Zemo Partnership
Accelerating Transport to Zero Emissions

TRANSPORT SCOTLAND
CÒMHDHAIL ALBA

Emissions Testing of Two Auxiliary Transport Refrigeration Units

The results of a Transport Scotland funded project to measure the baseline energy consumption and emissions performance of two refrigerated commercial vehicles

Prepared by Zemo Partnership
September 2021

Zemo.org.uk

Zemo Partnership
3 Birdcage Walk,
London,
SW1H 9JJ

T: +44 (0)20 7304 6880
E: Hello@Zemo.org.uk
Visit: Zemo.org.uk

Acknowledgements

Zemo Partnership is grateful to Cambridge Refrigeration Technology and Cambustion Ltd for carrying out the tests described in this report, to Transport Scotland (especially Dr Aisling Doyle) for their guidance and funding of the research and to Norman Highnam (Highnam Assist), Graham Usher (Hultsteins) and Tom Southall (Cold Chain Federation) for their peer review comments and assistance.

Authors:

Brian Robinson CEng CEnv MIMechE FCILT
Commercial Vehicle & Sustainability Consultant

Andrew Fraser CEng FIMechE
Technical Consultant

Reviewed by:

Andy Eastlake CEng FIMechE
Managing Director

This report has been prepared by Zemo Partnership, September 2021

Zemo Partnership
Accelerating Transport to Zero Emissions

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" but in the case of auxTRUs, the emissions are on the road in real terms.

In 2019, Zemo Partnership (LowCVP as was) was funded by Innovate UK to develop and validate an initial emissions test protocol for auxTRUs. As part of that preparatory work, pilot testing of a single diesel auxTRU was carried out. In 2021, Transport Scotland provided funding for Zemo Partnership to carry out further emissions testing on two other conventional diesel auxTRUs. This report presents the results. For the avoidance of any doubt, auxTRUs in the context of this report refers only to those truck or trailer mounted systems using a diesel engine that is completely separate from the heavy goods vehicle's propulsion system. Refrigeration units powered by the vehicle's main engine, as commonly used by smaller HGVs and vans, are not considered.

The test protocol involves loading a vehicle with water-filled containers and empty boxes to simulate realistic 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 (either chilled or frozen). 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 were taken of diesel auxTRU fuel consumption, internal and external temperatures and the emissions of oxides of Nitrogen (NOx) and particulates.

Two diesel auxTRU were tested, 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).

Earlier research by Cenex into TRU usage in London has then been used and scaled to estimate the number of diesel auxTRUs in daily use in Scotland, their operational characteristics and, when combined with the new evidence from testing on emissions production rates, their overall potential contribution to emissions of greenhouse gases and air pollutants in Scotland. Details of TRU usage in Scotland are not available so these estimates should be treated as indicative only.

The research suggests there are perhaps 450–700 articulated HGVs and 950–1,400 rigid HGVs using auxTRUs in Scotland, with each vehicle typically operating (with its auxTRU switched on) between 1,500 and 4,200 hours per year. The test programme presently used to evaluate auxTRUs produces the averaged fuel and emissions rates shown in Table ES1. These relate only to the auxTRUs, not the vehicles' propulsion engines.

Table ES1. Test-based averaged fuel and emissions factors

Per hour	Summer Semitrailers	Winter Semitrailers	Summer Rigid HGVs	Winter Rigid HGVs
Fuel consumption (litres per hour)	1.9	1.7	2.3	2.3
NOx production (grammes per hour)	45	32	39	38
PM production (grammes per hour)	1.4	0.9	1.0	0.9
PN production (x 10^{14} per hour)	38	42	44	38
	Annual (Semitrailers)		**Annual (Rigid HGVs)**	
Fuel consumption (litres per hour)	1.8		2.3	
NOx production (grammes per hour)	39		39	
PM production (grammes per hour)	1.2		1.0	
PN production (x 10^{14} per hour)	40		41	

By multiplying the estimated numbers of vehicles with auxTRU in use by their estimated annual hours of usage and their averaged per hour emission production rates, the research also produces the following estimated ranges of total emissions from all auxTRU in Scotland:

Greenhouse gases:	14-43 ktCO_2e per year
NOx:	104-311 tonnes per year
Particle Mass (PM):	3-9 tonnes per year
Particle Number (PN):	11-32 x10^{21} per year

The estimated 1,400-2,100 diesel-powered auxTRU-equipped vehicles in Scotland, on which the above figures are based, would represent about 4-6% of the 37,000 HGVs registered in Scotland (i.e. 4-6% of all Scottish HGVs are estimated to be fitted with a separate auxTRU unit or to frequently pull trailers so fitted). The estimated GHG emissions from these auxTRUs would represent around an additional 1-2% on top of those reported by the National Atmospheric Emissions Inventory (NAEI) as being from all the 37,000 HGV propulsion engines in Scotland (and what is conventionally thought of as the HGV emissions baseline) while the auxTRU NOx emissions would add 5-14% and Particle Mass emissions 9-26% to the respective NAEI baseline for annual Scottish HGV emissions figures.

The National Atmospheric Emissions Inventory also provides detailed speed-related emissions factors for NOx and PM from various road vehicle types and at various stages of Euro standard compliance. Vehicle testing by Zemo Partnership, such as that used for the Low Emission Freight and Logistics Trial (LEFT) add additional evidence, including PN emissions from Euro VI HGV propulsion engines. These additional data sources have allowed further comparisons to be made between the measured emission production rates from diesel auxTRU and a wide range of road vehicles.

To further place emissions from auxTRUs in context, the test evidence gathered by this research indicates that, in the specific example of a diesel auxTRU fitted to a Euro VI HGV, the auxTRU 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 (PN)**, in comparison to the vehicle's Euro VI compliant propulsion engine.

Although the PN figures are based on a quite limited set of LEFT tests, the averaged PN emission rates measured are entirely consistent with other international, published research.

When compared to emissions from earlier HGV Euro standards, diesel auxTRU NOx emission rates are about 75% lower than those of Euro V or Euro IV HGVs and Particle Mass emission rates are about 30-40% lower (comparisons based on non-refrigerated HGVs, i.e. without auxTRUs).

Information on PN emissions from non-Euro VI HGVs is not available from previous Zemo test programmes or standard datasets such as NAEI. Research by the European Union's Joint Research Centre (JRC), however, states that PN emissions from heavy duty vehicle engines without a Diesel Particulate Filter (DPF) would relate most closely to Euro III engines. This indicates that PN emissions from unfiltered diesel engines, such as those used as auxTRUs could be expected to be in the order of 100-1,000 times higher than those from systems fitted with a DPF (while Particle Mass emissions would be around 4-5 times higher).

The report ends 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.

Source

[1] Note that for articulated HGVs, the hours of auxTRU operation relate to all refrigerated semitrailers pulled by an individual tractor unit, not hours of operation by a single auxTRU. "Hours of usage" means the total amount of time the auxTRUs are providing cold-chain services, not just the hours of actual engine running.

1. Introduction

1.1 Background

Refrigerated vehicles are a key part of modern cold chain distribution systems. Currently predominantly powered by diesel fuel, temperature-controlled transport (TCT) is crucial to maintaining food safety standards, providing universal access to vaccines and medicines and protecting public health.

With tailpipe pollutant emissions from heavy vehicles falling rapidly as the latest Euro VI regulations take 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. 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.

For the avoidance of any doubt, auxTRUs in the context of this report refers only to those truck or trailer mounted systems using a diesel engine that is completely separate from the heavy goods vehicle's propulsion system. Refrigeration units powered by the vehicle's main engine, as commonly used by smaller HGVs and vans, are not considered.

The UK government announced at Budget 2020 (and confirmed in 2021) its intention to remove the entitlement to use red diesel from most sectors from April 2022, including for auxTRU usage. This will have the effect of increasing the fuel cost for auxTRU operators by almost 47 pence per litre and, it is hoped, provide additional financial incentive for the deployment of alternative technologies.

There is also a no less pressing need to decarbonise every sector of the economy. Road transport (which does not include NRMM) is currently responsible for just over a fifth of all UK greenhouse gas (GHG) emissions, and heavy goods vehicle propulsion engines produce about 17% of the road transport total. The road freight industry has committed itself to reduce GHG emissions from HGV propulsion engines by 15% between 2015 and 2025 but will need to go much further, much faster to achieve the target of net zero emissions by 2045 now enshrined in Scottish law (2050 for UK).

In 2018, Cenex, supported by Zemo Partnership (LowCVP as was), attempted to quantify the scale of the emissions challenge from Transport Refrigeration Units (TRUs) in London[2]. Amongst that study's conclusions was:

> **"There is a clear need to develop an emissions evidence base from real-world emissions testing."**

Source

[2] Auxiliary Temperature Reduction Units in the Greater London Area, March 2018. http://content.tfl.gov.uk/auxiliary-temperature-reduction-units-in-the-greater-london-area.pdf

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 auxTRUs[3]. As part of that preparatory work, pilot testing of a single diesel auxTRU was carried out. 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 see 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. This report presents the results.

1.2 Objectives

The objectives of this research were:

- To expand the emissions measurement evidence base for diesel auxTRUs.
- To estimate their real-world impacts on air quality.
- To inform Transport Scotland on the potential for policy interventions to control TRU emissions.

1.3 Methodology

The basic test methodology followed protocols developed by Zemo Partnership, as reported in 2019.

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 (either chilled or frozen). 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.

TRUs are known to be high risk emitters of refrigerant gases which themselves contribute to global heating (they are within scope of the Kyoto and Paris protocols and have high Global Warming Potential). Emissions of refrigerant were not, however, considered in scope of this test programme (and are in any case likely to have been negligible during the limited period of testing).

Source

[3] Development of Emissions Testing Procedures for Transport Refrigeration Units (TRUs), June 2019. https://www.zemo.org.uk/assets/reports/TRU%20report%20(fin).pdf

Two diesel auxTRU units were tested, 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. Chilled tests were at a target temperature of 2 °C, frozen at -15 °C for the rigid vehicle and -20 °C for the semitrailer. The rigid vehicle auxTRU was found to be unable to sustain the planned target temperature of -20 °C so a value of -15 °C was used. The full test programme thus consisted of eight separate conditions, as summarised in Table 1, with each test condition constituting one day of testing. Full details of the test methodologies are provided in Chapter 2.

The ambient temperatures were selected to be broadly representative of typical daytime summer and winter (shaded) temperatures in Scotland.

Table 1. Overall test matrix

Test/Day	auxTRU (power rating at 30/0 °C)	Ambient Temperature °C	Internal Temperature °C
1	Semitrailer (15 kW)	+15	+2
2	Semitrailer (15 kW)	+5	+2
3	Semitrailer (15 kW)	+15	-20
4	Semitrailer (15 kW)	+5	-20
5	Rigid (11 kW)	+15	+2
6	Rigid (11 kW)	+5	+2
7	Rigid (11 kW)	+15	-15
8	Rigid (11 kW)	+5	-15

To apply the auxTRU test results and estimate their real-world environmental impacts, various published data sources have been used to develop a simple emissions model. This model has then been applied to estimate the auxTRU impacts across Scotland.

1.4 Report structure

Chapter 2 fully describes the test procedures and measurement systems. Chapter 3 presents the fuel consumption and emissions results. Chapter 4 presents estimates of the real-world environmental impacts of auxTRUs, based on the test results and other published data. Chapter 5 summarises the research conclusions and makes a series of next step recommendations.

2. Test procedures

The test programme was carried out in January 2021 under the supervision of Cambridge Refrigeration Technology (CRT), an independent research and test organisation. CRT provides expertise for industry in 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, thus providing continuity and consistency with that earlier research.

2.1 Vehicle and auxTRU details

The first phase of testing was on an auxTRU fitted to a full-size semitrailer, in effect repeating the pilot testing carried out in 2019 but on a different unit to verify the results were not in some way atypical.

The semitrailer was a standard refrigerated 89 m3 box trailer, manufactured by Chereau in 2015 and fitted with a 2014 Carrier Transicold Vector 1550-11 auxTRU (Figure 1). This auxTRU is rated at 14.7 kW at 0 °C and 8.2 kW at -20°C (at 30°C ambient), converted to operate with R452A refrigerant.

The second phase involved testing a smaller auxTRU fitted to a rigid 26 tonne HGV. This 55 m3 capacity vehicle was manufactured in 2016 (with Euro VI compliant propulsion engine) and was fitted with a 2016 Carrier Transicold Supra 1150MT auxTRU (Figure 1). This auxTRU is rated at 11.1 kW at 0°C and 6.5 kW at -20 °C (at 30°C ambient), operating with R404A refrigerant.

Figure 1. Semi-trailer (left) and Rigid HGV (right) and their auxTRUs

This refrigeration unit fitted to the rigid HGV is capable of controlling two different temperatures inside the box but this capability was not required for testing purposes. The unit's City Speed mode was switched off so the unit would run in both high and low engine speeds (rather than low speed only), depending on cooling demand.

