefore, these data are considered to provide further supporting evidence that the above 15% estimate for the overall proportion of UK trailers being refrigerated is reasonable.

For rigid HGVs, official UK statistics provide a breakdown of the fleet by body type. At the end of 2021 (the latest year for which such figures are available), there were 11,500 rigid HGVs registered as having an "insulated van" body type. This is the only body type classification that implies temperature-controlled transport usage and thus it is reasonable to use this figure as our first estimate of the number of refrigerated rigid HGVs in use across the UK. Not all of these, however, will use auxTRU, some will use fridge units powered directly by the truck's main engine. The Cenex-led research for Transport for London (published in 2018) suggested, via their own market survey at the time, that around 25% of the insulated van rigid HGVs of less than 12 tonnes gross weight would have auxTRU and 50% of such vehicles over 12 t gross weight. Applying these numbers to the official UK insulated van body fleet statistics implies there are around 4,400 rigid HGVs in the UK fitted with auxTRU.

In total, therefore, we can estimate there are approximately 47,750 diesel auxTRU in use in the UK – 4,400 on rigid HGVs and 43,350 fitted to trailers.

The only other source of a national estimate for the auxTRU population across the UK comes from a report by the Cold Chain Federation (CCF) published in 2021[4]. That report provides an estimate of 30,000 articulated vehicles with auxTRU, 15,000 refrigerated rigid HGVs and 25,000 refrigerated vans, implying (after allowing for something like 40% of the rigid HGVs to be fitted with auxTRU but none of the vans) 36,000 auxTRU in total (30,000 artics and 6,000 rigids). However, the report recognises the "low confidence" in these estimates, which CCF based on sales data and average lifecycle of units. It is also not entirely clear from the report whether the 30,000 figure is for individual trailers fitted with auxTRU or tractor units used to pull such trailers. The ratio of trailers to tractor units is generally reckoned to be about 1.4:1 in the UK, so if it's referring to tractor units, then we can further estimate there are about 42,000 auxTRU trailers in the UK and about 48,000 auxTRU in total. While these numbers match very closely to our own estimate above, the uncertainties in the CCF figures mean we cannot have complete confidence in this apparent alignment.

To reflect these uncertainties and inherent risks of either under or over-estimating the true numbers of auxTRUs in regular use across the UK, for the environmental impact modelling we have chosen to use a range (for "N" in the basic equation above) from a minimum of 40,000 to a maximum of 55,000, with 47,500 as our mid-range, central estimate.

[4] The Journey to Emission Free Temperature-Controlled Refrigeration on Road Vehicles, CCF, 2021.

4.3 Operational characteristics

4.3.1 Age of auxTRUs

Survey respondents in the transport operator's category reported average auxTRU ages of between 3 and 10 years, with an overall average between them of 5.5 years. The rental and lease companies, on the other hand, reported a range of average ages of between 3 and 4 years, with 3.5 years being their overall average. The survey further suggests, however, that transport operators account for a larger proportion of the overall auxTRU fleet than the leasing and rental companies. Weighting between the two sectors by the numbers of units being used, the overall average age of auxTRU is reported as a little under 5 years. Although the detailed breakdown of the fleet by exact age is not available, we can reasonably assume there are a similar number of auxTRU younger than this average age to those older, and thus use this figure to estimate that there are likely to be around 50% of the auxTRU in use dating from January 2019 or later (i.e. up to just under 5 years old) and another 50% or so dating from before 2019.

4.3.2 Usage mode

The survey also asked respondents about whether their vehicles/trailers were mainly used for chilled, frozen or multi-temperature applications. The transport operators reported that 86% of their auxTRU fleet were capable of multi-temp operations but the rental and leasing companies reported this figure to be less than 5%. Overall, weighting between the two sectors, gives an estimate of roughly 50% of all auxTRU-equipped vehicles being multi-temp capable.

Respondents were also asked what proportion of the goods they transport are transported frozen. While, not surprisingly given the likely range of foodstuffs being transported, there was wide variation in the responses (from 2-100%), the overall average for the transport operators was about 35%.

The survey responses cannot reliably be broken down further, e.g. to identify the exact proportion of chilled and frozen loads in multi-temp operations but they do allow for overall estimates to be made as follows:

- 50% of the auxTRU fleet is used predominantly under multi-temp conditions
- 17.5% of the auxTRU fleet is used predominantly for frozen mode operations
- 32.5% of the auxTRU fleet is used predominantly for chilled mode operations

4.3.3 Ambient temperatures

The Transport Scotland modelling work used the test results at 5 °C to represent winter conditions and those at 15 °C for summer. The 2023 test programme described above added further evidence on ambient temperature effects, up to 30 °C. While a detailed review of historical UK temperature data is outside the scope of this research, it seems reasonable to speculate that, in very broad terms, a typical UK year might entail 4 months at roughly 5 °C average (Nov-Feb), 6 months at roughly 15 °C (Mar-May and Aug-Oct) and 2 months at, or at least close to, 30 °C (June and July). We will use this split in the overall environmental impact modelling that follows.

4.3.4 Usage hours

The Transport Scotland modelling work used a wide range of possible annual operating hours of between 1,500 and 2,750 for rigid HGVs and 3,000-4,200 for trailer-based systems.

Survey respondents in the transport operator category reported annual run hours of between 1,550 and 6,000 (2,150 on average) for their rigid HGVs and from 1,500-3,000 for their trailers (2,250 hours average). Note, however, that "run hours" reported here will be slightly less than the "operational hours" used in the modelling, particularly for frozen mode tests using stop-start engine capabilities.

The test programme data, based very largely on semitrailer auxTRU systems, does not provide a robust evidence base to separate out emissions from rigid and trailer systems. We therefore suggest a reasonable range of estimates for auxTRU in general, across the rigid HGV and trailer fleets, to be 1,800 – 3,600 operational hours per annum (central estimate 2,700).

4.3.5 Overall summary of operational characteristics assumptions

Table 11 summarises the above findings and presents the overall ranges of numbers to be used in the overall environmental impact modelling for both "N" (the numbers of various types of auxTRU) and "H" (their annual operating hours).

Table 11. Modelled auxTRU usage scenarios

	Low range	Central estimate	High range
All UK auxTRU	40,000	47,500	55,000
Numbers of pre-2019 units (50%)			
Chilled use (32.5%)	6,500	7,719	8,938
Frozen use (17.5%)	3,500	4,156	4,812
Multi-temp use (50%)	10,000	11,875	13,750
Numbers of post-2019 units (50%)			
Chilled use (32.5%)	6,500	7,719	8,938
Frozen use (17.5%)	3,500	4,156	4,812
Multi-temp use (50%)	10,000	11,875	13,750
Annual operational hours			
At 5 °C (4 months)	600	900	1,200
At 15 °C (6 months)	900	1,350	1,800
At 30 °C (2 months)	300	450	600

4.4 Fuel consumption and emission production rates

The test results described in the preceding section, combined with those from the 2019 and 2021 testing, provide the best available current evidence regarding likely per hour fuel consumption and emissions production rates from diesel auxTRUs in the real world.

Table 12 presents the modelled hourly rates based on the test results, split by pre and post-2019 units and by ambient temperature.

Table 12. Modelled average fuel and emissions production rates

	5 °C			15 °C			30 °C		
Chilled/Frozen/Multi-Temp	**C**	**F**	**MT**	**C**	**F**	**MT**	**C**	**F**	**MT**
Pre-2019 units									
Fuel consumption (litres per hour)	1.5	1.8	1.6	1.8	2.2	2.0	2.6	3.0	2.9
NOx production (grammes per hour)	42	31	36	48	37	42	54	43	48
PM production (grammes per hour)	0.9	1.0	0.8	1.0	1.1	0.9	2.3	2.4	2.2
PN production (x 10^{14} per hour)	25	28	26	30	33	31	44	47	45
Post-2019 units									
Fuel consumption (litres per hour)	1.1	1.7	1.4	1.3	2.0	1.7	2.1	2.8	2.7
NOx production (grammes per hour)	19	24	23	25	30	29	31	36	35
PM production (grammes per hour)	0.3	0.8	0.6	0.4	0.9	0.7	1.7	2.2	2.0
PN production (x 10^{14} per hour)	6	29	14	11	34	19	25	48	33

4.5 Total auxTRU emissions estimates for UK

Combining the figures in the preceding sections allows for low, high and central scenario estimates to be made for the fuel and environmental impacts of diesel auxTRUs in the UK using the basic equation I = N x H x R.

The overall impact for any given emission type is derived by summing the products of the various N, H and R's that correspond to the proportions of auxTRU estimated to be used in chilled, frozen and multi-temp mode (N's), the hours each run in each of the three ambient temperature conditions (H's) and the emission production rates for each combination of mode and ambient temperature (R's).

Table 13 shows the results of these calculations for each scenario and impact parameter.

Table 13. AuxTRU emissions estimates for the UK

	Pre-2019 units	Post-2019 units	All diesel auxTRU
Low numbers and low hours scenario (lower bound estimates)			
Fuel consumption (million litres per year)	72	61	132
NOx emissions (ktonnes per year)	1.5	1.0	2.5
$PM_{2.5}$ emissions (tonnes per year)	42	29	71
PN emissions (x 10^{21} per year)	114	71	185
High numbers and high hours scenario (upper bound estimates)			
Fuel consumption (million litres per year)	197	167	364
NOx emissions (ktonnes per year)	4.1	2.7	6.8
$PM_{2.5}$ emissions (tonnes per year)	114	81	195
PN emissions (x 10^{21} per year)	314	196	510
Central scenario (central estimate)			
Fuel consumption (million litres per year)	128	108	235
NOx emissions (ktonnes per year)	2.7	1.7	4.4
$PM_{2.5}$ emissions (tonnes per year)	74	52	126
PN emissions (x 10^{21} per year)	204	127	330

The following sections provide more detail on these overall UK-wide estimates and set them in their wider context.

4.5.1 Fuel consumption and GHG emissions

Fuel consumption can be converted to overall (tailpipe) greenhouse gas (GHG) impacts using the official (at source) emissions factor for pump average diesel, currently 2.51 $kgCO_2e$ per litre. Note, however, that our estimates for GHG emissions are, at this stage, based only on fuel directly combusted by the auxTRU. Loss of refrigerant is likely to be another important source of GHG emissions from the temperature-controlled transport sector but the research to date has not attempted to quantify its overall impacts.

