Zemo Partnership

Accelerating Transport to Zero Emissions

Diesel-powered fridge testing:

Emissions from refrigerated vans and auxTRU

The results of a DfT funded programme to measure the baseline energy consumption and emissions performance of diesel refrigerated vans and provide further data on ultrafine particle emissions from HGV auxTRUs

Prepared by Zemo Partnership

October 2024

This report has been published by
Zemo Partnership, October 2024

Zemo Partnership
3 Birdcage Walk,
London,
SW1H 9JJ

T: +44 (0)20 3832 6070
E: Hello@Zemo.org.uk
Visit: Zemo.org.uk

@Zemo_org
Zemo
Zemo YouTube Channel

Acknowledgements
Zemo Partnership is grateful to UTAC for carrying out the van tests described in this report, to Cambustion Ltd for providing the additional particle emissions data, to Highnam Assist for help with analysis of market survey data, to the Department for Transport for their guidance and funding of the research and to various industry experts for their peer review comments and assistance.

Author:
Brian Robinson CEng CEnv MIMechE FCILT
Commercial Vehicle Emissions Consultant

Project Lead:
Emily Stevens
Project Manager

Reviewed by:
Gloria Esposito CEnv FIEMA
Director of Sustainable Business

Andy Eastlake CEng FIMechE
Chief Technical Consultant

Zemo Partnership
Accelerating Transport to Zero Emissions

Contents

Executive Summary

In 2022, the Department for Transport (DfT) commissioned Zemo to take forward further research into emissions from auxiliary engines including refrigeration units used on heavy goods vehicles (HGVs), building upon earlier work for Transport Scotland. In 2023, the scope of the research was further extended to cover emissions from refrigerated vans.

The DfT funded research programme began towards the end of 2022 and is scheduled to complete in November 2024. The first report arising from this research[1] was published in February 2024 and covers the main results from the first phase of the research, namely further emissions testing of conventional HGV diesel auxiliary transport refrigeration units (auxTRU), combined with a comprehensive market review to model their UK-wide emissions impacts.

This second report covers two main topics. First, it expands the HGV diesel auxTRU evidence base by presenting additional data from both the Transport Scotland and DfT test programmes on particle emissions. Second, it describes a short series of emissions tests carried out in 2024 on two diesel-fuelled refrigerated vans, presents the results and uses them to estimate UK environmental impacts of the UK's fleet of such vehicles.

New data from the programme of baseline testing of diesel auxTRU systems has been analysed to further strengthen the evidence base (specifically in relation to particle number emissions) 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[2] started to impose limits on some auxTRU emissions from January 2019.

These new data allow for our earlier overall estimates of particle number (PN) emissions from UK auxTRU to be revised upwards, from a central estimate of 330 x 10^{21} to 353 x 10^{21} (range 198-554 x 10^{21}).

It can now also be estimated that most (75-90%) of these particles would likely be of 100 nm in diameter or less and therefore fall into the definition of ultrafine particles, of greatest concern from a public health perspective.

A short programme of tests has assessed the emissions and fuel consumption impacts of two diesel-powered refrigerated vans. The results indicate that the fridge units fitted to such vehicles (powered via the van's main Euro 6 propulsion engine) consume about 0.75-1.5 litres of fuel per 100 km driven and generate an extra 20-40 g/km of tailpipe CO_2 emissions. The results further indicate that such fridge units have minimal impact on overall NOx emissions and are unlikely to significantly and adversely impact particulate emissions when used on Euro 6 standard vans.

Combining the test results with estimates of the numbers of refrigerated vans in use in the UK and their typical annual mileages has generated a central estimate that such vehicles emit an additional 54 kt of tailpipe CO_2 emissions, relative to those vans operating without a fridge unit, and consume around 20 million litres of extra fuel (about 0.3% of all fuel burnt annually by UK vans).

[1] HGV Auxiliary Engines: Baseline auxTRU testing and modelling of UK impacts, Zemo Partnership, 2024.

[2] The Non-Road Mobile Machinery (Type-Approval and Emission of Gaseous and Particulate Pollutants) Regulations 2018

1. Introduction

1.1 Background

In 2021, Transport Scotland provided funding for Zemo Partnership to carry out emissions testing on two conventional heavy goods vehicle (HGV) diesel auxiliary transport refrigeration units (auxTRUs), each at two separate ambient temperatures and under both chilled and frozen loading conditions.

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.

In 2022, the Department for Transport (DfT) commissioned Zemo 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). In 2023, the scope of the research was further extended to cover emissions from refrigerated vans and auxiliary engines fitted to vans.

The DfT funded research programme began towards the end of 2022 and is scheduled to complete in November 2024. The first report arising from this research[3] was published in February 2024 and covers the main results from the first phase of the research, namely further emissions testing of conventional HGV diesel auxTRUs, combined with a comprehensive market review to model their UK-wide emissions impacts.