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

Data on the precise makeup of the auxTRU fleet in the UK, Scotland or elsewhere is not available. It is therefore not possible to draw firm conclusions as to how representative the specific auxTRU models tested are of the wider fleet. That said, expert opinion provided to Zemo Partnership in the course of developing the test protocol suggested very strongly that conventional diesel-powered auxTRU were unlikely to vary significantly in performance terms between the main manufacturers (of which there are two). This provides at least some high-level confidence that the results from this current test programme are likely to be broadly representative of the wider auxTRU fleet and can thus form a good basis for first-order estimates of their overall environmental impacts.

Across the two test programmes (in 2021 and 2019), the auxTRUs tested have ranged in age from one to six years. This is also a reasonable representation of the wider fleet as auxTRUs are known to have a typical service life of around seven years (Cenex, 2018).

This also means that the majority of auxTRU in current service are likely to pre-date the introduction of the NRMM Stage V requirements in January 2019. Prior to that date, there were no emissions standards or regulations covering auxTRU, as engines rated below 19 kW were out of scope of the NRMM regulations. In January 2019, all auxTRU were brought into scope of the regulations, regardless of rated power. These EU regulations imposed, for the first time, NOx and Particle Mass limits (as a function of output energy, kWh) on auxTRU below 19 kW, but no Particle Number limits.

None of the units tested date from after this change in regulatory scope, therefore it cannot be assumed the results obtained would be representative of the very latest auxTRU products. That said, expert opinion gathered by Zemo Partnership in 2018, shortly before the change in regulations, suggested that the limit values for auxTRU were unlikely to prompt dramatic changes in engine design or performance.

By way of comparison between NRMM standards and those applying to HGV propulsion engines, the NRMM Stage V per kWh limits for auxTRU are 7.5g/kWh for NOx (and hydrocarbons, HC, combined) and 0.4 g/kWh for PM. For HGV propulsion engines, the equivalent current Euro VI limit values are 0.62 g/kWh for NOx and HC, and 0.01 g/kWh for PM. While an exact like for like comparison between the two standards is not possible, because of differing test methods, in broad terms the NRMM Stage V requirements for auxTRU are most closely equivalent to the Euro II requirements for HGVs (8.1 g/kWh for NOx and HC, 0.25 g/kWh for PM), which applied between 1996 and 1998.

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 average internal temperatures reported thus relate to the space around the load, not the load itself, and are likely to fluctuate (e.g. during door openings) more than would be the case for the temperatures within the load.

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 2. The rigid HGV, having a shorter load box than the semi-trailer shown, had fewer pallets of cardboard boxes between the IBCs.

Figure 2. Boxes and IBC locations

2.2.2 Fuel and emissions measurement

Cambustion used their DMS500 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 CO_2)
- Particle size distributions from 5nm-1µm
- Particle number (PN)
- Particle mass (PM)

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

2.3 Test protocol

The tests on each auxTRU involved two modes:

- Chilled (setpoint 2 °C, 4-5 hours total duration)
- Frozen (setpoint -20 or -15 °C, 6-7 hours)

Six phases were used for each mode, at each of two different ambient test chamber temperatures, 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 (5 or 15 °C).
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.
4. AuxTRU is run in continuous mode (chilled) or stop/start mode (frozen) for three hours.
5. 30-minute door opening (with auxTRU running).
6. Close doors and auxTRU pulls down again to setpoint, 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 outside ambient temperatures were, at the time of testing, a few degrees above freezing. 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 TCT vehicle operators.

It should be noted that "normal practice" for the fifth phase door opening (which simulates load being removed) is the subject of some debate within the industry. Best practice would be to switch off the auxTRU during this period and that is likely to be "normal" for some operators, but others are thought to routinely leave the auxTRU running. The test procedure has been selected to follow this latter usage case.

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 at each ambient temperature, for the semitrailer and rigid HGV auxTRU tests. Fuel consumption is also converted to overall greenhouse gas (GHG) impacts using the official (at source) emissions factor for pump average diesel, currently 2.56 kgCO_2e per litre consumed.

For the semitrailer auxTRU, there is a clear reduction in overall fuel consumed in moving from the higher to lower ambient temperature and shorter durations for the pull-down phases.

This logical pattern is not evident, however for the rigid HGV where pull down durations are longer and fuel consumption rates slightly higher, despite the reduced cooling load at 5 °C compared to 15 °C ambient.

One reason for this is that the auxTRU automatically defrosted part way through the first pull-down phase of the 5 °C tests, causing it to temporarily stop cooling (but still consume fuel) and then re-start, but by then the average internal temperature had risen so the unit had to then pull down the temperature once again before the steady state could begin. Another reason may be that the auxTRU operates at slightly lower overall efficiency at the lower ambient temperature.

Table 2. Chilled mode temperatures and fuel results

Phase	Ambient °C	Duration mins	Internal °C			Fuel litres used	Fuel consumption litres per hour	Calculated CO_2e Kg/hour
			Max	Mean	Min			
Semitrailer								
3 Pull-Down 1	15	56	10	4	2	1.57	1.69	4.33
4 Steady State	15	180	5	3	2	5.05	1.68	4.30
5 Doors Open	15	30	12	6	2	0.84	1.68	4.30
6 Pull-Down 2	15	42	9	3	2	1.28	1.82	4.66
All	**15**	**308**				**8.74**	**1.70**	**4.35**
3 Pull-Down 1	5	2	4	4	3	0.05	-	-
4 Steady State	5	180	4	2	1	4.90	1.63	4.17
5 Doors Open	5	30	4	3	1	0.81	1.63	4.17
6 Pull-Down 2	5	19	4	2	1	0.51	1.66	4.25
All	**5**	**230**				**6.28**	**1.63**	**4.17**
Rigid HGV								
3 Pull-Down 1	15	21	10	3	-2	0.77	2.23	5.71
4 Steady State	15	180	6	1	-2	6.67	2.22	5.68
5 Doors Open	15	30	12	5	-2	1.10	2.20	5.63
6 Pull-Down 2	15	5	12	1	-2	0.20	-	-
All	**15**	**236**				**8.74**	**2.22**	**5.68**
3 Pull-Down 1	5	36*	10	2	-3	1.32	2.20	5.63
4 Steady State	5	180	6	1	-3	6.79	2.26	5.79
5 Doors Open	5	30	4	2	-2	1.13	2.25	5.76
6 Pull-Down 2	5	7	4	2	1	0.23	-	-
All	**5**	**253**				**9.46**	**2.24**	**5.73**

***Pull-down phase extended due to unit defrosting**

On average, fuel consumption for the semitrailer auxTRU was 1.70 litres per hour (l/h) at 15 °C and 1.63 l/h at 5 °C ambient temperature. For the rigid HGV auxTRU, with its defrost event during the lower ambient temperature test, the consumptions were 2.22 l/h at 15 °C and 2.24 l/h at 5 °C ambient temperature. The higher rate of fuel consumption for the rigid HGV, despite it having a smaller load box, may be due to less effective insulation (rigid insulated HGVs are less likely to be ATP certified for international TCT operations than semitrailers) or perhaps its auxTRU being inherently less efficient than the semitrailer's (but this could not be verified by testing). The rigid HGV auxTRU did achieve slightly lower internal temperatures than the semitrailer unit, which may further explain some of the higher fuel consumption, as might its use of R404A refrigerant, known to be less efficient than the R452A refrigerant used by the semitrailer auxTRU.

There were no significant differences in fuel consumption rates between the pull-down and steady state phases for either auxTRU, suggesting that under these chilled conditions (and at relatively modest ambient temperatures) the units ran at a fairly constant speed throughout the tests.

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 (percentages of the NOx emissions by mass that were NO_2).

Within each phase, NOx production rates were broadly similar, as would be expected given the uniformity in engine running/fuel consumption. For the semitrailer auxTRU, NOx emissions averaged 56 g/h at 15 °C and 32 g/h at 5 °C ambient temperature. For the rigid HGV auxTRU they averaged 36 g/h at 15 °C and 39 g/h at 5 °C ambient temperature.

Table 3. Chilled mode NOx emissions results

Phase	Ambient °C	Duration mins	NOx grammes	NOx rate grammes per hour	Primary NO_2 %
Semitrailer					
3 Pull-Down 1	15	56	53	57	13
4 Steady State	15	180	166	55	18
5 Doors Open	15	30	29	58	23
6 Pull-Down 2	15	42	39	55	24
All	**15**	**308**	**287**	**56**	**18**
3 Pull-Down 1	5	2	<1	-	-
4 Steady State	5	180	97	32	9
5 Doors Open	5	30	16	33	8
6 Pull-Down 2	5	19	10	32	9
All	**5**	**231**	**123**	**32**	**9**
Rigid HGV					
3 Pull-Down 1	15	21	11	32	11
4 Steady State	15	180	111	37	11
5 Doors Open	15	30	18	36	11
6 Pull-Down 2	15	5	3*	32*	11*
All	**15**	**236**	**143**	**36**	**11**
3 Pull-Down 1	5	36	27	44	11
4 Steady State	5	180	115	38	11
5 Doors Open	5	30	18	37	11
6 Pull-Down 2	5	7	3	-	11
All	**5**	**253**	**163**	**39**	**11**

*NOx equipment unavailable during this phase, results estimated

3.1.3 Particle emissions

Table 4 shows the total cumulative particulate emissions in each phase, in both mass (PM) and number (PN) form.

Within each phase, particle emission rates were broadly similar, as would be expected given the uniformity in engine running/fuel consumption. For the semitrailer auxTRU, mass emissions averaged 0.90 g/h at 15 °C and 0.97 g/h at 5 °C ambient temperature. For the rigid HGV auxTRU they averaged 1.15 g/h at 15 °C and 1.02 g/h at 5 °C ambient temperature. PN emissions were also quite similar between the two auxTRUs, ranging from 38-45 x 10^{14} per hour for the semitrailer and 29-41 x 10^{14} per hour for the rigid HGV.

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
Semitrailer						
3 Pull-Down 1	15	56	870	0.94	37	40
4 Steady State	15	180	2580	0.86	113	38
5 Doors Open	15	30	500	0.99	19	39
6 Pull-Down 2	15	42	680	0.96	27	39
All	**15**	**308**	**4630**	**0.90**	**196**	**38**
3 Pull-Down 1	5	2	30	-	<1	-
4 Steady State	5	180	3040	1.01	139	46
5 Doors Open	5	30	430	0.86	21	41
6 Pull-Down 2	5	19	230	0.74	12	40
All	**5**	**231**	**3730**	**0.97**	**172**	**45**
Rigid HGV						
3 Pull-Down 1	15	21	510	1.48	18	49
4 Steady State	15	180	3370	1.12	123	41
5 Doors Open	15	30	530	1.07	19	39
6 Pull-Down 2	15	5	100	-	3	-
All	**15**	**236**	**4520**	**1.15**	**163**	**41**
3 Pull-Down 1	5	36	640	1.07	20	33
4 Steady State	5	180	3080	1.03	85	28
5 Doors Open	5	30	480	0.96	14	27
6 Pull-Down 2	5	7	90	-	3	-
All	**5**	**253**	**4300**	**1.02**	**121**	**29**

3.2 Frozen mode

The following sections present the main results from the frozen setpoint tests at -20/-15 °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, fuel consumed and calculated GHG emissions during each phase of the frozen mode tests at each ambient temperature, for the semitrailer and rigid HGV. Note that some fuel supply difficulties with the auxTRU fitted to the rigid HGV meant all testing (at both ambient temperatures) with that unit had to be carried out in continuous mode, rather than the intended stop-start mode. Though the fuel consumption during the steady-state phase would likely be higher as a result than would be strictly representative of real-world conditions (which would use stop-start mode for frozen loads), this is at least partly compensated by the higher setpoint temperature used for the rigid HGV (-15 °C instead of -20 °C). Overall, therefore, it is thought likely that these enforced modifications to the test procedure would broadly cancel each other out and thus have no significant impacts on the averaged measured fuel consumption or emissions for this auxTRU.

For both auxTRUs, there are reductions in overall fuel consumption in moving from the higher to lower ambient temperature.

On average, fuel consumption for the semitrailer auxTRU was 2.0 litres per hour (l/h) at 15 °C and 1.7 l/h at 5 °C ambient temperature. For the rigid HGV auxTRU (which went into defrost mode once during the first pull-down phase of both tests), the consumptions were 2.3 l/h at 15 °C and at 5 °C ambient temperature. The higher rate of fuel consumption for the rigid HGV auxTRU, despite it having a smaller load box, may be due to a lower level of insulation and/or the unit being inherently less efficient (but this could not be verified by testing and would also have been affected by the differences in operating modes between the two auxTRUs).

The semitrailer auxTRU consumed fuel at a notably lower rate during the steady-state phases (in stop/start mode) than when pulling down. This fuel efficiency, though, was to some extent at the expense of internal temperature, averaging around –13 °C compared to the nominal setpoint of -20 °C. For the rigid HGV however, operating in continuous mode, the average internal temperatures achieved (-17 °C) were actually colder than the nominal -15 °C setpoint. Note that the auxTRUs' internal temperature probes would be in different locations to those used by CRT for testing.