The modelling suggests that across the UK, diesel auxTRU currently consume around 235 million litres of fuel per annum, with an uncertainty margin on this of around ± 100 million litres. Their tailpipe GHG impacts are therefore estimated to be around 590 ± 250 kilo-tonnes CO_2e. Putting this in the context of tailpipe emissions from all UK HGVs, our modelling suggests that auxTRU add around a further 3% to the roughly 20 $MTCO_2e$ total. UK HGVs currently consume around 8 billion litres of diesel fuel per annum.

4.5.2 NOx emissions

The National Atmospheric Emissions Inventory suggests that UK HGVs produced around 21 ktonnes of NOx emissions in 2021 (the latest year for which estimates are available). Our estimate for the NOx emissions from diesel auxTRU is 4.4 ± 2 ktonnes, meaning that auxTRU are estimated to contribute an additional 20% or so to the UK's overall HGV NOx impacts.

4.5.3 Particulate emissions

The National Atmospheric Emissions Inventory suggests that UK HGVs produced around 1,930 tonnes of $PM_{2.5}$ emissions in 2021 (the latest year for which estimates are available). Our estimate for the PM emissions from diesel auxTRU is 126 ± 60 tonnes, meaning that auxTRU are estimated to contribute an additional 7% or so to the UK's overall HGV $PM_{2.5}$ impacts, which include tailpipe emissions and those arising from brake and tyre wear and road abrasion. If only tailpipe PM emissions are considered, the UK HGV total for 2021 was just 336 tonnes, according to NAEI, meaning diesel auxTRU may contribute around a further 40%, possibly as much as 55%, to this total.

National estimates for particle number (PN) emissions are not available. It is possible, however, to provide context at a per vehicle level, which the following section presents, for particle number and the other emissions modelled/measured.

4.6 Euro standard (vehicle) emission comparisons

The 2021 test programme report compared the measured per hour fuel consumption and emissions rates for diesel auxTRUs (averaged across chilled and frozen mode tests) with the equivalent real-world rates for Euro VI-compliant HGV propulsion engines. That report concluded that:

"A single diesel auxTRU fitted to a Euro VI HGV would:

- Consume about 1/8th the fuel.
- Produce about 1/8th the GHG emissions.
- Produce at least double (2x) the NOx.
- Emit at least five times (5x) the Particle Mass, and
- Emit about 500 times (500x) the number of particles, in comparison to the vehicle's Euro VI compliant propulsion engine."

This latest programme of testing has provided additional evidence and allows, for the first time, distinctions to be made between pre-2019 and post-2019 auxTRUs. Combining the 2023 test results with those from the earlier tests, the above statement can now be modified as follows:

A single diesel auxTRU fitted to a Euro VI HGV would in comparison to the vehicle's Euro VI compliant propulsion engine (in a city/urban environment during periods of reasonably average ambient temperatures):

- Consume about **1/9th the fuel if manufactured prior to 2019 or about 1/10th if after 2019.**
- Produce about **1/9th or 1/10th the GHG emissions respectively.**
- Produce at least **double (2x) the NOx if pre-2019 and at least 50% more (1.5x) if post-2019.**
- Emit at least **five times (5x) the Particle Mass ($PM_{2.5}$) if pre-2019 and around triple (3x) if post-2019.**
- Emit about **400 times (400x) the number of particles if pre-2019 and around 300 times (300x) if post-2019.**

The latest programme has also provided further evidence on the effects of ambient temperatures, indicating that fuel consumption, NOx, PM and PN emissions from diesel auxTRU will all increase substantially during periods of very hot weather. In city centres, these will tend to exacerbate the adverse public health impacts already associated with summer heatwave conditions.

While not examined in detail during the tests, it is also likely that a correlation will exist between fuel use/emissions and the number and duration of door openings, meaning operators doing multi-drop operations in city-centres will experience particularly high fuel consumption levels in hot weather, and emit higher levels of pollutants than otherwise similar vehicles doing less frequent drops.

5. Other (non-TRU) auxiliary engine types

Research on this topic was initiated by conducting an interview with the Chief Engineer of Leyland-DAF trucks, who are the leading supplier of >7.5T HDVs in Britain, including powertrain and chassis combinations for subsequent conversion into specialist vehicles, which may require ancillary power systems. It was therefore felt that Leyland-DAF would be extremely well placed to confirm applications of this type.

The findings from this interview were that the only known application of ancillary engines which exist in any volume, are for large road sweeper units, where they are used to drive the suction machinery, which on large units exceeds the power take-off (PTO) capability of the propulsion engine. Identified manufacturers of these units are Bucher Municipal (formerly Johnston Sweepers), Quattro Group and Stock Sweepers.

These initial findings were further supported by a consultation with Zemo commercial vehicle experts, during which one of the members, a former manager at IVECO trucks, another major HDV supplier, also confirmed large road sweepers as the main ancillary engine user. Other applications do exist, such as large cranes and concrete pumping vehicles, but these can more appropriately be categorised as construction vehicles, rather than on-road.

Online research conducted by Zemo Partnership has confirmed that both Bucher Municipal and Stock Sweepers do offer large sweeping machines with ancillary engines, both supplied by JCB DieselMax, with power ranges from 55 to 129kW. Current models meet the EU Stage V NRMM emissions requirements. It is proposed that samples of these units be considered for testing as part of the ancillary engine emissions test project and additional industry contacts be established to support further market analyses and test protocol development.

6. Conclusions and next step recommendations

6.1 Conclusions

A major new programme of baseline testing of diesel auxTRU systems has been completed. Combined with data from earlier tests, we now have a much stronger evidence base as to their overall environmental impacts under different usage conditions (chilled, frozen and multi-temperature), at different ambient temperatures (from 5 to 30 °C) and how those emissions vary between pre-2019 and post-2019 units – the Non-Road Mobile Machinery (NRMM) regulations started to impose limits on some auxTRU emissions from January 2019.

A market survey has also been conducted and its results used to more robustly characterise the operational duties of the UK's auxTRU fleet, including their use across the three operational modes and their typical annual hours of use.

National data sources and published literature have been used to estimate the overall numbers of diesel auxTRU in use in the UK (reckoned to be in the range 40,000-55,000) and combined with the survey and test programme results to produce the following overall estimates for UK environmental impacts:

- UK diesel auxTRU consume around 235 million litres of fuel per annum (range 132-364 Ml).
- They contribute about 590 kilo-tonnes of tailpipe GHG emissions (range 330-910 kt). Note this does not include other GHG emissions, e.g. from loss of refrigerant.
- They produce around 4.4 kt of NOx emissions (range 2.5-6.8 kt).
- They emit about 126 tonnes of $PM_{2.5}$ particulate mass emissions (range 71-195 t).
- And they emit about 330 x 10^{21} particle number (PN) emissions (range 185-510 x 10^{21}).

The test results indicate that a single diesel auxTRU fitted to a Euro VI HGV would in comparison to the vehicle's Euro VI compliant propulsion engine (in a city/urban environment during periods of reasonably average ambient temperatures):

- Consume about **1/9th the fuel if manufactured prior to 2019 or about 1/10th if after 2019.**
- Produce about **1/9th or 1/10th the GHG emissions respectively.**
- Produce at least **double (2x) the NOx if pre-2019 and at least 50% more (1.5x) if post-2019.**
- Emit at least **five times (5x) the Particle Mass ($PM_{2.5}$) if pre-2019 and around triple (3x) if post-2019.**
- Emit about **400 times (400x) the number of particles if pre-2019 and around 300 times (300x) if post-2019.**

6.2 Next step recommendations for the research project

The project should continue broadly as planned, in that the remaining key piece of the refrigerated HGV jigsaw needed to fully understand their overall environmental impacts and, crucially, what can be done to reduce those impacts, is to measure the energy and emissions performance of a range of alternative technologies.

In the broader context of evaluating the environmental impacts of other auxiliary HGV engine types, not used for refrigeration, the project should also continue as planned to explore the aux-engine road sweeper market and, if feasible within time and budgetary constraints, establish and pilot an emissions test procedure for them.

The final project report, due in November 2024, should cover progress made on these topics and, alongside a short summary of this report's findings, draw some overall conclusions and make suggestions for future research activity and potential future policy interventions.

Appendix A: AuxTRU tests - results graphs

Unit 1 – Tests at 15 °C ambient (chilled and frozen mode tests)

Figure A. 1 Temperatures (Unit 1 @ 15°C)

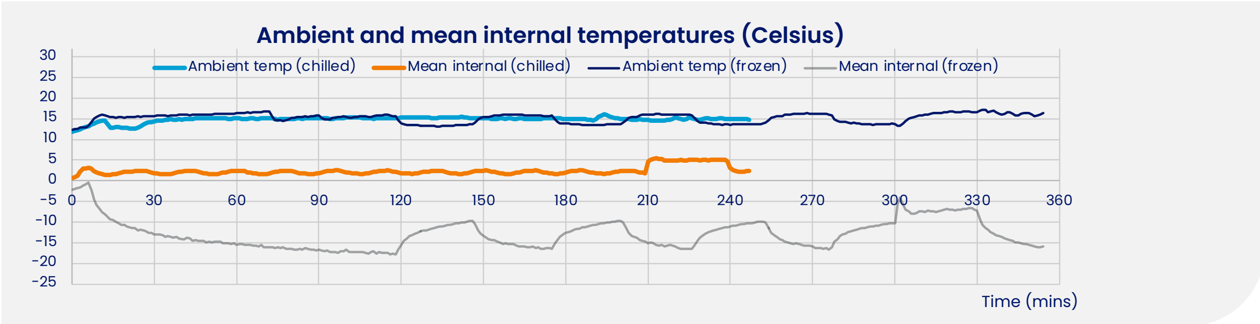


Figure A. 2 NOx emissions (Unit 1 @ 15°C)