Table 5. Frozen mode temperatures and fuel results

Phase	Ambient °C	Duration mins	Internal °C			Fuel litres used	Fuel consumption litres per hour	Calculated CO_2e Kg/hour
			Max	Mean	Min			
Semitrailer								
3 Pull-Down 1	15	91	2	-11	-19	4.72	3.11	7.96
4 Steady State	15	180	-8	-13	-20	3.80	1.27	3.25
5 Doors Open	15	30	11	1	-11	1.34	2.68	6.86
6 Pull-Down 2	15	43	11	-11	-18	1.52	2.12	5.43
All	**15**	**344**				**11.38**	**1.98**	**5.07**
3 Pull-Down 1	5	124*	1	-12	-20	3.68	1.78	4.56
4 Steady State	5	180	-9	-13	-19	3.80	1.27	3.25
5 Doors Open	5	30	3	-6	-18	1.37	2.73	6.99
6 Pull-Down 2	5	32*	4	-10	-19	1.34	2.49	6.37
All	**5**	**366**				**10.18**	**1.67**	**4.28**
Rigid HGV								
3 Pull-Down 1	15	192*	4	-14	-22	6.10	1.91	4.89
4 Steady State	15	180	-11	-17	-22	8.06	2.69	6.89
5 Doors Open	15	30	10	-2	-16	1.35	2.71	6.94
6 Pull-Down 2	15	24	5	-12	-19	1.03	2.59	6.63
All	**15**	**426**				**16.54**	**2.33**	**5.96**
3 Pull-Down 1	5	120*	0	-14	-22	4.31	2.16	5.53
4 Steady State	5	180	-11	-17	-23	7.54	2.51	6.43
5 Doors Open	5	30	2	-6	-22	1.10	2.20	5.63
6 Pull-Down 2	5	22	2	-15	-22	0.77	2.10	5.38
All	**5**	**352**				**13.72**	**2.34**	**5.99**

*** Pull-down phase extended due to unit defrosting**

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 (percentages of the NOx emissions by mass that were NO_2).

NOx emissions rates for the semitrailer auxTRU averaged around 30 g/h. When pulling down, the rates were around 40 g/h, falling to a little less than 20 g/h in stop/start steady state mode.

For the rigid HGV auxTRU, the NOx production rates were generally higher than the semitrailer unit, broadly in proportion to its higher rates of fuel consumption. They were also quite uniform across each phase, reflecting its continuous mode operation. Overall rates were around 40 g/h.

Table 6. Frozen mode NOx emissions results

Phase	Ambient °C	Duration mins	NOx grammes	NOx rate grammes per hour	Primary NO_2 %
Semitrailer					
3 Pull-Down 1	15	91	62	41	2
4 Steady State	15	180	55	18	2
5 Doors Open	15	30	21	42	<1
6 Pull-Down 2	15	43	31	43	<1
All	**15**	**344**	**169**	**29**	**<1**
Semitrailer					
3 Pull-Down 1	5	124	86	42	7
4 Steady State	5	180	53	18	7
5 Doors Open	5	30	27	54	5
6 Pull-Down 2	5	32	24	44	6
All	**5**	**366**	**190**	**31**	**6**
Rigid HGV					
3 Pull-Down 1	15	192	145	45	11
4 Steady State	15	180	115	38	11
5 Doors Open	15	30	24	48	11
6 Pull-Down 2	15	24	18	45	11
All	**15**	**426**	**302**	**43**	**11**
3 Pull-Down 1	5	120	83	41	2
4 Steady State	5	180	105	35	2
5 Doors Open	5	30	20	41	10
6 Pull-Down 2	5	22	14	37	<1
All	**5**	**352**	**222**	**38**	**2**

3.2.3 Particle emissions

Table 7 shows the total cumulative particulate emissions in each phase, in both mass (PM) and number (PN) form.

For the semitrailer auxTRU, mass emissions averaged 1.17 g/h at 15 °C and 0.90 g/h at 5 °C ambient temperature. PN emissions averaged around 40 x 10^{14} per hour – less than 30 x 10^{14} per hour when in the stop/start steady state phase but closer to 60 x 10^{14} per hour during the pull-down and doors open phases.

For the rigid HGV auxTRU, within each phase, particle emission rates were broadly similar, as would be expected given the uniformity in engine running in continuous mode. Mass emissions averaged 0.96 g/h at 15 °C and 0.86 g/h at 5 °C ambient temperature. Number emissions averaged 47 x 10^{14} per hour across the two tests.

Table 7. Frozen mode particle emissions results

Phase		Duration mins	Particle Mass mg	PM rate g per hour	Particle Number x 10^{14}	PN rate x 10^{14} per hour
Semitrailer						
3 Pull-Down 1	15	91	2520	1.66	85	56
4 Steady State	15	180	2210	0.74	78	26
5 Doors Open	15	30	810	1.62	29	57
6 Pull-Down 2	15	43	1200	1.67	44	61
All	**15**	**344**	**6730**	**1.17**	**235**	**41**
Semitrailer						
3 Pull-Down 1	5	124	2520	1.22	110	53
4 Steady State	5	180	1340	0.45	57	26
5 Doors Open	5	30	830	1.66	33	57
6 Pull-Down 2	5	32	820	1.53	34	61
All	**5**	**366**	**5520**	**0.90**	**234**	**41**
Rigid HGV						
3 Pull-Down 1	15	192	3110	0.97	172	54
4 Steady State	15	180	2640	0.88	111	37
5 Doors Open	15	30	590*	0.97*	27*	54*
6 Pull-Down 2	15	24	460*	0.97*	21*	54*
All	**15**	**426**	**6800**	**0.96**	**332**	**47**
3 Pull-Down 1	5	120	1820	0.91	113	57
4 Steady State	5	180	2550	0.85	122	41
5 Doors Open	5	30	400	0.81	26	52
6 Pull-Down 2	5	22	280	0.76	17	45
All	**5**	**352**	**5050**	**0.86**	**277**	**47**

*** Particle measurement equipment unavailable during this phase, results estimated**

3.3 Comparisons to 2019 test results

This section compares the main fuel consumption and emissions results from the semitrailer auxTRU with those obtained from a very similar unit (but under slightly different test conditions) during the pilot testing programme reported in 2019[4].

Source

[4] Development of Emissions Testing Procedures for Transport Refrigeration Units (TRUs), June 2019. https://www.zemo.org.uk/assets/reports/TRU%20report%20(fin).pdf

The semitrailer auxTRU tested in 2019 was very similar to the semitrailer unit tested in 2021, a 1.5 litre TRU rated at 15 kW. It was, however, somewhat newer, being a 2017 model (two years old) as opposed to the 2014 model tested in 2021 (six years old).

The only differences in test procedures were that only one ambient temperature was used in 2019, 18 °C, an extra pull-down phase was used, with the trailer un-loaded and the final door-opening and pull-down phases were combined into one 30-minute phase (15 minutes of each). With that slight difference in chamber temperature (3 °C) and disregarding the unloaded pull-down results from 2019, Table 8 compares the main fuel consumption and emissions production rates from the chilled and frozen tests from the semitrailer auxTRU tests in 2019 and 2021.

The fuel consumption rates from the 2021 tests are only very slightly lower than in 2019, most probably due to the lower ambient temperature, and PM emissions are also rather more markedly lower (the potential reason for this is not clear), but NOx and PN emissions rates are remarkably similar.

Table 8. Comparisons of semitrailer auxTRU test results, 2019 and 2021 (using 15°C ambient temperature data)

Rates	Fuel litres per hour		NOx grammes per hour		PM grammes per hour		PN x 10^{14} per hour	
Year of tests	2019	2021	2019	2021	2019	2021	2019	2021
Chilled mode								
Pull-Down 1	1.9	1.7	56	57	1.6	0.9	33	40
Steady State	1.7	1.7	58	55	1.6	0.9	34	38
Doors Open	1.7	1.7	58	58	1.7	1.0	34	39
Pull-Down 2		1.8		55		1.0		39
Whole test	**1.7**	**1.7**	**58**	**56**	**1.6**	**0.9**	**34**	**38**
Frozen mode								
Pull-Down 1	3.4	3.1	56	41	3.5	1.7	59	56
Steady State	1.3	1.3	27	18	1.5	0.7	27	26
Doors Open	3.0	2.7	48	42	2.4	1.6	45	57
Pull-Down 2		2.1		43		1.7		61
Whole test	**2.0**	**2.0**	**37**	**29**	**2.1**	**1.2**	**37**	**41**

4. Estimates of environmental impact

The following sections describe how published data has been used to estimate the number of diesel auxTRUs in daily use in Scotland, 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 Scotland.

4.1 Number of auxTRUs

There is no known source of direct information on exactly how many refrigerated vehicles are in use in the UK in general or Scotland in particular.

The 2018 report by Cenex[5] for Transport for London (with support from Zemo/LowCVP and Brunel University) estimated the environmental impacts of TCT vehicles and auxTRUs in London. That study combined licenced vehicle data, ANPR traffic data, and information gathered via an industry survey, to estimate that there were around 3,500 HGVs fitted with diesel auxTRUs operating in London on average, per day.

That depth of raw data has not been available for this study for Transport Scotland. Instead, this London estimate has been scaled in two different ways to produce a range of numbers potentially representative of the situation in Scotland. The two scaling factors chosen are population and numbers of HGVs licenced. For this type of scaling to be possible it is necessary to use GB or UK-wide data sources that provide regional figures for both London and Scotland in a consistent way.

The latest statistics report that the population of Scotland is around 60% that of London (5.5 million compared to 9 million). If it is assumed that the per capita distribution of chilled or frozen products is broadly similar between Scotland and London, and that the Cenex estimate of 3,500 auxTRU HGVs in London is correct, then around 2,100 HGVs with auxTRUs would be a reasonable estimate for Scotland.

The latest DfT statistics for UK regions report that there are around 19,700 HGVs licenced in London. Land for HGV depots, however, is very much at a premium in London so it is very likely that many of the HGVs used in London are actually based (and licenced) a little further afield. Combining London and South East regions, the number of licenced HGVs is reported as 91,800. The number reported by the same source for Scotland is 36,800, which is 40% of the London & South East figure. If it is assumed that the proportion of licenced HGVs performing TCT tasks fitted with auxTRUs is similar between the two regions, and that the Cenex estimate of 3,500 auxTRU HGVs in London is correct, then around 1,400 auxTRUs would be another reasonable estimate for Scotland.

It is not possible to know with certainty which of these two estimates is likely to be the most accurate, so it makes sense to model the environmental impacts on the basis of two (low and high) estimates spanning the range 1,400–2,100 HGVs with diesel auxTRUs in daily use in Scotland.

Source

[5] Auxiliary Temperature Reduction Units in the Greater London Area, March 2018. http://content.tfl.gov.uk/auxiliary-temperature-reduction-units-in-the-greater-london-area.pdf

The Cenex study estimated that auxTRU usage in London was split in a two to one ratio between rigid and articulated HGVs. In the absence of other data, this ratio is assumed to apply to Scotland, meaning there are estimated to be 450–700 articulated HGVs regularly pulling semitrailers fitted with auxTRU in Scotland and 950–1,400 auxTRU fitted to rigid HGVs.

Industry experts advise that TCT operators with articulated vehicles typically use around 2-2.5 semitrailers for every one tractor unit. This would mean that the estimated 450–700 refrigerated articulated HGVs would make use of around 900–1,750 individual semitrailer auxTRUs. This suggests an overall split of around 60:40 between semitrailer auxTRUs and rigid HGV units. Experts advise that a ratio of 80:20 may be more realistic for Scotland, reflecting perhaps that rigid HGVs would be used more than articulated HGVs in a densely populated area like London but less in more sparsely populated regions such as Scotland. Given the general similarity in emissions performance between the rigid and semitrailer units tested, however, any such possible bias in the London-Scotland scaling estimates are unlikely to materially affect the overall emissions estimates.

4.2 Operational characteristics

The Cenex study used data gathered from industry to estimate that auxTRU equipped HGVs are typically operational for around 14-18 hours per day and for around 275-300 days per year. The study also indicated that articulated vehicles tend to be used at the high end of these ranges while smaller rigid HGVs operate more towards the low end. The Cenex report did acknowledge, however, that these usage profiles were quite likely to be biased somewhat to reflect the operations of large supermarket fleets, with many smaller hauliers likely to operate their vehicles considerably less than 14 hours per day and fewer than 275 days per year.

The detailed distribution of operator types for TCT vehicles in Scotland is not known so it again makes sense to base our modelling estimates on two scenarios. These are described in Table 9 in terms of operating days per year and hours per day for diesel auxTRU fitted to rigid and articulated HGVs (totals reflecting such vehicles will often pull more than one semitrailer per day).