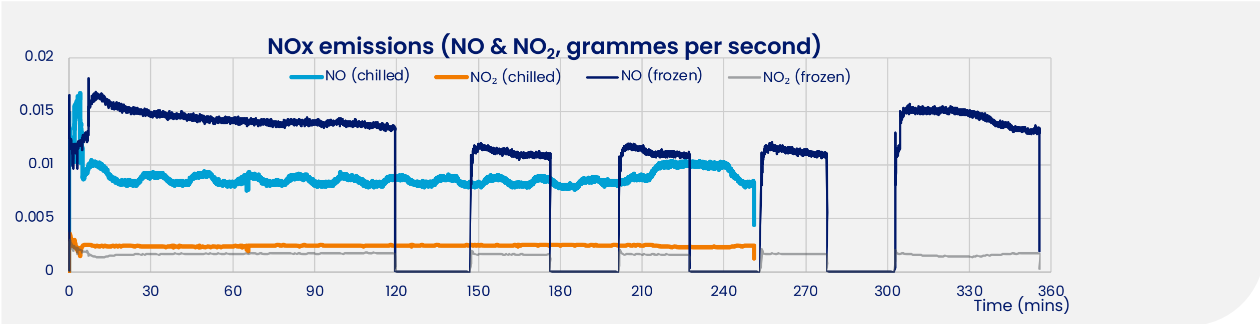


Figure A. 3 Particle mass emissions (Unit 1 @ 15°C)

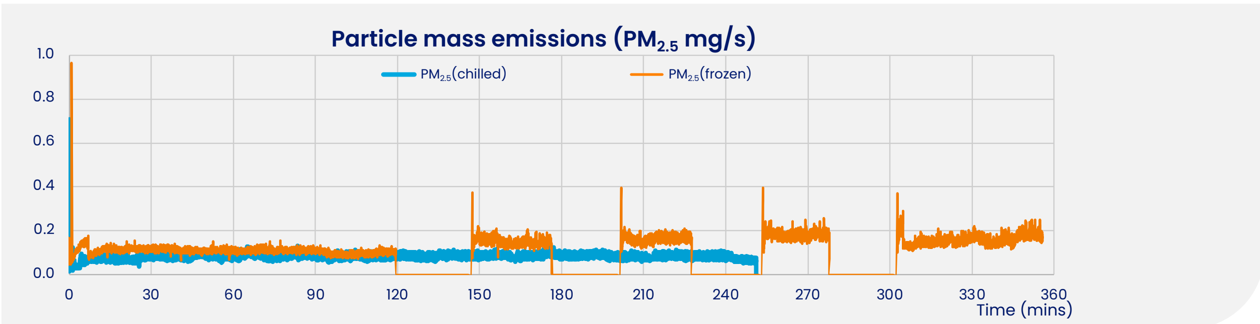
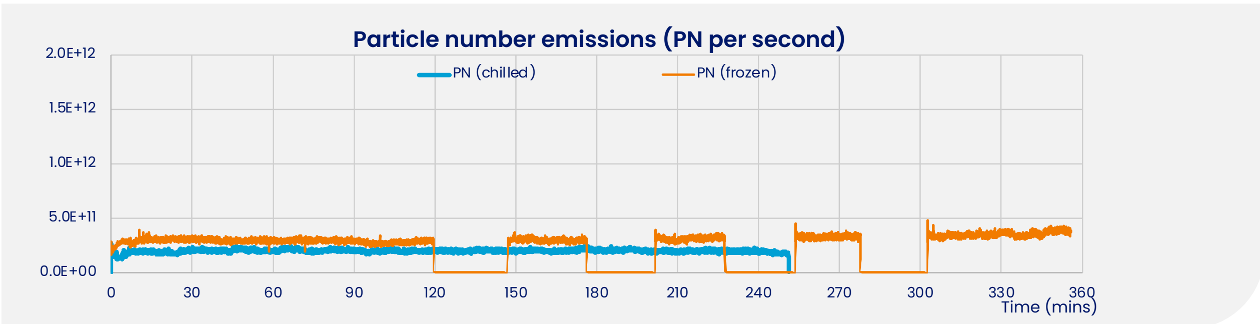


Figure A. 4 Particle number emissions (Unit 1 @ 15°C)



Unit 2 – Tests at 15 °C ambient (chilled and frozen mode tests)

Figure A. 5 Temperatures (Unit 2 @ 15°C)

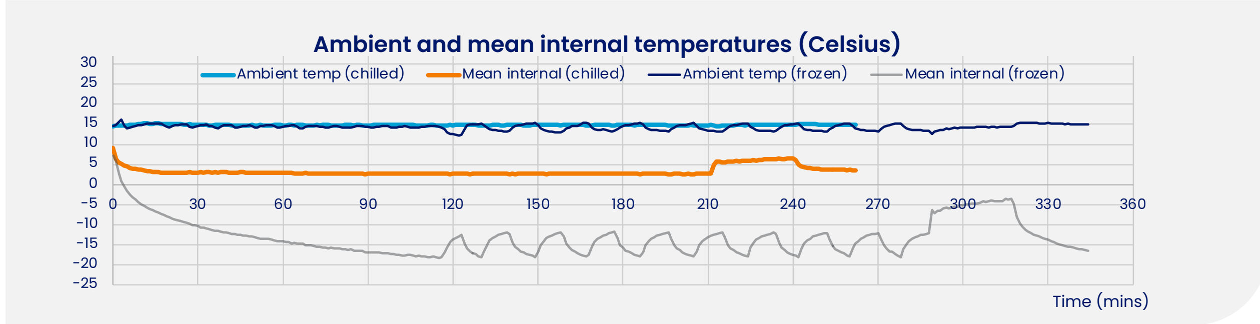


Figure A. 6 NOx emissions (Unit 2 @ 15°C)

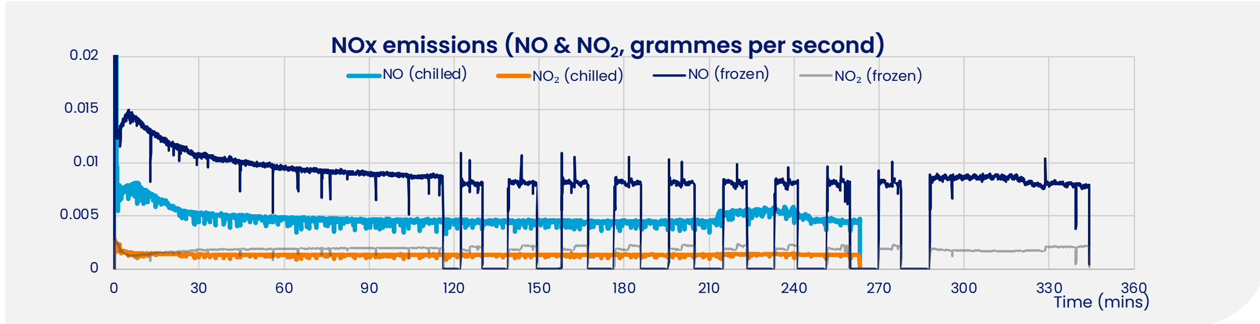


Figure A. 7 Particle mass emissions (Unit 2 @ 15°C)

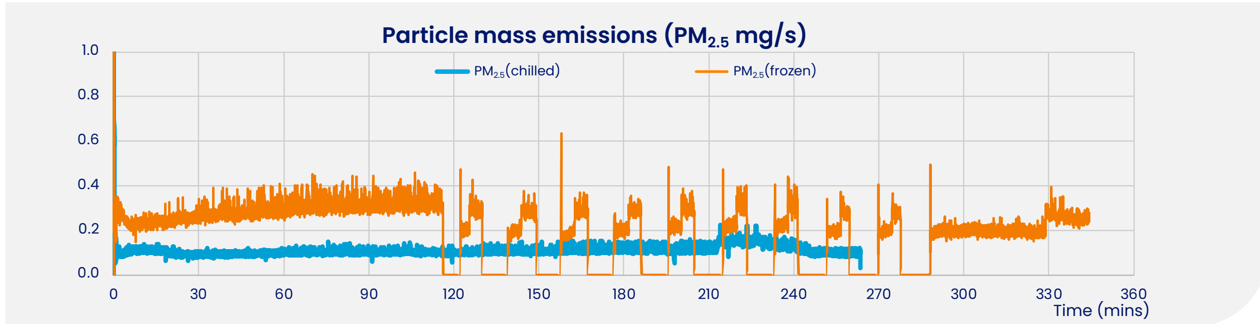
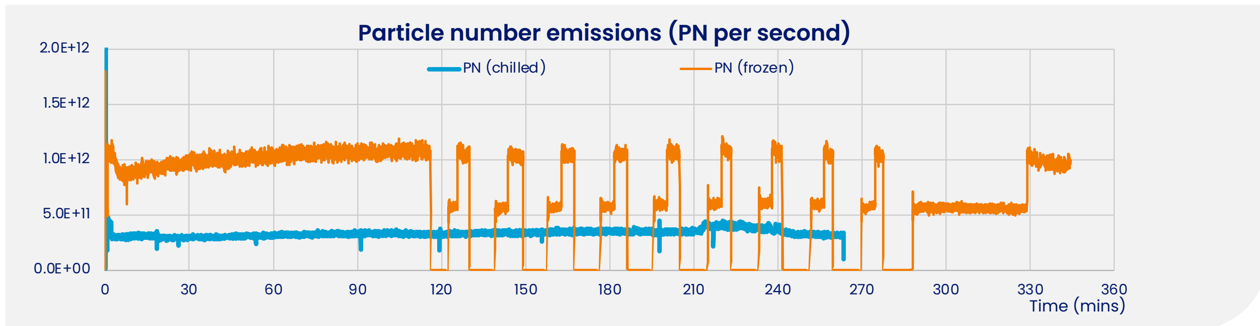


Figure A. 8 Particle number emissions (Unit 2 @ 15°C)



Unit 3 – Tests at 15 °C ambient (chilled and frozen mode tests)

Figure A. 9 Temperatures (Unit 3 @ 15°C)