The operational hours referred to in the Cenex study include time spent loading the vehicle which would normally be done with the auxTRU switched off. For the purposes of calculating overall environmental impacts, the hours of auxTRU usage in the Table correspond to the test procedure by removing these periods, assumed to be between 2 and 4 hours per day. These auxTRU usage hours include periods spent in stop-start mode (typical for frozen loads) so will be higher than typical auxTRU running hours (which only relate to periods while the auxTRU is on).

Table 9. Modelled auxTRU usage scenarios

Scenario	Low Use Scenario		High Use Scenario	
	Rigids	Artics	Rigids	Artics
Days per year	250	275	300	300
Hours per day	6	10	12	14
Total hours per year	**1,500**	**2,750**	**3,600**	**4,200**

4.3 Fuel consumption and emission production rates

The test results described in the preceding section, combined with those from the 2019 pilot testing, provide the best available current evidence regarding likely per hour fuel consumption and emissions production rates from diesel auxTRUs in the real world. The tests at 15-18 ºC ambient temperature are likely to be broadly representative of typical UK summertime operations, while those at 5 ºC would be a good indicator of winter performance. Averaging between the two is assumed to provide realistic estimates of fuel and emissions performance across a typical year.

Detailed information is not available regarding the precise composition of TCT loads in Scotland and what proportions are transported chilled or frozen. The Cenex study concluded that the vast majority of TCT loads were a mixture of both. In the absence of data to the contrary, it can thus also be assumed that simply averaging between the fuel and emissions performance measured during the chilled and frozen tests, will provide reasonable estimates of real-world auxTRU performance.

There are other potential discrepancies between the averaged test conditions and those typical in-service, but in the absence of detailed evidence to the contrary it seems reasonable to assume they will broadly cancel each other out. For example, while leaving the auxTRU running while the doors are opened in the test process will inevitably lead to over-estimates of overall fuel consumption and emission rates than if known best practice was commonly followed (auxTRU switched off when doors open), testing each unit indoors at ambient temperatures typical of in-shade conditions would quite significantly under-estimate the real-world performance (in direct sun on the open road). Testing in single temperature conditions (either chilled or frozen) may also under-estimate real world fuel consumption and emissions performance because the auxTRU will tend to not have to work as hard to maintain a single temperature as when it is controlling multi-temperature compartments within the load space, conditions also typical in the real world.

Table 10 presents the summary test results and calculated averaged annual fuel consumption and emission production rates for diesel auxTRU fitted to rigid HGVs and semitrailers in Scotland. The data for "Summer Semitrailers" are derived by averaging both the 2021 and 2019 test results.

Table 10. Calculated average fuel and emissions production rates

Per hour	Summer Semitrailers	Winter Semitrailers	Summer Rigid HGVs	Winter Rigid HGVs
Fuel consumption (litres per hour)	1.9	1.7	2.3	2.3
NOx production (grammes per hour)	45	32	39	38
PM production (grammes per hour)	1.4	0.9	1.0	0.9
PN production (x 10^{14} per hour)	38	42	44	38
	Annual (Semitrailers)		Annual (Rigid HGVs)	
Fuel consumption (litres per hour)	1.8		2.3	
NOx production (grammes per hour)	39		39	
PM production (grammes per hour)	1.2		1.0	
PN production (x 10^{14} per hour)	40		41	

4.4 Total auxTRU emissions estimates

Combining the figures in the preceding sections allows for low and high scenario estimates to be made for the fuel and environmental impacts of diesel auxTRUs in Scotland. The basic equation for doing this is:

I = N x H x R

Where I is the annual total impact being estimated, N is the number of auxTRUs in use (from section 4.1), H the hours of use per annum (section 4.2) and R the relevant annual average per hour fuel consumption or emission production rate (section 4.3).

Table 11 shows the results of these calculations for each scenario and impact parameter. Fuel consumption is also converted to overall greenhouse gas (GHG) impacts using the official (at source) emissions factor for pump average diesel, currently 2.56 $kgCO_2e$ per litre consumed.

Table 11. AuxTRU emissions estimates for Scotland

Scenario		Low Use Scenario			High Use Scenario	
	Rigids	Artics	All auxTRU	Rigids	Artics	All auxTRU
Number of auxTRU vehicles (N)	950	450	1,400	1,400	700	2,100
Operating hours per year, per auxTRU (H)	1,500	2,750		3,000	4,200	
Rates per hour (R)						
Fuel consumption (litres per hour)	2.3	1.8		2.3	1.8	
GHG emissions ($kgCO_2e$ per hour)	6	5		6	5	
NOx emissions (grammes per hour)	39	39		39	39	
PM emissions (grammes per hour)	1.0	1.2		1.0	1.2	
PN emissions (x 10^{14} per hour)	41	40		41	40	
Calculated overall annual environmental impacts (I = N x H x R)						
Fuel consumption (Million litres per year)	**3**	**2**	**6**	**12**	**5**	**17**
GHG emissions ($ktCO_2e$ per year)	**8**	**6**	**14**	**30**	**14**	**43**
NOx emissions (tonnes per year)	**56**	**48**	**104**	**197**	**115**	**311**
PM emissions (tonnes per year)	**1**	**1**	**3**	**5**	**4**	**9**
PN emissions (x 10^{21} per year)	**6**	**5**	**11**	**21**	**12**	**32**

With the quite broad range of estimates regarding the numbers of HGVs with auxTRU and their typical daily usage profiles, there is inevitably quite a wide range of estimated environmental impacts for Scotland. The low to high estimated ranges for each emissions type, shown shaded in the bottom four rows of Table 11, for the low and high use scenarios, are:

Greenhouse gases:	**14 (in low use scenario) to 43 (high use scenario) ktCO_2e per year**
NOx:	**104 (low) to 311 (high) tonnes per year**
Particle Mass:	**3 (low) to 9 (high) tonnes per year**
Particle Number:	**11 (low) to 32 (high) x10^{21} per year**

The National Atmospheric Emissions Inventory (NAEI) estimates that total GHG emissions from HGV engines in Scotland per year are around 2,000 ktCO_2e, so these auxTRU estimates represent an additional 1-2%. Reassuringly, the NAEI also estimates GHG emissions from transport refrigeration in Scotland are 42 ktCO_2e, towards the top of the range estimated above.

NAEI also provides estimates of NOx and PM from HGVs (but not PN). Specific NAEI estimates for pollutant emissions from transport refrigeration are not published. Total NOx emissions from HGVs in Scotland for the latest year available (2019) are estimated at 2,160 tonnes (from the whole fleet, the 2019 mix of Euro VI, Euro V, Euro IV and earlier propulsion engines). The above estimates imply diesel auxTRUs would add 5-14% to that figure. Total PM emissions from HGVs in Scotland are estimated at 34 tonnes for 2019. The above estimates imply diesel auxTRUs would add 9-26% to that figure.

For further context, the estimated 1,400-2,100 HGVs operating with auxTRUs in Scotland would represent about 4-6% of the 37,000 HGVs registered in Scotland.

4.5 Euro standard (vehicle) emission comparisons

The National Atmospheric Emissions Inventory also provides detailed speed-related emissions factors for NOx and PM from various road vehicle types and at various stages of Euro standard compliance[6]. This allows further comparisons to be made between the measured emission production rates from diesel auxTRU and a wide range of road vehicles. NAEI does not, however, contain any detailed information on Particle Number (PN) emissions.

Over recent years, through involvement in programmes such as the Low Emission Freight and Logistics Trial (LEFT), Zemo Partnership have developed a detailed evidence base of real-world emissions from modern HGVs, including PN emissions. As well as contextualising the measured auxTRU emissions in terms of the existing Scottish HGV fleet, it is thus also possible to compare directly the PN emissions from diesel auxTRUs with those from Euro VI compliant HGV propulsion engines.

Source

[6] https://naei.beis.gov.uk/data/ef-transport

As pollutant emissions impacts are most significant from a public health perspective in urban and city environments, it makes sense to draw these comparisons on the basis of HGV emissions in such areas. Testing for LEFT included standardized Urban Delivery and City-Centre cycles with average speeds of around 40 and 20 km/h respectively. To allow a proper comparison with the auxTRUs, we need to convert the LEFT measured per km vehicle tailpipe PN emissions into per hour emissions. 30 km/h has been chosen as the most appropriate speed for this, being representative of typical HGV speeds in urban and city environments, with the per km values for Euro VI HGVs derived by averaging those measured from the urban and city-centre test cycles. The same 30 km/h average speed value has been used to derive the NAEI standard values for road vehicle emissions of NOx and PM.

Table 12 summarises the overall per hour average NOx and PM emissions for various vehicle types at various Euro standards from the NAEI database, as well as some PN emissions derived from LEFT testing of Euro VI HGVs, and compares them to the measured emissions from diesel auxTRUs (from the preceding sections). All the road vehicle figures relate to tailpipe emissions from propulsion engines on non-refrigerated vehicles.

LEFT testing of large diesel HGVs[7] (>26t) indicates that the fuel consumption of such vehicles (all Euro VI) averages about 58 litres per 100 km in the city and urban test cycles, equivalent to 17 litres per hour at an average speed of 30 km/h. This generates around 44 kgCO_2e per hour of greenhouse gas emissions. Testing of diesel auxTRUs suggests a GHG emissions rate of 5-6 kgCO_2e per hour, corresponding to their much lower rate of fuel consumption (around 2 litres per hour, Table 11).

It can therefore be estimated that a single diesel auxTRU fitted to a Euro VI HGV would:

- Consume about **$^1/_8$th the fuel**
- Produce about **$^1/_8$th 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

Although these PN figures are based on a quite limited set of LEFT tests, the averaged PN emission rates measured (2.8 x 10^{11} per km = 0.08 x 10^{14} per hour at 30 km/h) are entirely consistent with other research. Research by the European Union's Joint Research Centre (JRC), for example, found PN emissions of Euro VI HGVs tested to lie within the range 0.2-7 x 1011 per kilometre[8].

When compared to emissions from earlier HGV Euro standards, diesel auxTRU NOx emission rates are about 75% lower than those of (non-refrigerated) Euro V or Euro IV HGVs and Particle Mass emission rates are about 30-40% lower.

Information on PN emissions from non-Euro VI HGVs is not available from previous Zemo test programmes or standard datasets such as NAEI. The JRC research mentioned above, however, states that PN emissions from heavy duty vehicle engines without a DPF (Diesel Particulate Filter) lie in the range 0.2-2 x 10^{14} per km. These figures would relate most closely to Euro III engines.

Source

[7] https://www.zemo.org.uk/assets/reports/LowCVP-LEFT_Dissemination_Report-2020.pdf

[8] https://www.mdpi.com/1660-4601/15/2/304

This indicates that PN emissions from unfiltered diesel engines, such as those used as auxTRUs could be expected to be in the order of 100-1,000 times higher than those from systems fitted with a DPF (while Particle Mass emissions would be around 4-5 times higher, Table 12). This provides additional evidence that the auxTRU test results and comparisons with Euro VI or earlier vehicle types are broadly robust.

Table 12. AuxTRU emissions to road vehicle and Euro standard comparisons (all at 30 km/h)

Engine/vehicle	NOx emissions rate g per hour	Particle Mass (PM) emissions rate g per hour	Particle Number (PN) emissions rate x 10^{14} per hour
Diesel auxTRU (from testing, Table 10, emissions from propulsion engines not considered)			
26t rigid HGV auxTRU	39	1.0	41
40t artic HGV auxTRU	39	1.2	40
Rigid HGVs (26 tonnes, from NAEI, non-refrigerated)			
Euro VI	16	0.2	
Euro V (EGR)	145	1.5	
Euro IV	166	1.3	
Euro III	250	6.4	
Euro II	307	5.8	
Euro I	280	13	
Articulated HGVs (40 tonnes, NOx & PM from NAEI, PN from LEFT testing, non-refrigerated)			
Euro VI	15	0.2	0.08
Euro V (EGR)	175	1.8	
Euro IV	206	1.6	
Euro III	307	7.5	
Euro II	380	7.6	
Euro I	353	16	
Diesel passenger cars (1.4-2l, from NAEI)			
Euro 6.1	17	0.1	
Euro 5	20	0.1	
Euro 4	19	1.0	
Euro 3	23	1.0	
Euro 2	23	1.6	
Euro 1	21	1.9	
Petrol passenger cars (1.4-2l, from NAEI)			
Euro 6.1	1	0.05	
Euro 5	1	0.05	
Euro 4	2	0.04	
Euro 3	2	0.04	
Euro 2	5	0.1	
Euro 1	9	0.1	

A visual (but not scientifically robust) indicator of the particle emissions from an auxTRU and how they compare to those from a modern Euro 6 refrigerated diesel van engine is provided by Figure 3. For the van, the emissions arise from a single engine providing both propulsion and refrigeration energy during the test. The comparison is not strictly like-for-like, given that the photos were taken after different test methods of different durations (about 6 hours for the auxTRU test and 2 hours for the van tests), but the basic premise of the auxTRU generating many times more particles than the Euro-6 compliant van engine is quite clearly demonstrated.