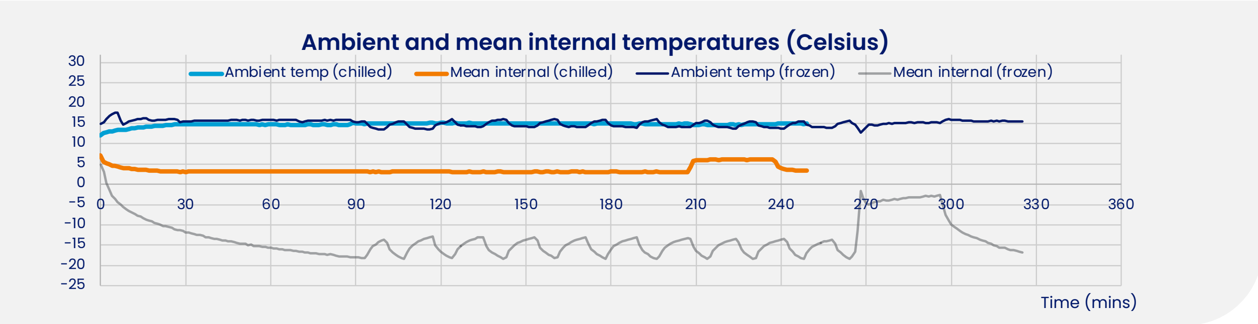


Figure A. 10 NOx emissions (Unit 3 @ 15°C)

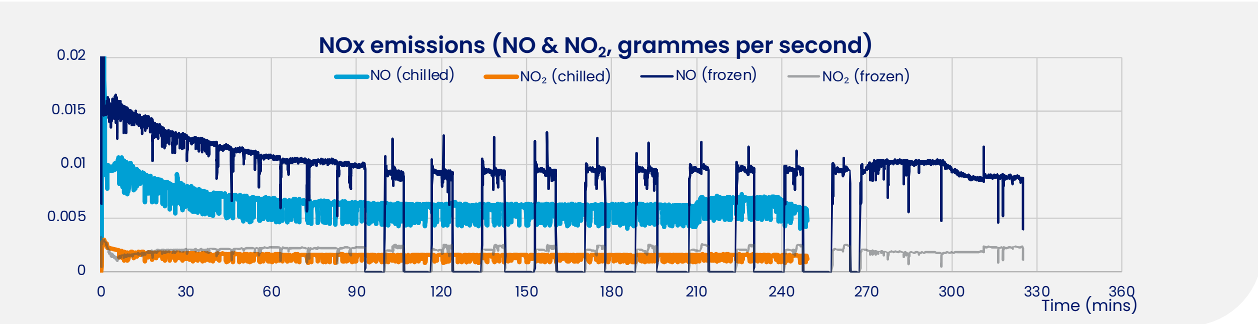


Figure A. 11 Particle mass emissions (Unit 3 @ 15°C)

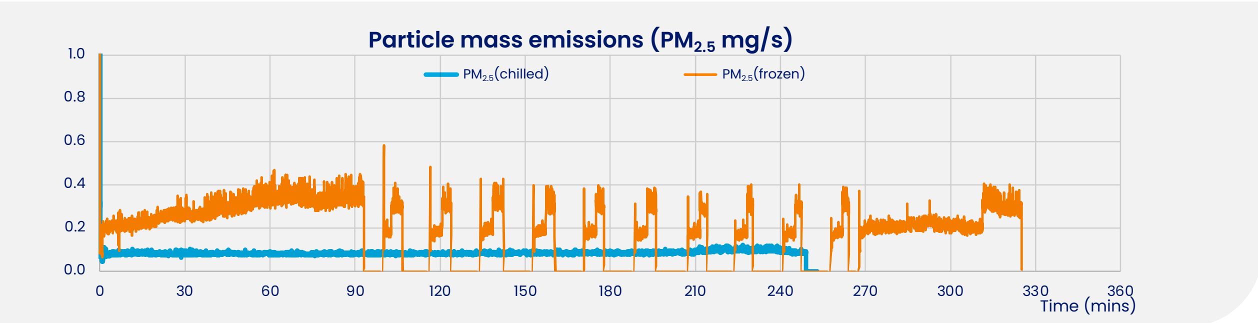
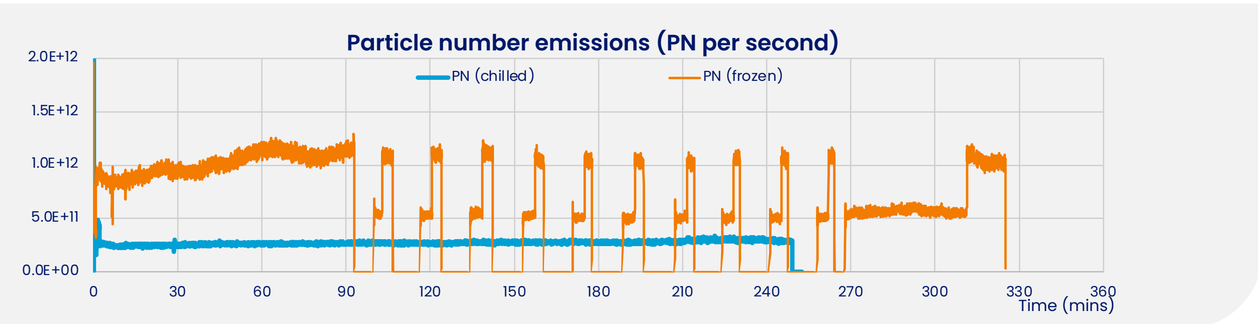


Figure A. 12 Particle number emissions (Unit 3 @ 15°C)



Unit 4 – Tests at 15 °C ambient (two chilled mode tests)

Figure A. 13 Temperatures (Unit 4 @ 15°C)

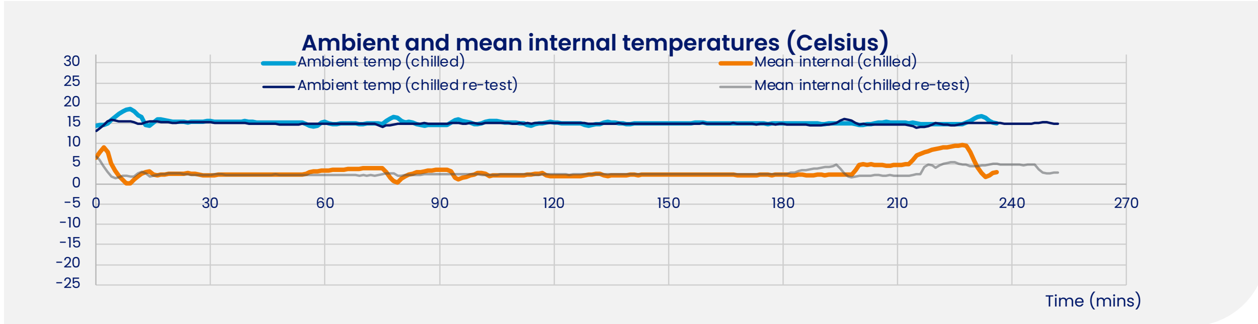


Figure A. 14 NOx emissions (Unit 4 @ 15°C)

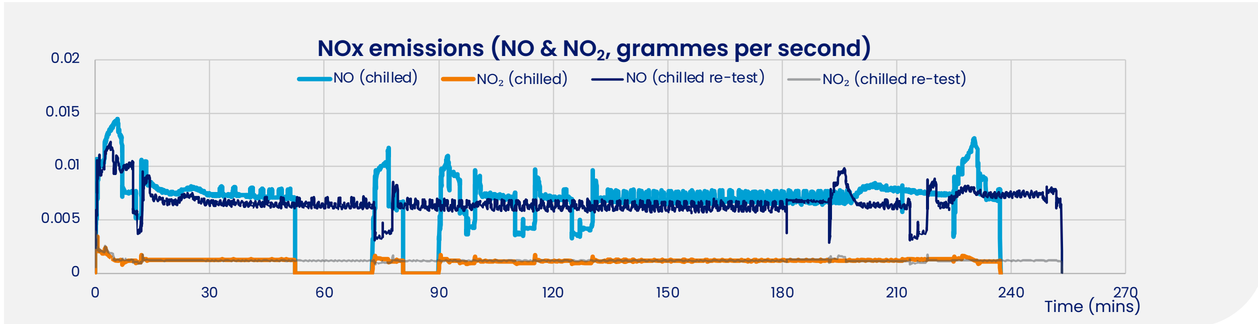


Figure A. 15 Particle mass emissions (Unit 4 @ 15°C)

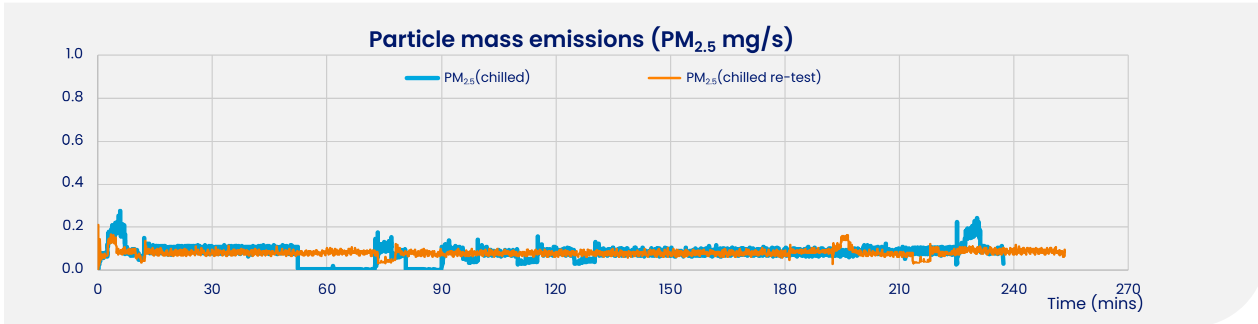
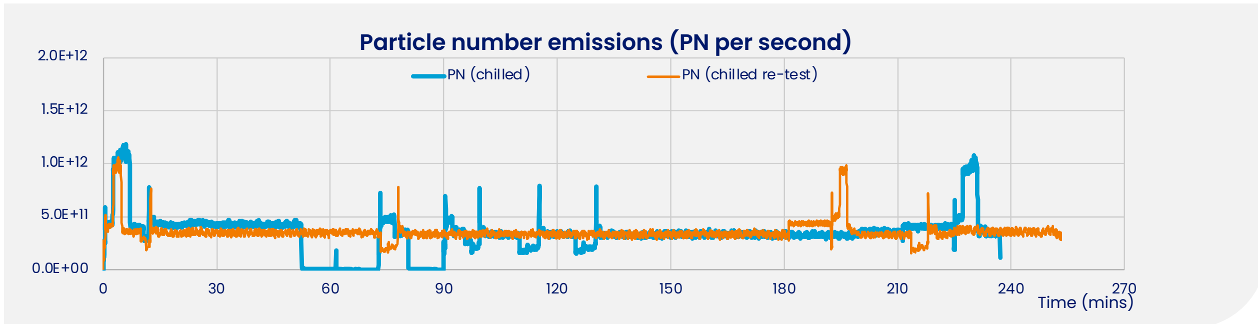