Figure 3. Filters from testing auxTRU (left) and Euro 6 diesel van (right)

5. Conclusions and next step recommendations

5.1 Conclusions

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. In 2021, Transport Scotland provided funding for Zemo Partnership to carry out further emissions testing on two more conventional diesel auxTRUs.

The objectives of this research were:

- To expand the emissions measurement evidence base for diesel auxTRUs.
- To estimate their real-world impacts on urban air quality.
- To inform Transport Scotland regarding the potential for policy interventions to control TRU emissions.

Two diesel auxTRU units were tested, one fitted to a full-size semitrailer and the other to a (smaller) three-axle rigid HGV (26t 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).

Published data has then been used to estimate the number of diesel auxTRUs in daily use in Scotland, their operational characteristics and, when combined with the evidence from testing on emissions production rates, their overall potential contribution to emissions of greenhouse gases and air pollutants in Scotland. Details of TRU usage in Scotland are not available so these estimates should be treated as indicative only.

The research suggests there are perhaps 450–700 articulated HGVs and 950–1,400 rigid HGVs using auxTRUs in Scotland, with each vehicle typically operating with a diesel auxTRU switched on between 1,500 and 4,200 hours per year.

When combined with per hour emissions production rates measured during the tests, the low-to-high total annual Scotland estimated ranges for each auxTRU emissions type, from all diesel auxTRU are:

Greenhouse gases:	**14 (in low use scenario) to 43 (high use scenario) ktCO_2e per year**
NOx:	**104 (low) to 311 (high) tonnes per year**
Particle Mass:	**3 (low) to 9 (high) tonnes per year**
Particle Number:	**11 (low) to 32 (high) x10^{21} per year**

The estimated 1,400-2,100 HGVs with auxTRUs in Scotland would represent about 4-6% of the 37,000 HGVs registered in Scotland. Their estimated GHG emissions would add around 1-2% to those from HGV propulsion engines while NOx emissions would add 5-14% and Particle Mass emissions 9-26%. it has further been estimated that a diesel auxTRU fitted to a Euro VI HGV would:

- Consume about 1/8th the fuel of the base HGV propulsion engine
- 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 particle

When compared to emissions from earlier HGV Euro standards, diesel auxTRU NOx emission rates are about 75% lower than those of (non-refrigerated) Euro V or Euro IV HGVs and Particle Mass emission rates are about 30-40% lower. PN emissions, however, are likely to be at least 100 times higher. The research further indicates that NOx, PM and PN emissions from a diesel auxTRU would all be many times higher than those from Euro 5 diesel cars when driving in urban environments and may be more like those typical of Euro 3 diesel cars.

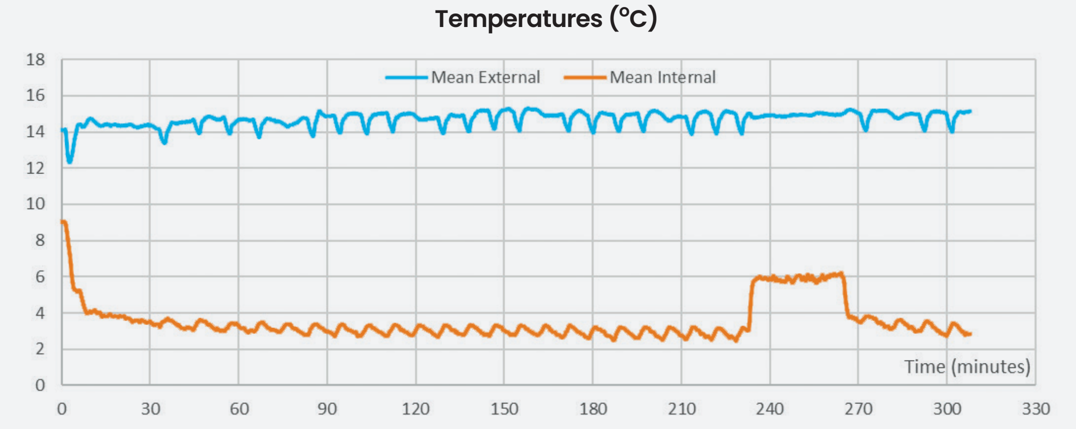
5.2 Next step recommendations

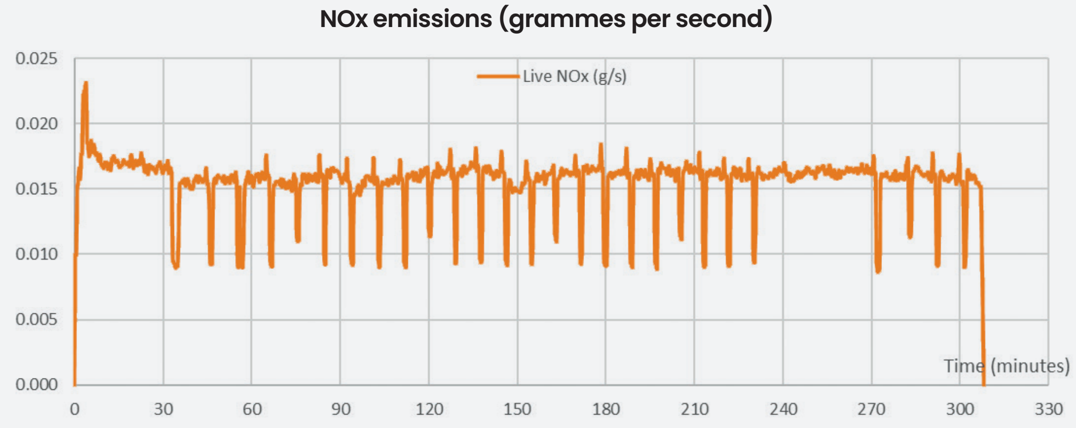
The research described in this report has added considerably to our understanding of the potential environmental impacts of diesel auxTRUs. There remain, however, key gaps in the evidence base that this short programme was not able to address. Zemo Partnership recommends the following further research activities:

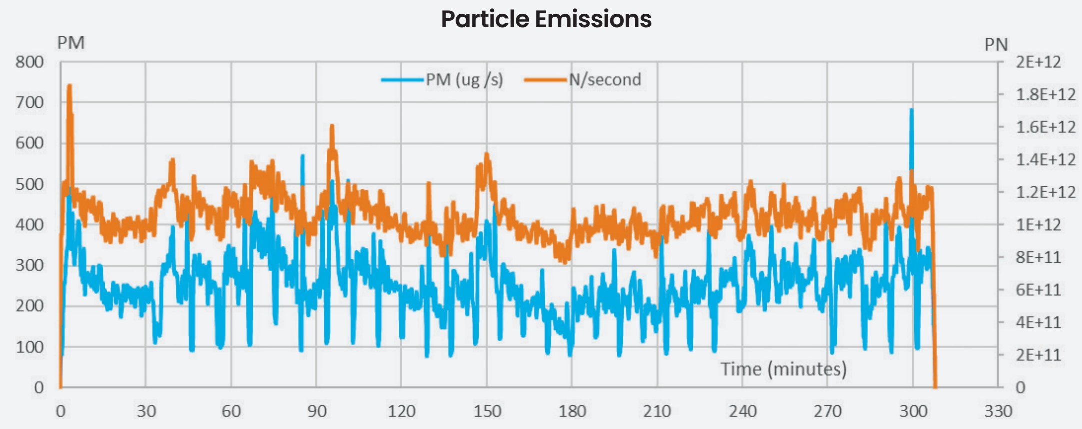
- Test at least one new auxTRU, certified as being compliant with NRMM Stage V, which came into effect for all units entering the market after 1st January 2019. This will provide evidence as to whether such units have demonstrably lower emissions impacts than pre-2019 models.
- Extend baseline auxTRU testing to include at least one other manufacturer. All three units tested to date have been from the same supplier, so testing of competitor models will ensure the baseline evidence base is more fully representative of the in-service fleet.
- Gather more comprehensive and nationally/regionally representative data on typical auxTRU operations and duty cycles to inform test process development and allow greater confidence in making overall fleet environmental impact estimates by expanding on the evidence base developed by Cenex in a previous study.
- Develop the test procedures to include combined systems that provide both propulsion and refrigeration (e.g. via an alternator) and to assess multi-temperature operations typical of normal cold-chain distribution systems. This will help to strengthen the emissions testing protocols, e.g. by combining refrigeration and drive cycles and by being more fully representative of normal in-service conditions.
- Extend baseline testing to other conventional TRU types and vehicles, e.g. alternator driven/3.5t home delivery vans. AuxTRUs are but one part of the cold chain distribution system. This will help broaden the evidence base to cover the key alternative approaches to vehicle refrigeration.
- Evaluate emissions savings from alternative technologies and fuels. As well as expanding our understanding of the environmental impacts of the key incumbent technologies, there will be a growing need to understand the potential for alternative solutions through like-for-like testing and in-service assessments. This should include consideration of technologies that do not rely on hydrofluorocarbon (HFC) gases with high Global Warming Potential.
- Assess options for provision of operational reviews to encourage uptake of existing best practice emissions saving interventions within the industry (e.g. switching auxTRU off when doors open) and to broaden awareness of alternative technologies and fuels.
- Evaluate the potential for retrofit solutions to be deployed on the existing auxTRU fleet, including the feasibility and likely effectiveness of fitting Diesel Particulate Filters (DPFs). DPFs have been very effective in reducing PN emissions from road vehicle engines, as demonstrated by testing of Euro III (non DPF) and Euro V/VI (with DPF) engines. They may (or may not) have a role to play for some operators to dramatically reduce particle emissions from their diesel auxTRUs at modest cost.