Figure A. 16 Particle number emissions (Unit 4 @ 15°C)



Unit 5 – Tests at 5 & 15 °C ambient (frozen mode tests)

Figure A. 17 Temperatures (Unit 5 @ 5 & 15°C)

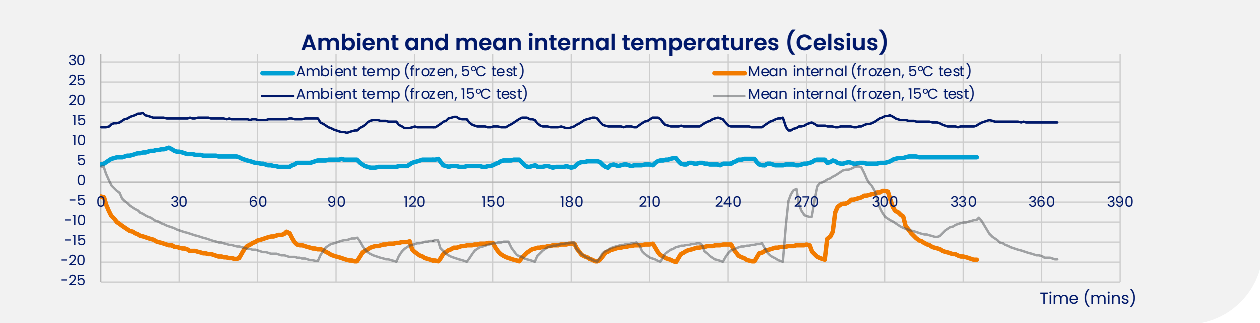


Figure A. 18 NOx emissions (Unit 5 @ 5 & 15°C)

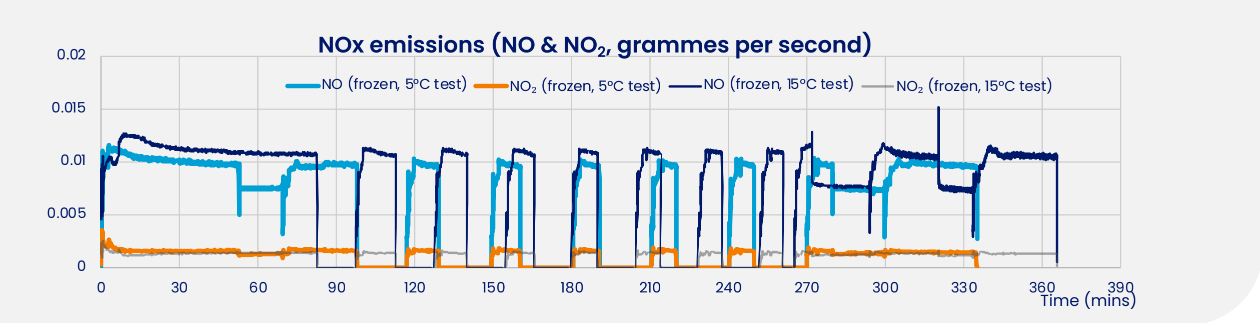


Figure A. 19 Particle mass emissions (Unit 5 @ 5 & 15°C)

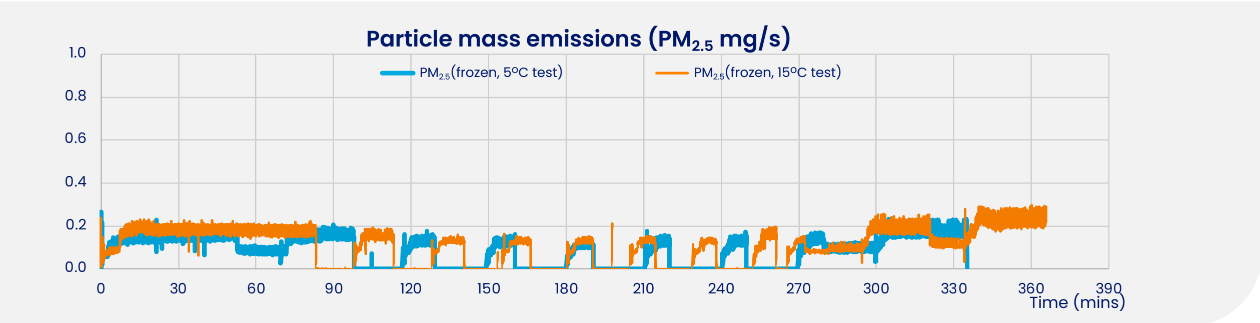
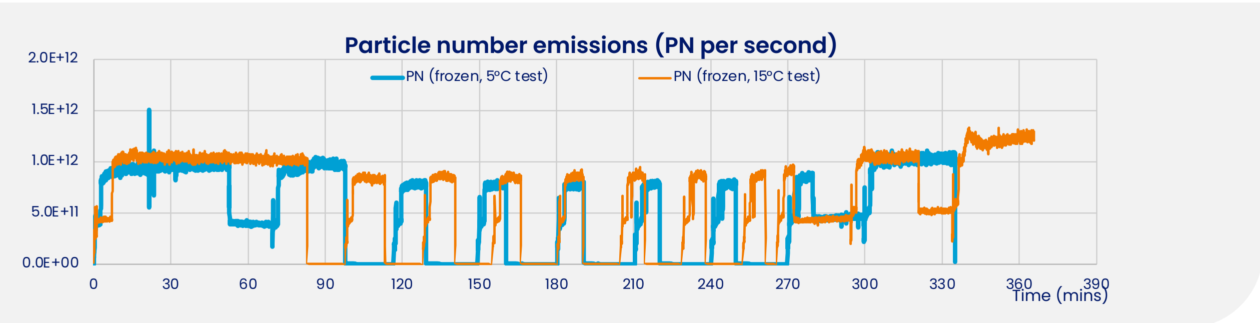


Figure A. 20 Particle number emissions (Unit 5 @ 5 & 15°C)



Unit 6 – Tests at 30 °C ambient (chilled and frozen mode tests)

Figure A. 21 Temperatures (Unit 6 @ 30°C)

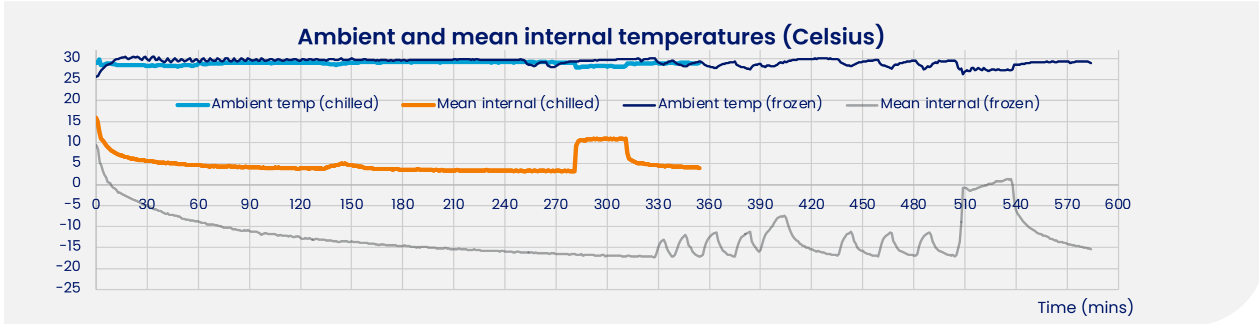


Figure A. 22 NOx emissions (Unit 6 @ 30°C)

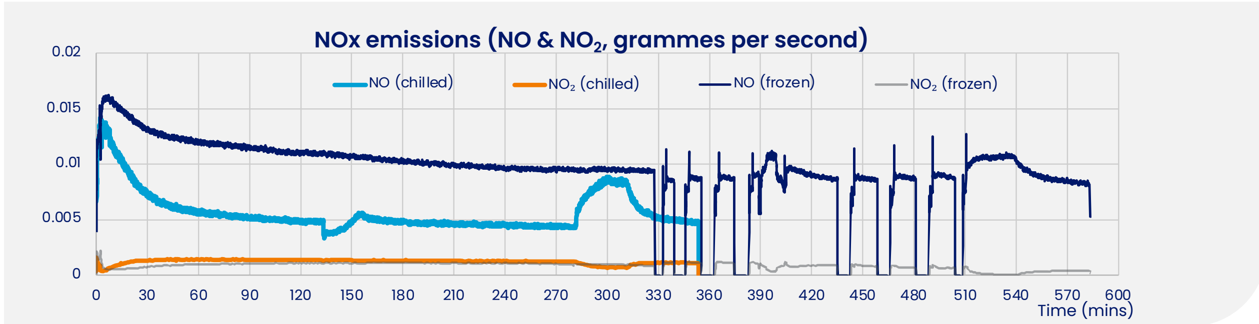


Figure A. 23 Particle mass emissions (Unit 6 @ 30°C)

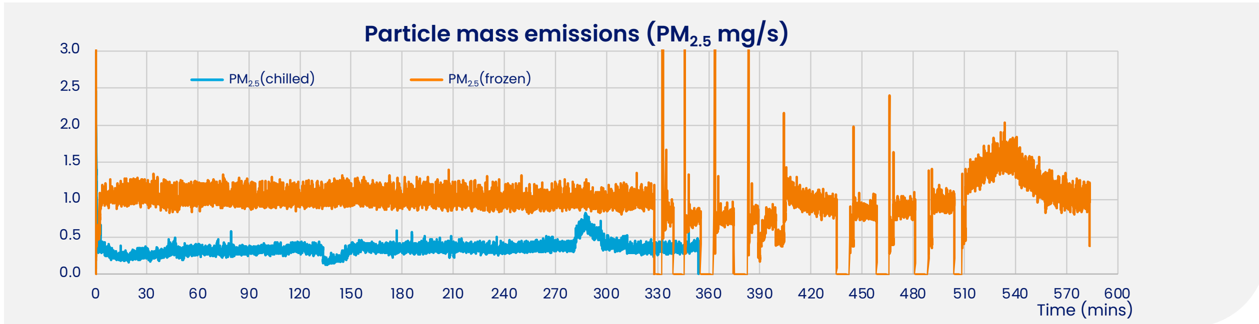
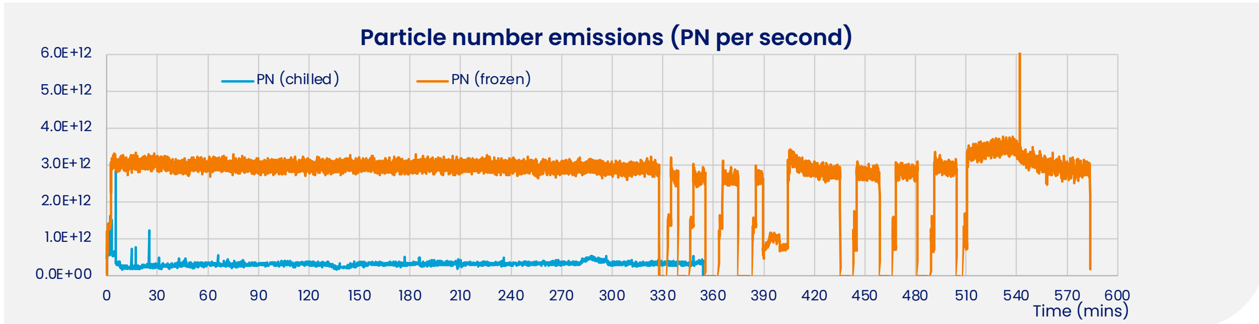


Figure A. 24 Particle number emissions (Unit 6 @ 30°C)



Unit 6 – Tests at 15 °C ambient (chilled and frozen mode tests)

Figure A. 25 Temperatures (Unit 6 @ 15°C)

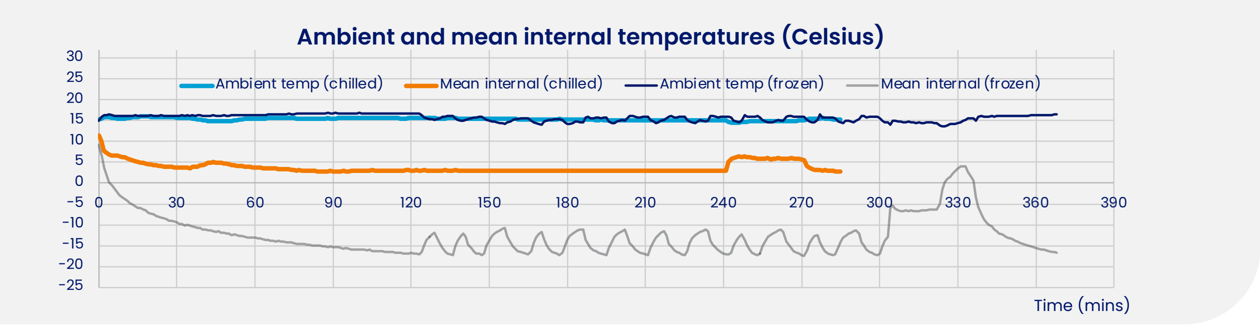


Figure A. 26 NOx emissions (Unit 6 @ 15°C)

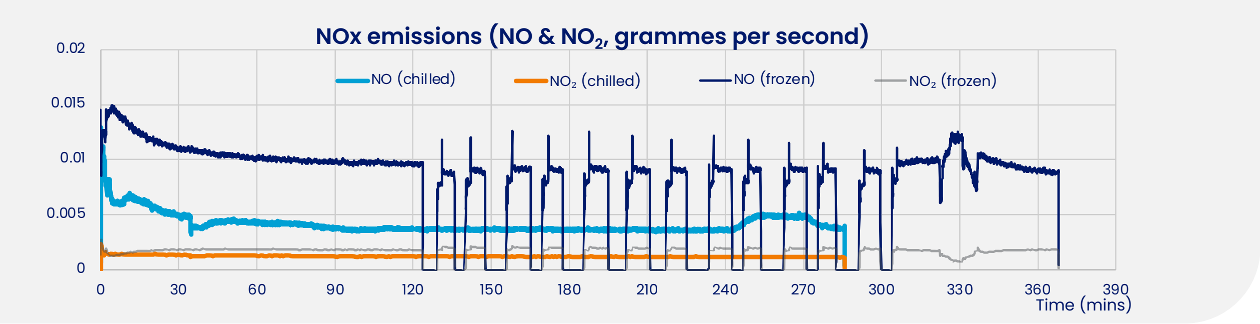


Figure A. 27 Particle mass emissions (Unit 6 @ 15°C)

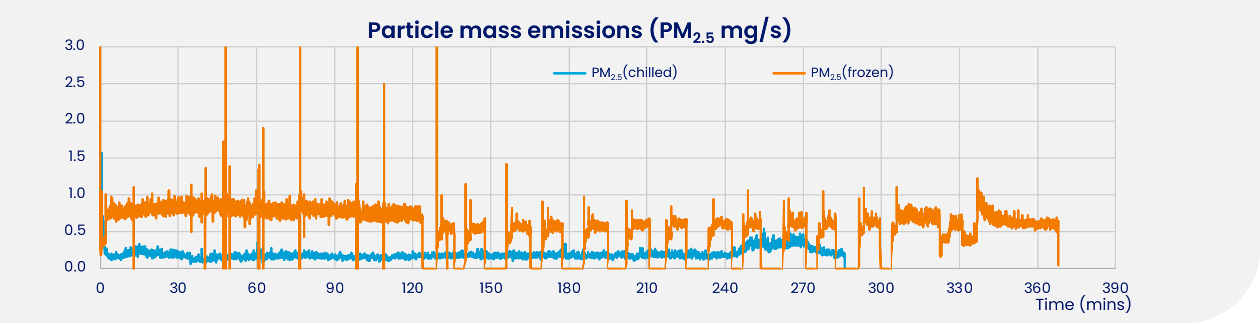
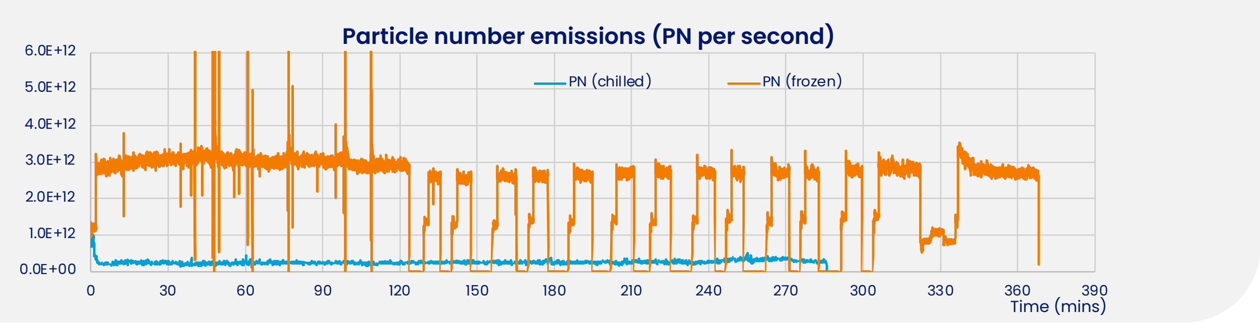


Figure A. 28 Particle number emissions (Unit 6 @ 15°C)



Unit 6 – Tests at 5 °C ambient (chilled and frozen mode tests)

Figure A. 29 Temperatures (Unit 6 @ 5°C)

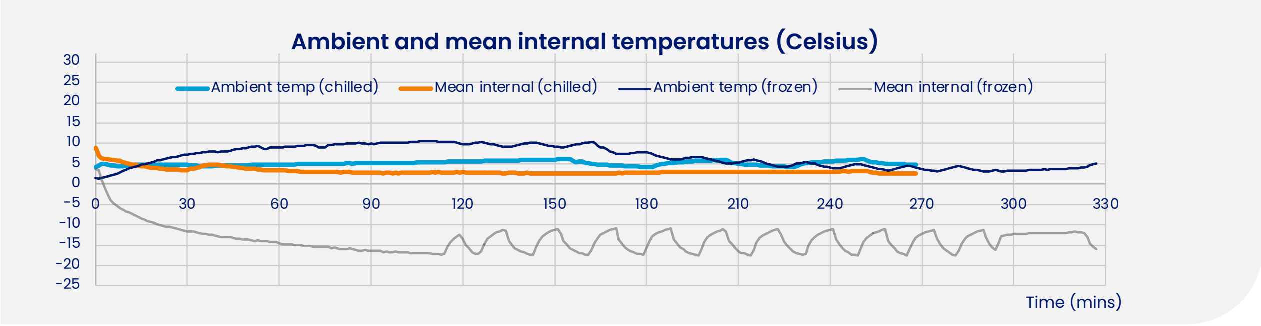


Figure A. 30 NOx emissions (Unit 6 @ 5°C)

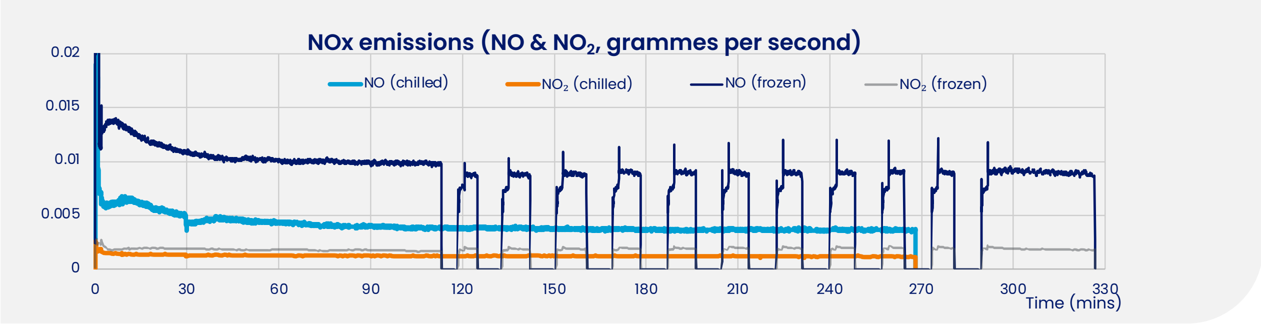


Figure A. 31 Particle mass emissions (Unit 6 @ 5°C)