Appendix 1: Semitrailer auxTRU results graphs

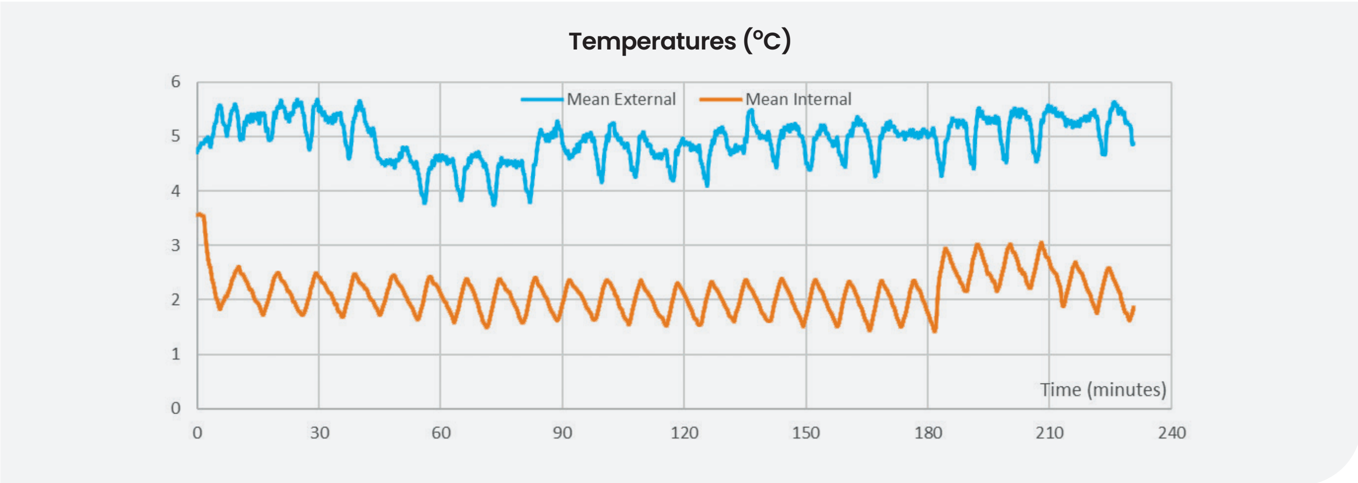
Test 1 – 15 °C Ambient, 2 °C Setpoint

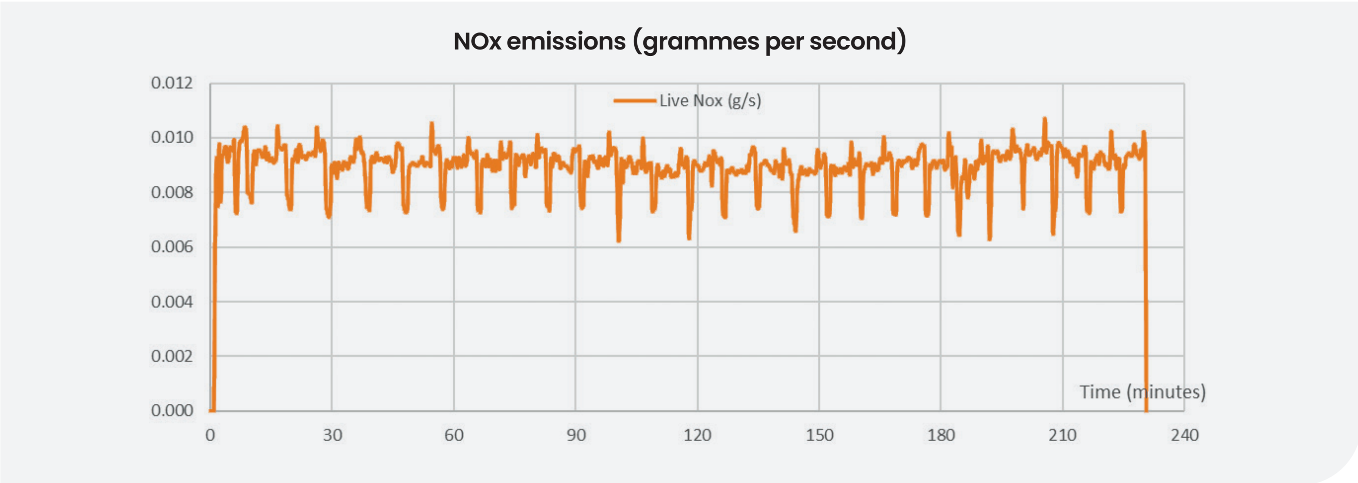


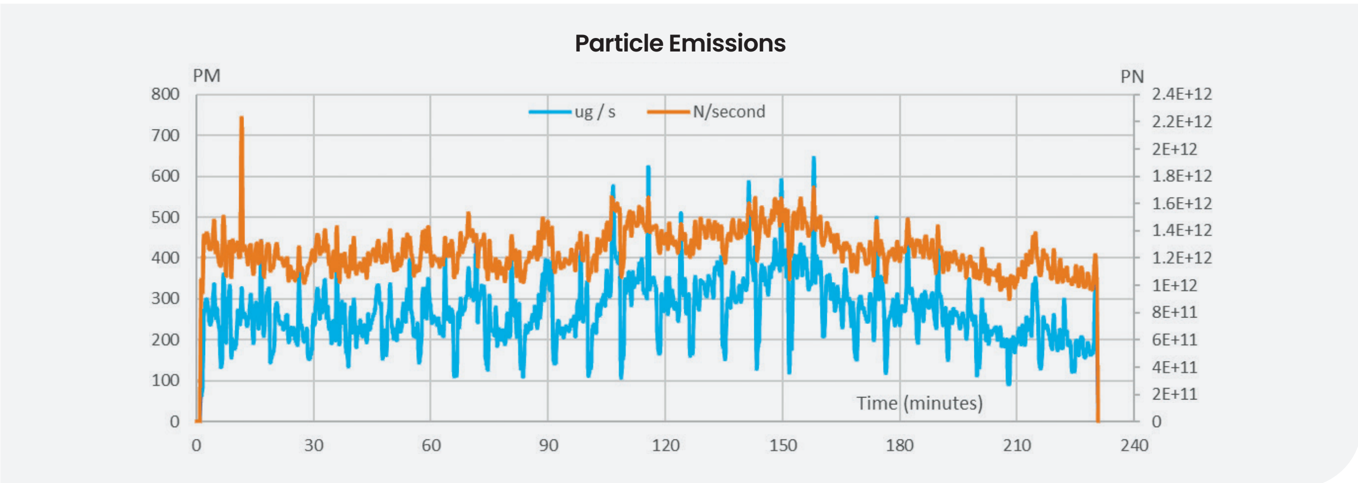




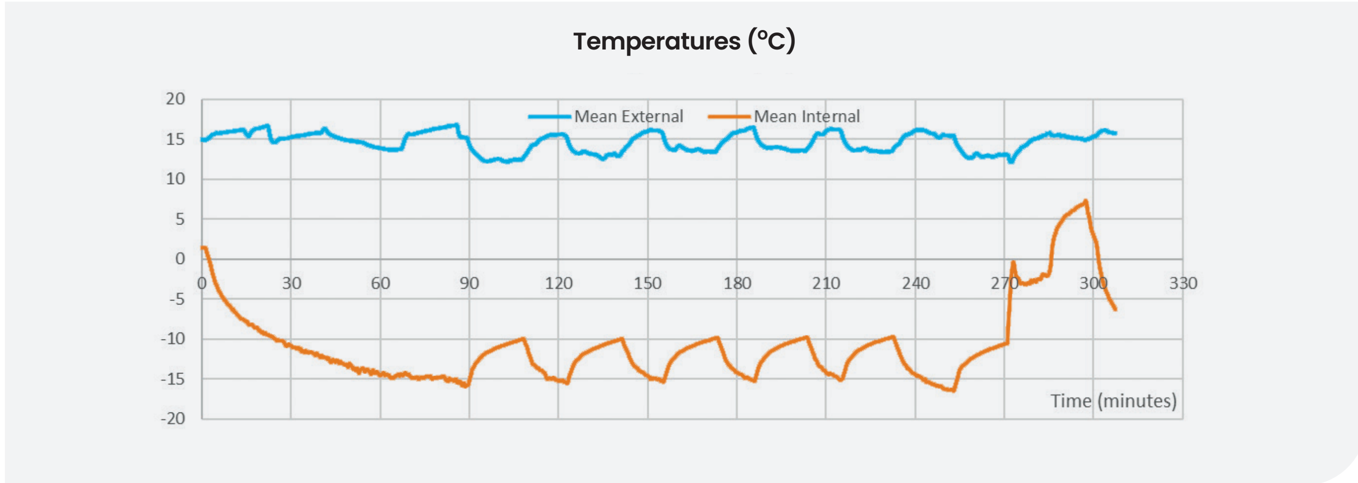
Test 2 – 5 °C Ambient, 2 °C Setpoint

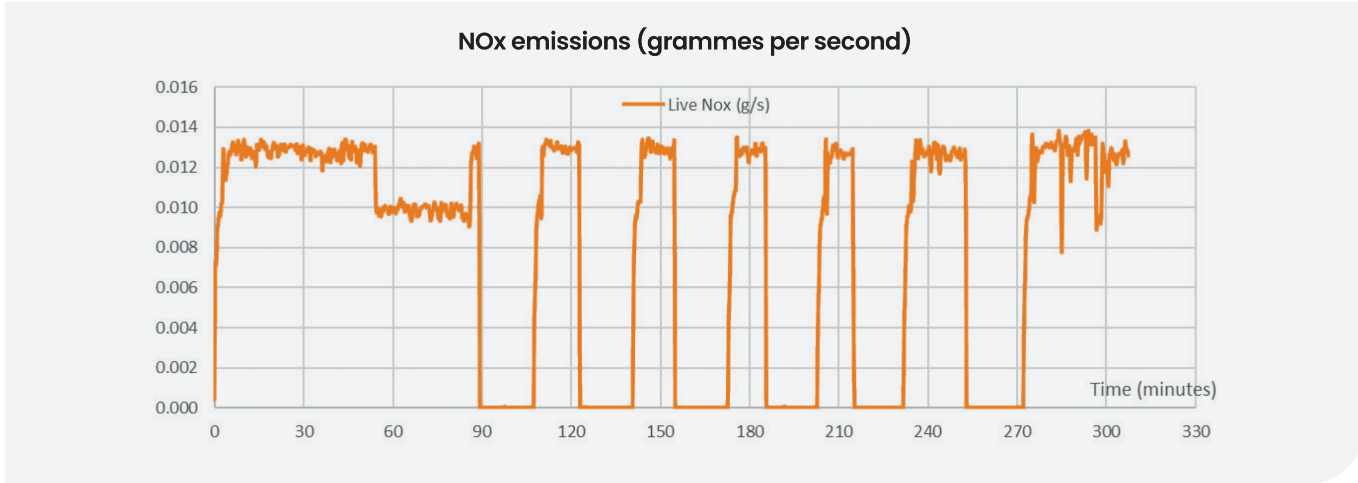


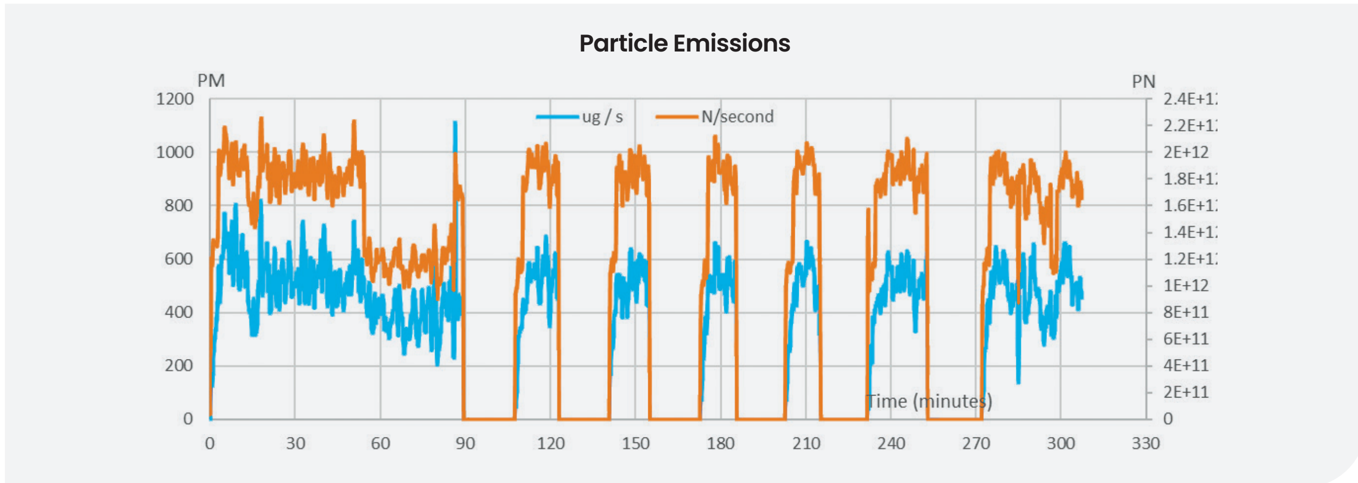




Test 3 – 15 °C Ambient, -20 °C Setpoint

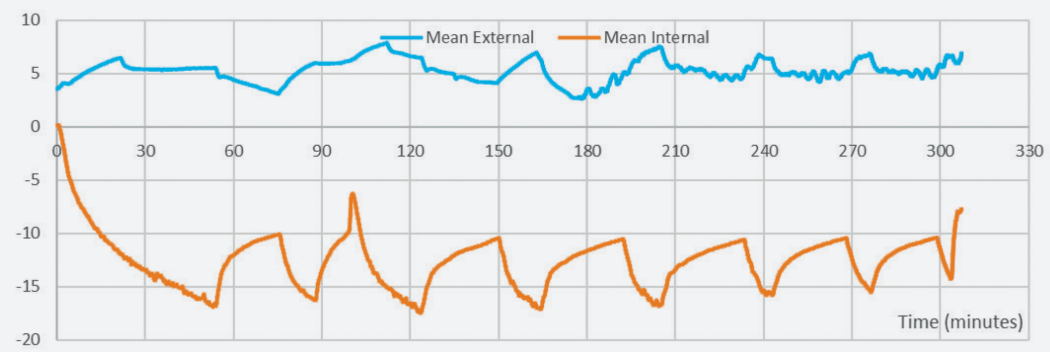




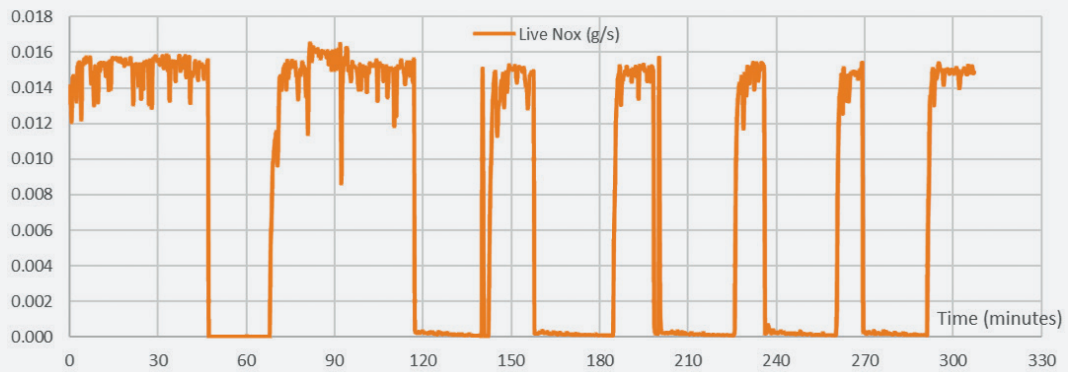


Test 4 – 5 °C Ambient, -20 °C Setpoint

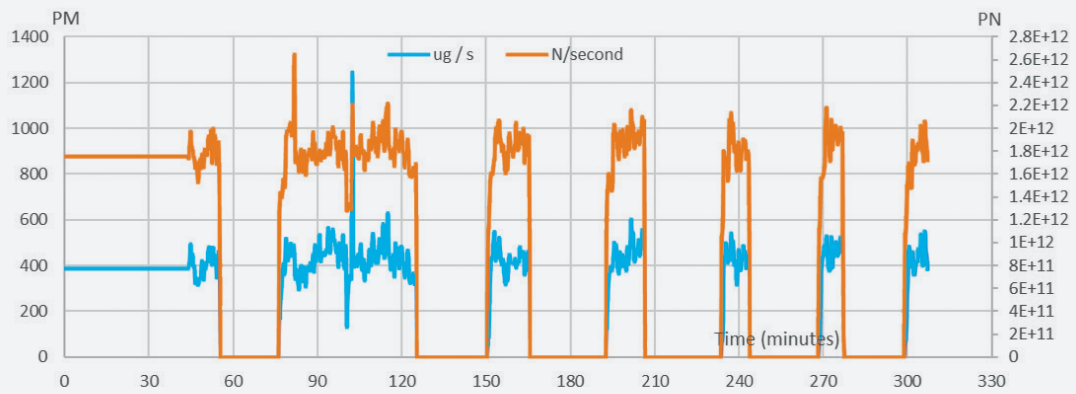
Temperatures (°C)



NOx emissions (grammes per second)



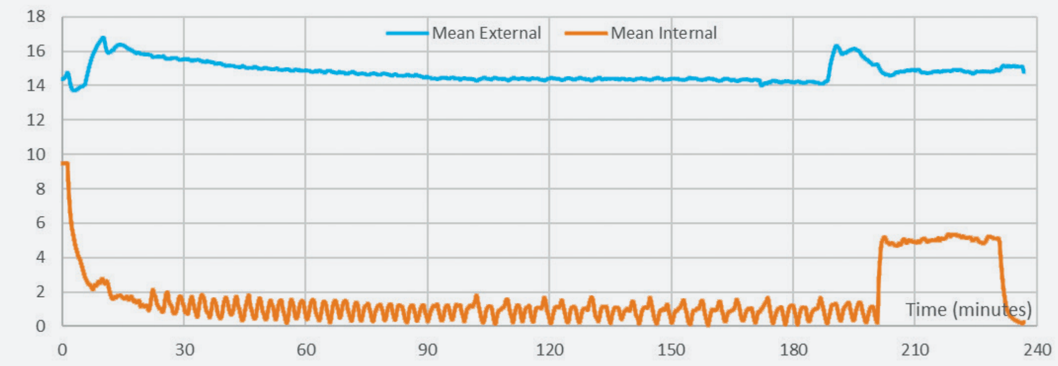
Particle Emissions



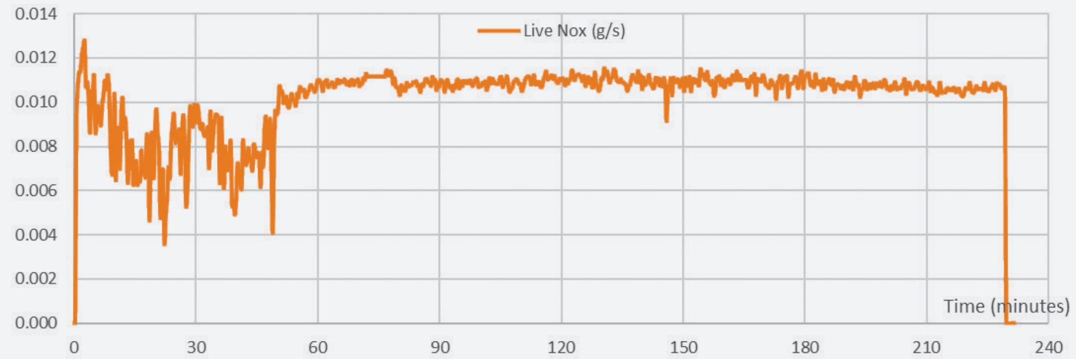
Appendix 2: Rigid HGV auxTRU results graphs

Test 5 – 15 °C Ambient, 2 °C Setpoint

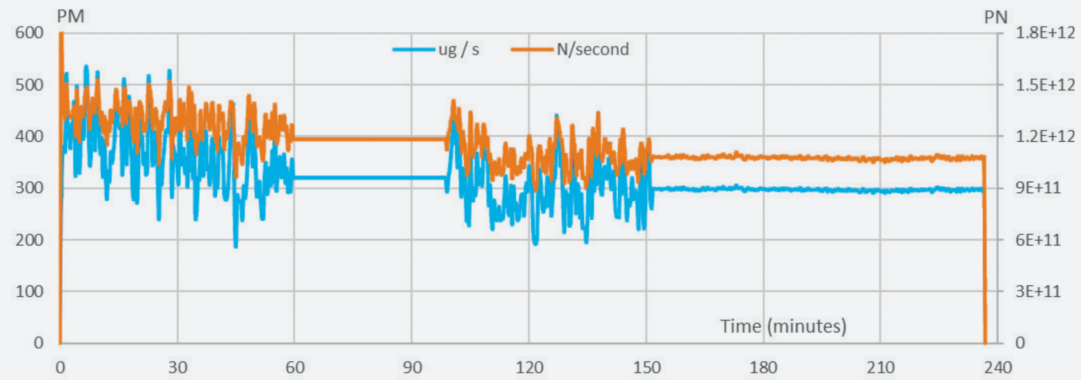
Temperatures (°C)



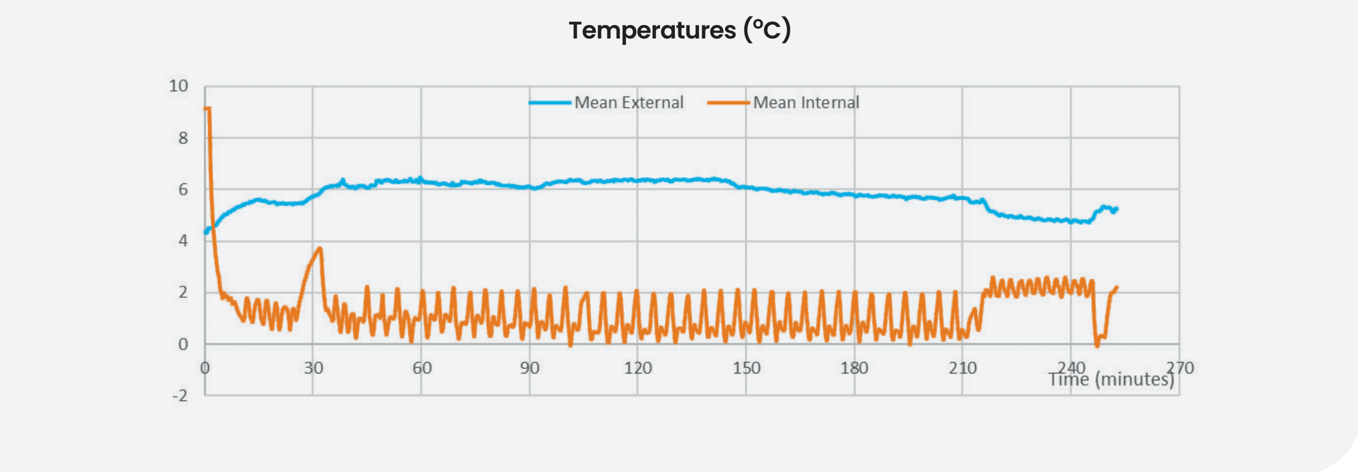
NOx emissions (grammes per second)