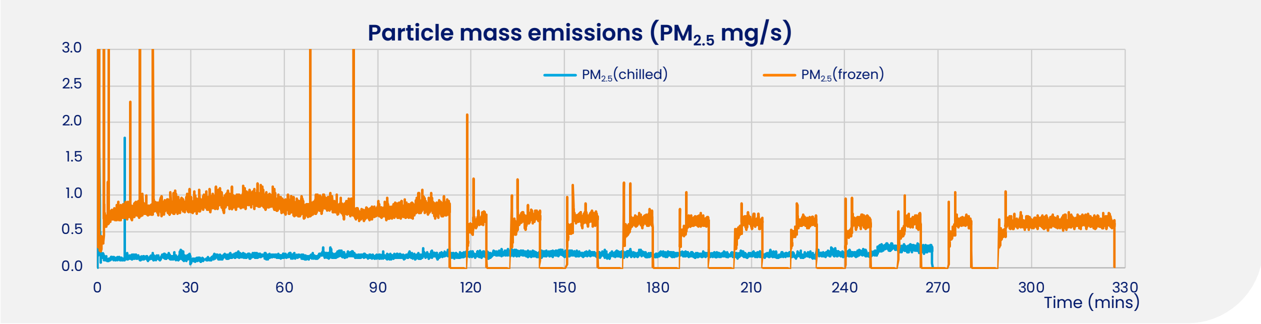
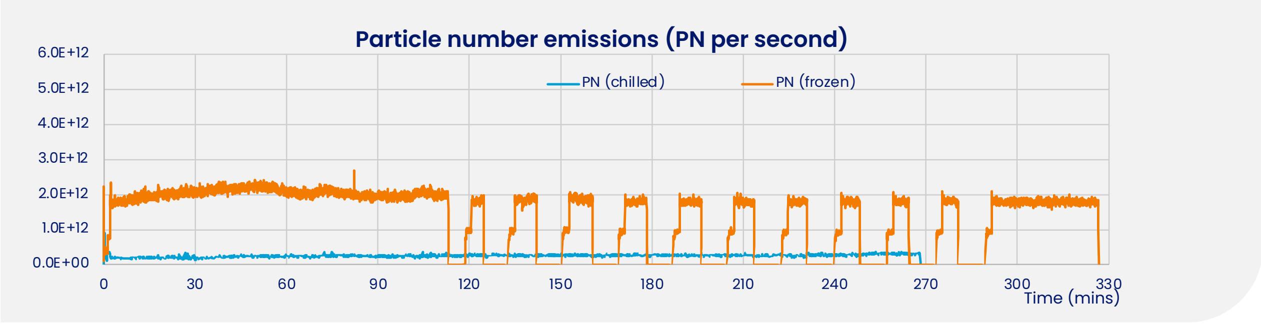


Figure A. 32 Particle number emissions (Unit 6 @ 5°C)



Unit 6 – Test at 30 °C ambient (multi-temperature mode)

Figure A. 33 Temperatures (Unit 6 @ 30°C)

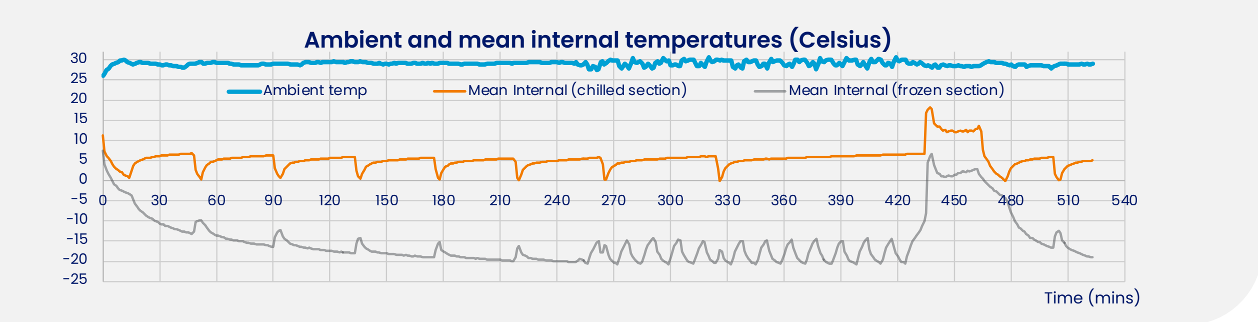


Figure A. 34 NOx emissions (Unit 6 @ 30°C)

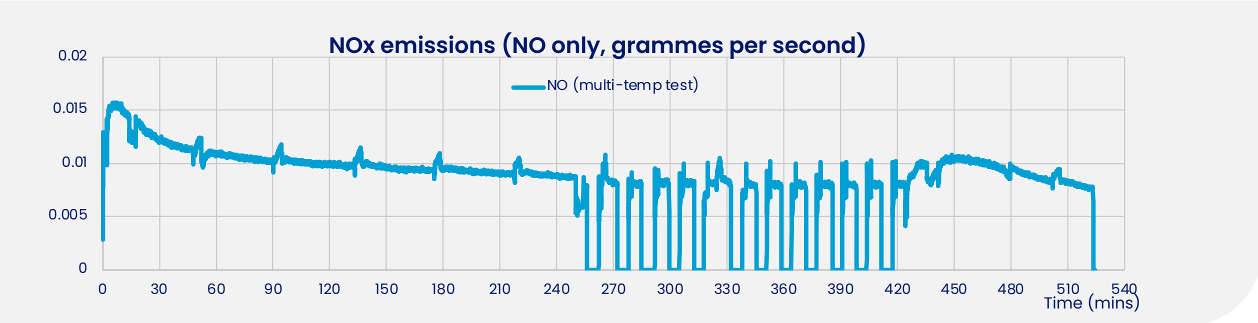


Figure A. 35 Particle mass emissions (Unit 6 @ 30°C)

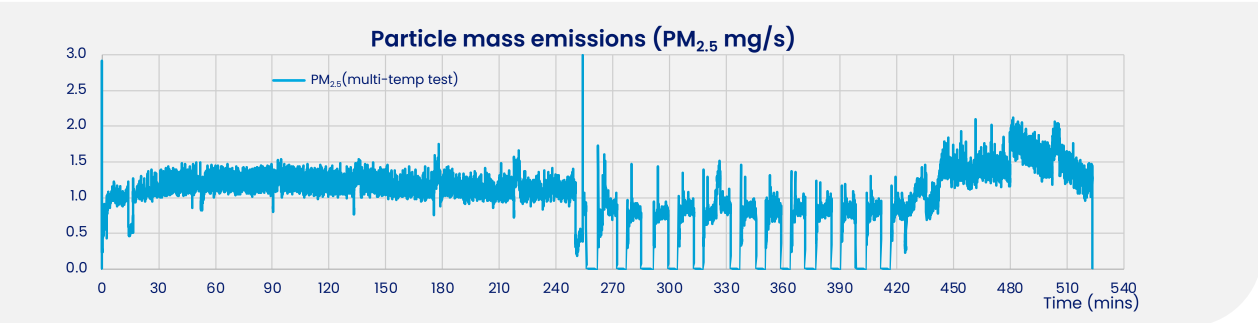
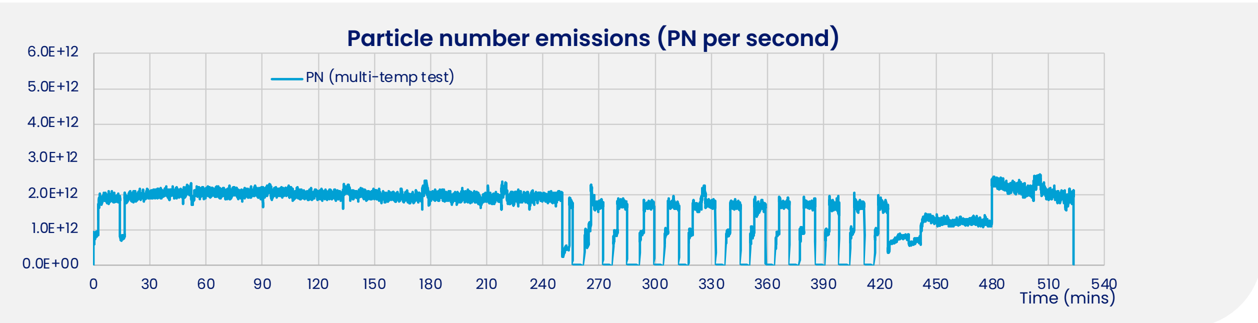


Figure A. 36 Particle number emissions (Unit 6 @ 30°C)



Unit 6 – Test at 15 °C ambient (multi-temperature mode)

Figure A. 37 Temperatures (Unit 6 @ 15°C)

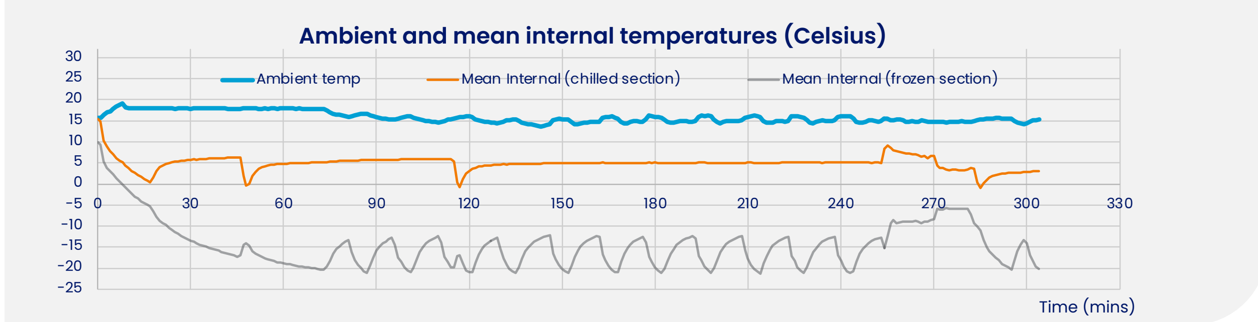


Figure A. 38 NOx emissions (Unit 6 @ 15°C)