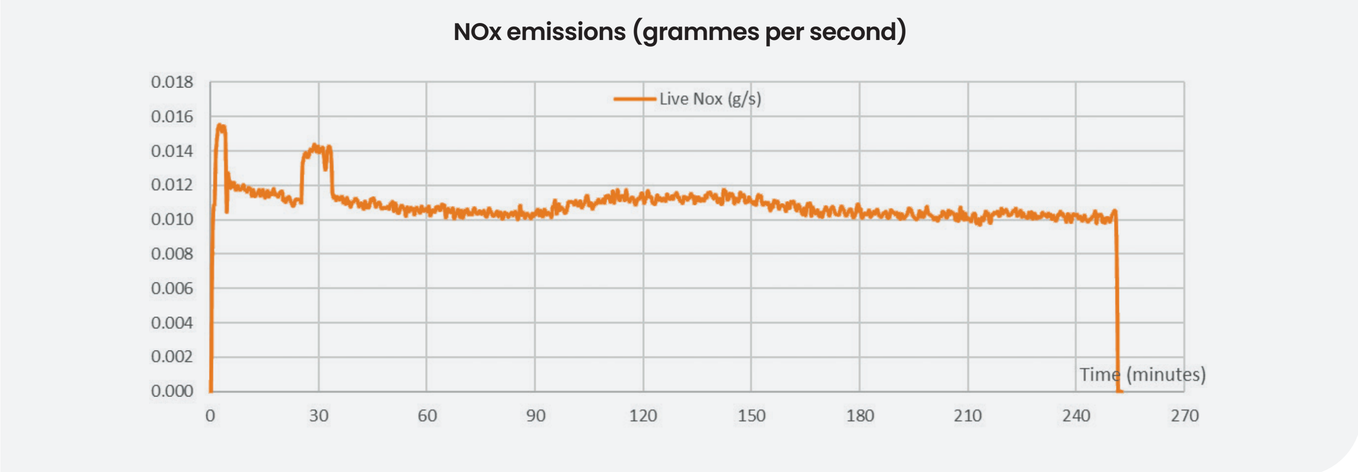


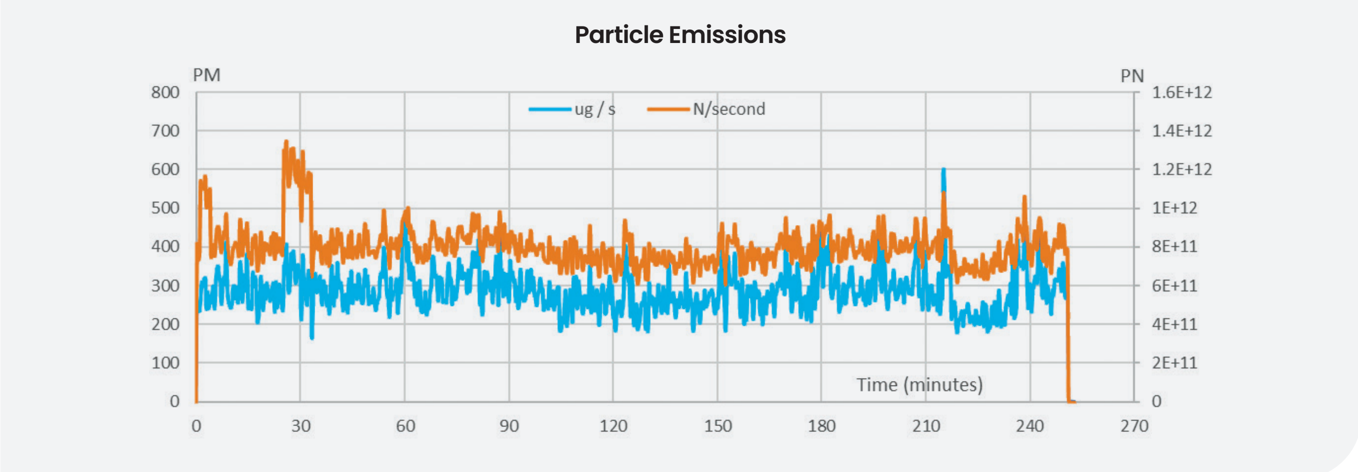
Particle Emissions



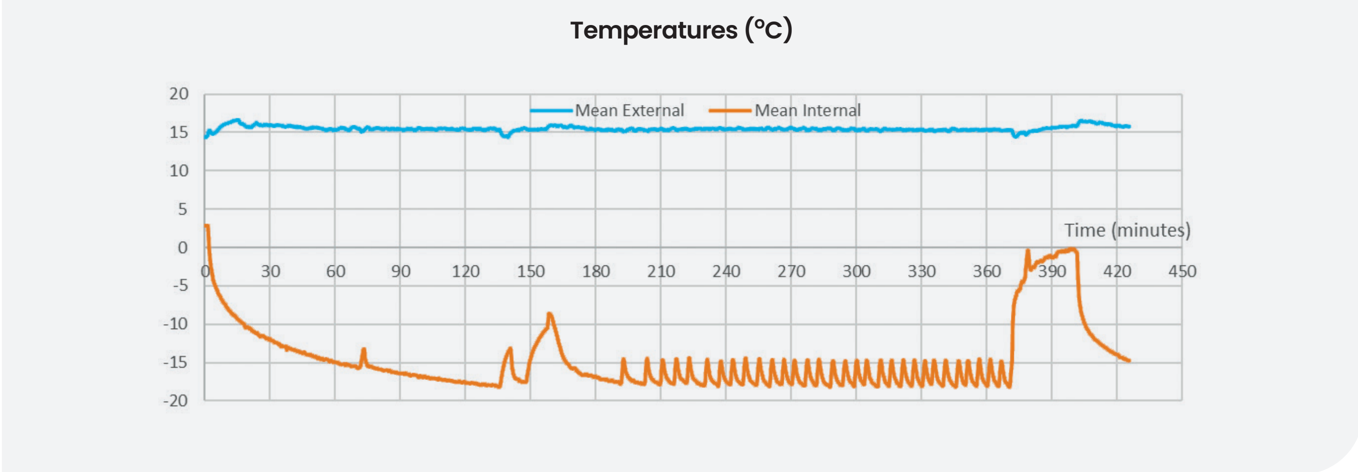
Test 6 – 5 °C Ambient, 2 °C Setpoint

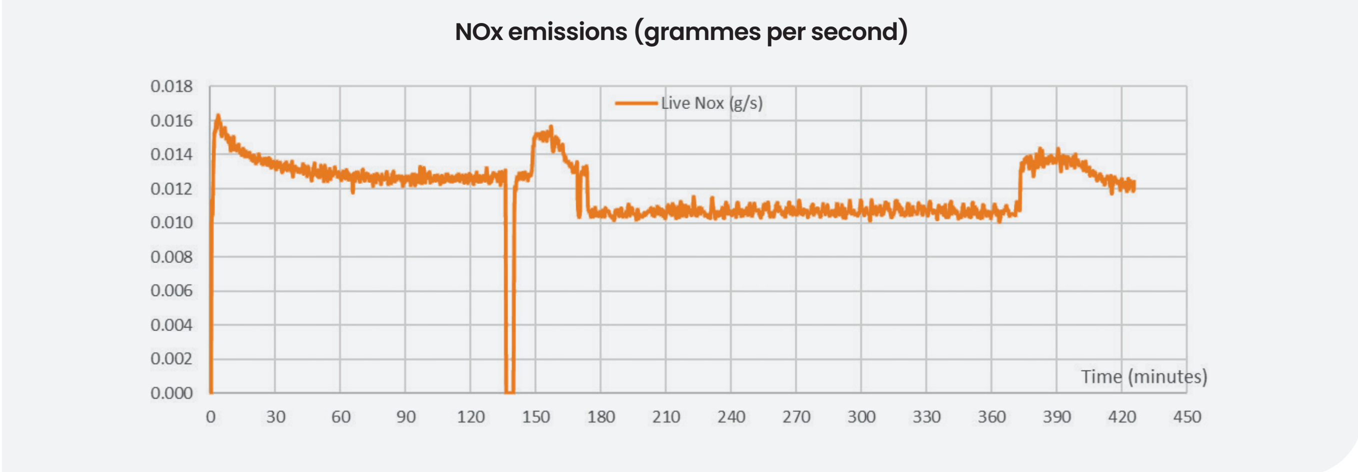


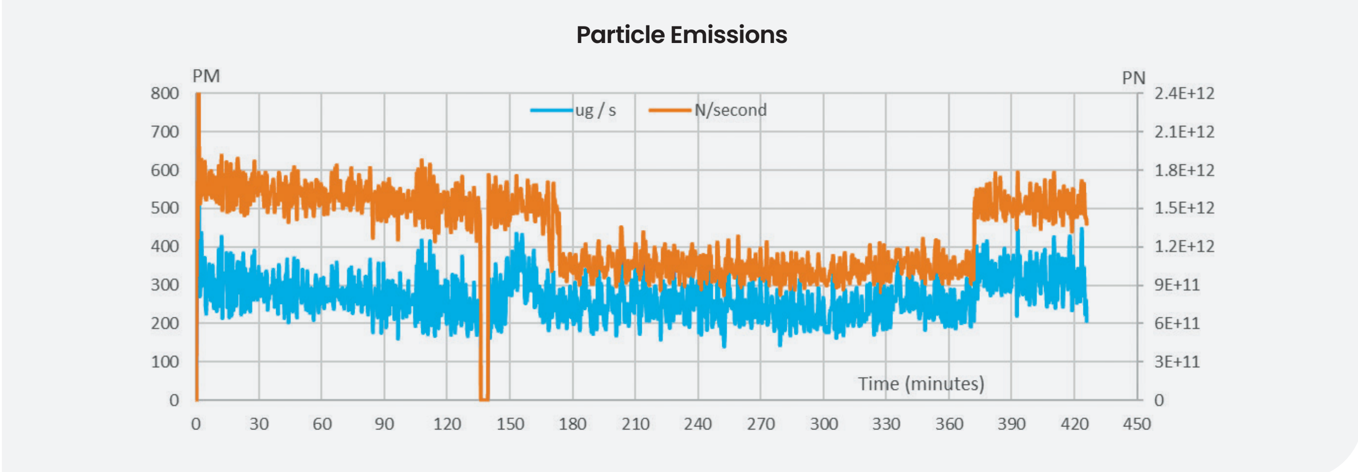




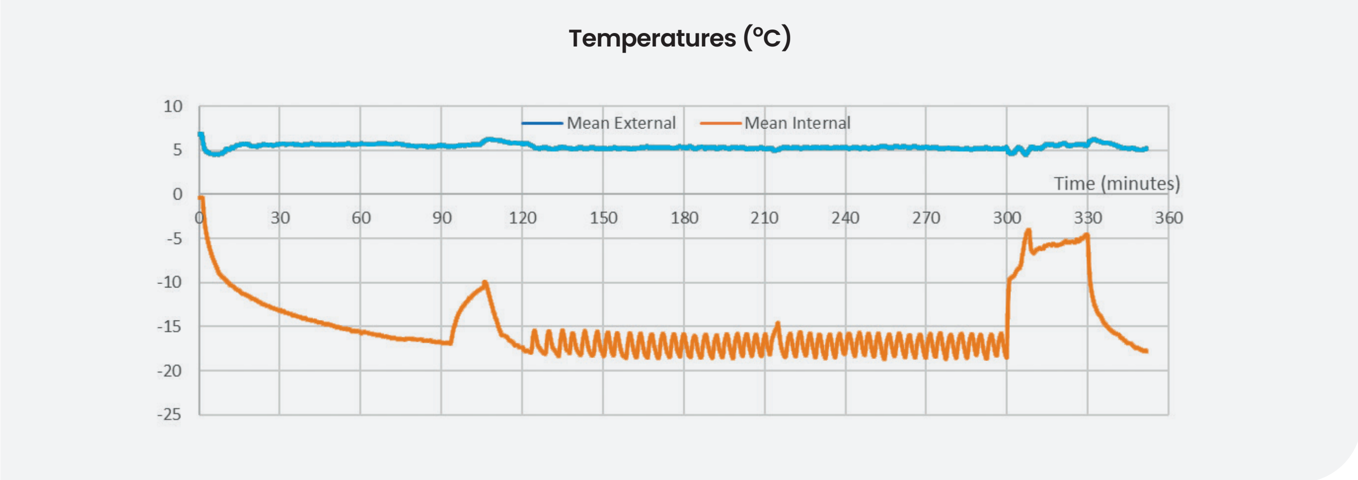
Test 7 – 15 °C Ambient, -15 °C Setpoint

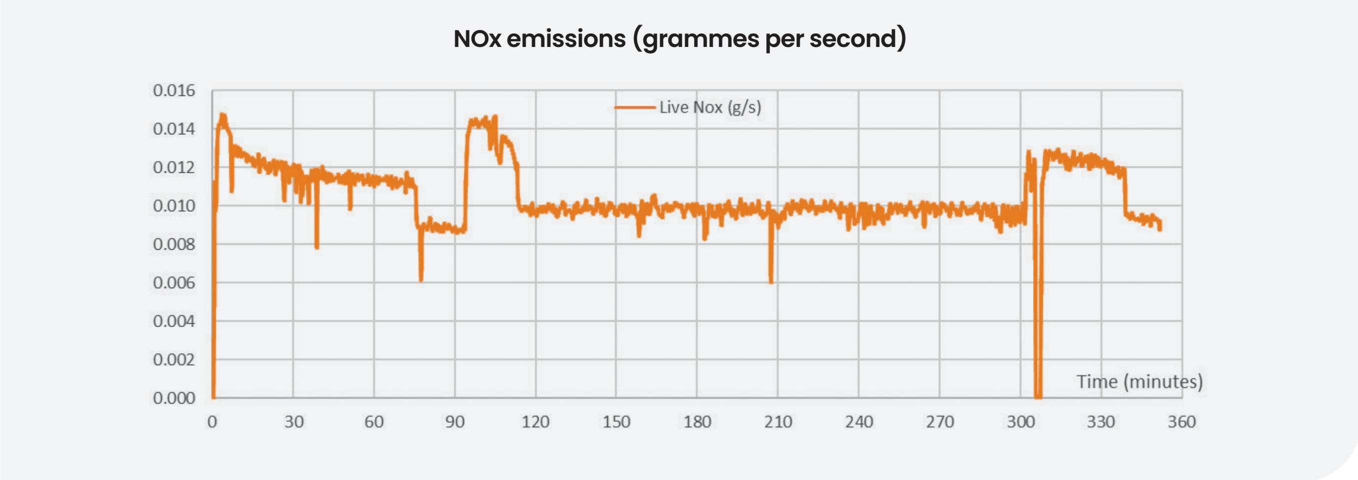


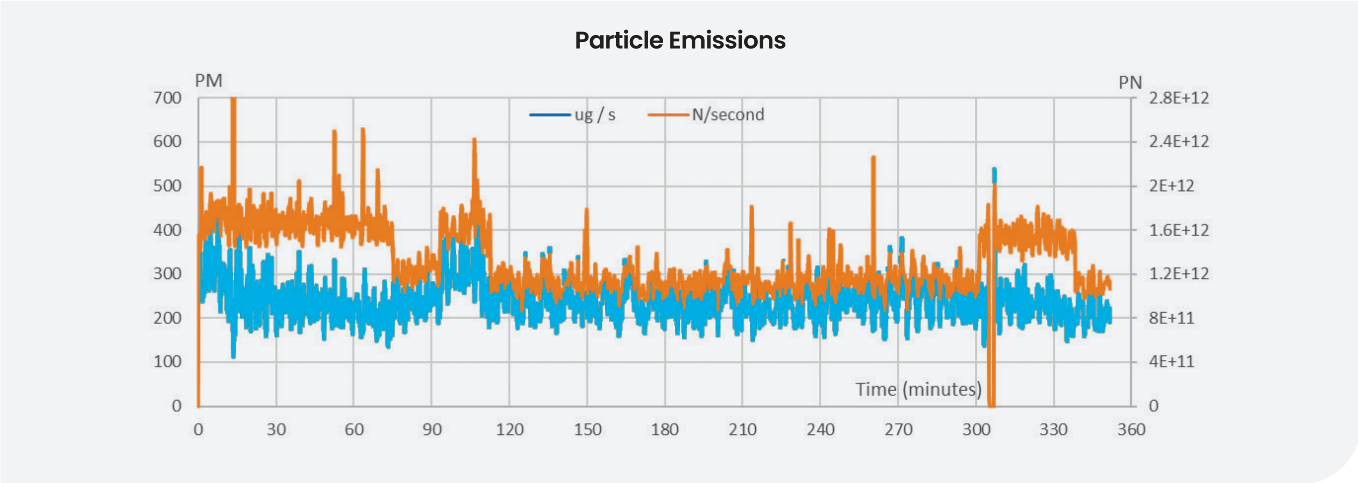




Test 8 – 5 °C Ambient, -15 °C Setpoint







Appendix 3: Cambustion observations on emissions data

Main difficulties encountered (NOx measurement)

- Soot blocked sampling system and lost some data (especially later each day and especially total NOx). Note, for example, that total NOx data was inferred from NO data as fixed proportion on for rigid HGV auxTRU Tests 6 and 7.
- Reliance upon "indication only" flow meter to calculate gravimetric emissions data – no exhaust flow data available from engine manufacturer.
- Awkward installation requirements: exhaust pipe exit at top of vehicle so 3 metre sample pipe fitted to convey sample to ground level with minimum bends to avoid water pooling as much as possible.

NO and NOx measurement procedure

- NO_2 can be calculated from NOx-NO, however, NOx channel was particularly prone to soot blockage due to its narrower and unfiltered sampling system.
- Calibration checked at end of day to allow for any data correction if required. During any engine-off periods, opportunity to check calibration was taken.
- Gas ppm data combined with (uncalibrated) flow from Bosch air flow meter which was temporarily fitted to air intake path. Exhaust flow therefore calculated by assuming Lambda=1.5 engine operation.

Zemo Partnership
Accelerating Transport to Zero Emissions

Zemo Partnership
3 Birdcage Walk, London, SW1H 9JJ

T: +44 (0)20 7304 6880
E: Hello@Zemo.org.uk
Visit: Zemo.org.uk

@Zemo_org
Zemo
Zemo YouTube Channel