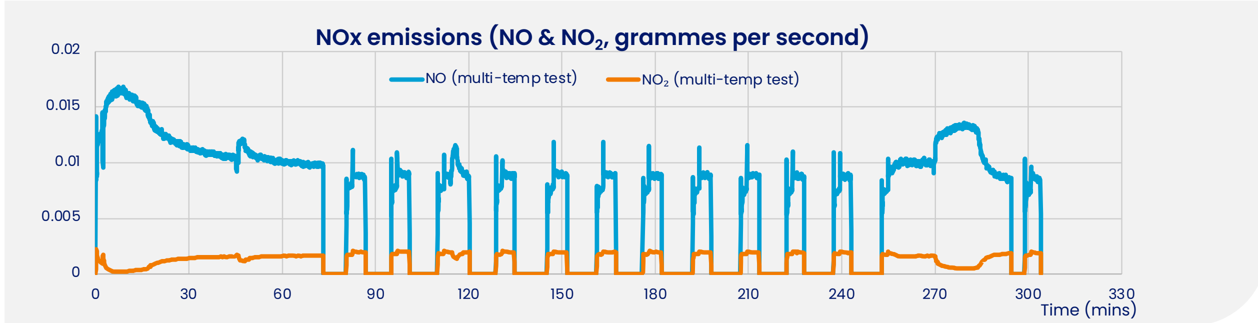


Figure A. 39 Particle mass emissions (Unit 6 @ 15°C)

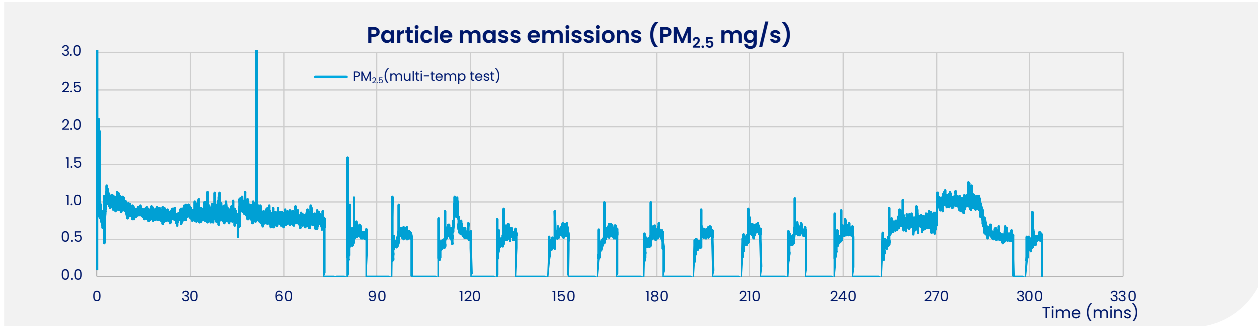
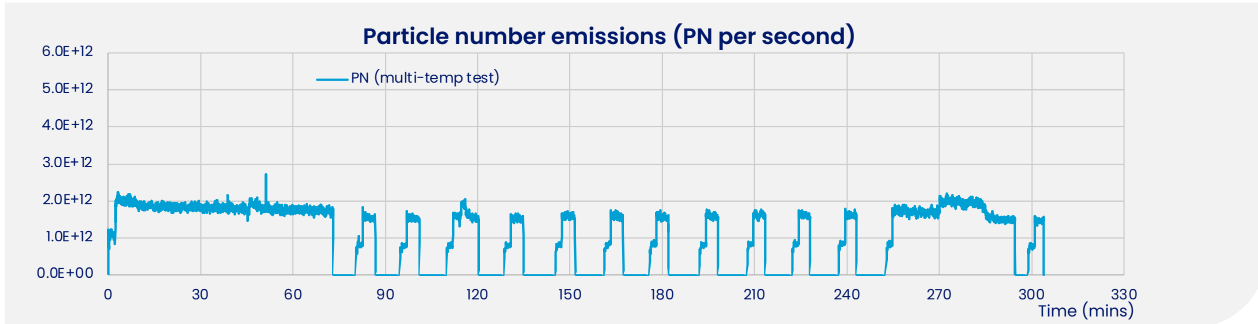


Figure A. 40 Particle number emissions (Unit 6 @ 15°C)



Unit 6 – Test at 5 °C ambient (multi-temperature mode)

Figure A. 41 Temperatures (Unit 6 @ 5°C)

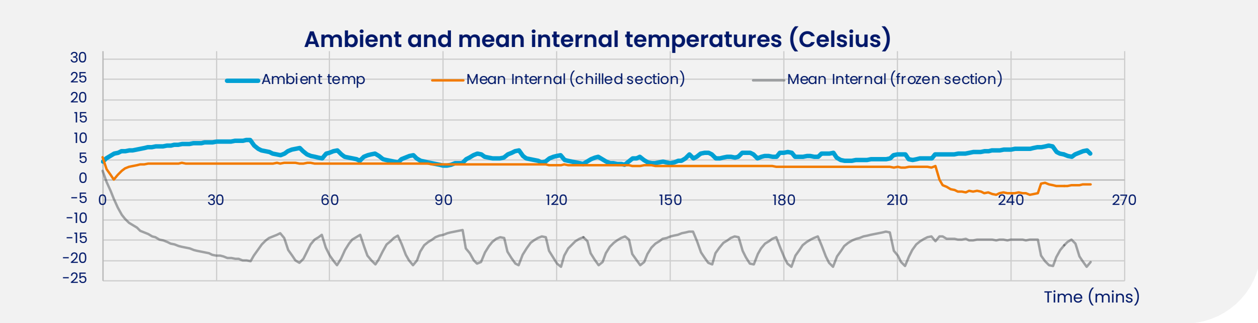


Figure A. 42 NOx emissions (Unit 6 @ 5°C)

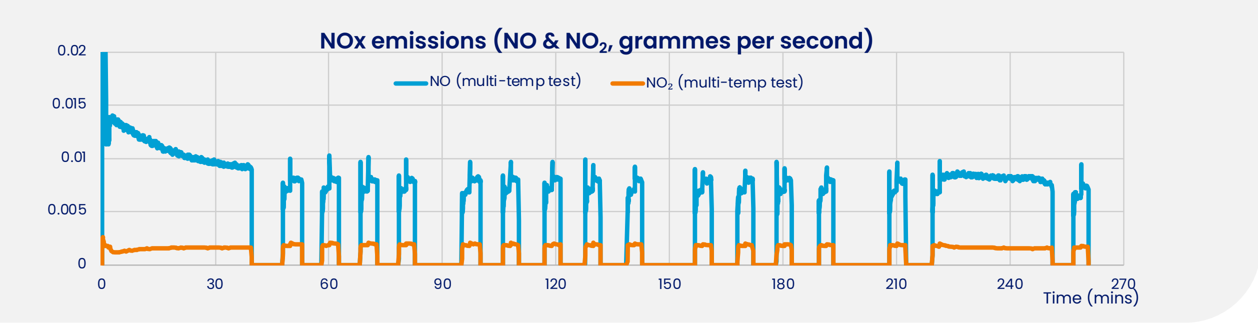


Figure A. 43 Particle mass emissions (Unit 6 @ 5°C)

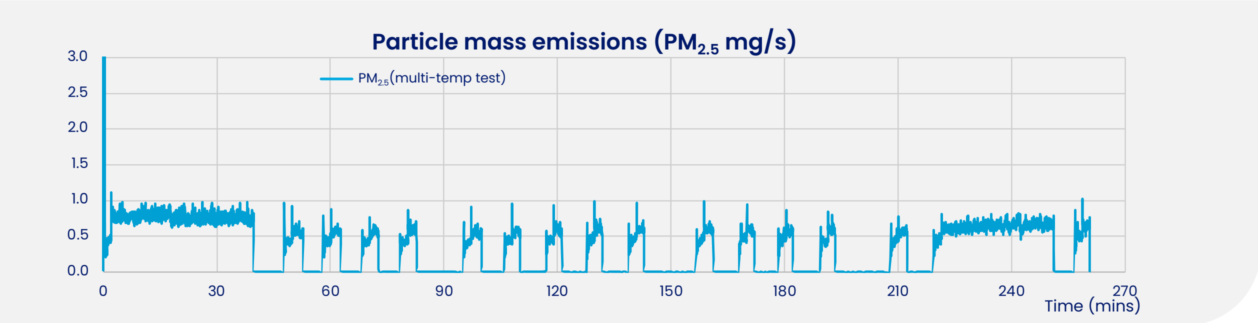
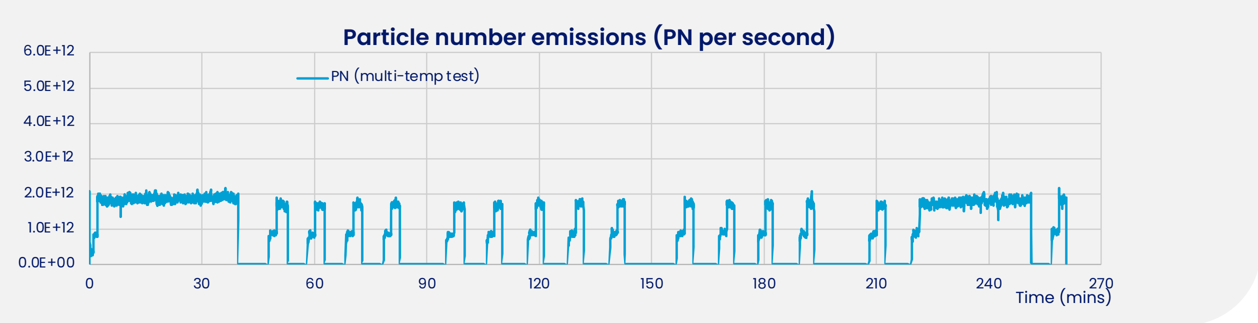


Figure A. 44 Particle number emissions (Unit 6 @ 5°C)



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