This second report covers two main topics. First, it expands the HGV diesel auxTRU evidence base by presenting additional data from both the Transport Scotland and DfT test programmes on particle emissions. Second, it describes a short series of emissions tests carried out in 2024 on two diesel-fuelled refrigerated vans, presents the results and uses them to estimate UK environmental impacts.

[3] HGV Auxiliary Engines: Baseline auxTRU testing and modelling of UK impacts, Zemo Partnership, 2024.

1.2 Objectives

The objectives of the research described in this report were:

Further analysis of particle emissions data from previous testing of conventional diesel auxiliary TRUs:

- Obtain, analyse and report on a more comprehensive set of particle emissions data, collected during the two previous rounds of HGV auxTRU tests.
- Specifically, these new analyses cover emissions of ultrafine particles (those with an aerodynamic diameter of less than 0.1 µm [4]) and provide particle number results in accordance with Euro VI protocols (which exclude most particles smaller than 23 nm in diameter).

Extend baseline testing to include diesel-fuelled refrigerated vans:

- Develop the test procedures to include assessment of fridge systems fitted to vans typical of normal cold-chain distribution systems (home grocery delivery). This will help to strengthen the emissions testing protocols by being more fully representative of normal in-service conditions. Fridge systems fitted to vans are typically not driven by an auxiliary engine but rather by the van's main propulsion engine, via either an alternator or power take-off. These tests focus on how tailpipe emissions from a Euro 6 regulated engine vary between the fridge-on and fridge-off conditions, to establish the extra load that running the TRU places on the diesel van engine and emissions output compared to a similarly loaded van that is not running a TRU and how this extra engine load contributes to overall fleet level emissions.

Note that tests have also been carried out on a battery-electric refrigerated van, but the results from those tests will be included in a later report (alongside results from planned tests of alternative HGV auxTRU technologies).

[4] 0.1 µm = 100 nm

1.3 Methodology

For the HGV auxTRU tests, 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, and number, PN).

Similar protocols were followed for the van testing programme, with some essential differences to reflect their different operational usage characteristics.

The first and most fundamental difference is that the vehicle itself needs to be running during the tests, not just the fridge unit. The method chosen to achieve this was to run each test on an indoor chassis dynamometer. This allows full control over the external ambient temperatures while following realistic and representative vehicle and fridge duty cycles.

A second difference was the nature of the chilled or frozen product carried. For the van tests, individual water-filled containers were placed in totes (baskets) within the load compartments. These had been pre-chilled or frozen in advance of being placed in the test vehicle (as per HGV auxTRU testing). These arrangements ensured the most realistic and representative treatment of the chilled and frozen product and operating cycle of the fridges.

The third difference was that the van tests involved only multi-temperature conditions, i.e. both chilled and frozen product being carried (in separate dedicated compartments) during all the tests. Our market survey and other research indicates that most home grocery delivery vans do not operate in chilled or frozen-only mode (though some do).

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

1.4 Report structure

Chapter 2 fully describes the test procedures and measurement systems. Chapters 3 and 4 present and discuss the additional particle data from the previous HGV auxTRU test programmes. Chapter 5 updates our UK-wide particle emission estimates for auxTRUs. Chapter 6 summarises the results of the refrigerated van tests and Chapter 7 uses those to make some estimates of the overall UK environmental impacts of refrigerated vans. Chapter 8 presents an analysis of the combined environmental impacts of refrigerated vans and HGVs with auxTRUs. Chapter 9 summarises our conclusions.

2. Test procedures

The HGV auxTRU test programmes were carried out during 2021 (for Transport Scotland) and 2023 (for the DfT) 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.

The refrigerated van tests were carried out in February and March 2024 by UTAC using certification level chassis dynamometer facilities at their Millbrook site in Bedfordshire.

2.1 HGV auxTRU testing

Full details of the auxTRU test procedures are provided in the published February 2024 Zemo report and for brevity are not repeated here. Six different auxTRUs were tested in 2023, following on from testing of two units in 2021.

Of the eight units tested across the two test programmes:

- One was a pre-2019 unit manufactured by Thermo King (TK).
- Two were pre-2019 units manufactured by Carrier.
- Three were post-2019 units also manufactured by Thermo King.
- Two were post-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 anonymised 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. The units have been categorised as pre or post-2019 to facilitate assessments of the impacts on emissions, if any, from the regulatory changes in January 2019, whereby auxTRU became subject to the requirements of the NRMM Directive.

Table 1. Details of auxTRUs tested

Manufacturer	Model	Capacity at 0 °C	Age	Refrigerant
Carrier	Supra 1150 MT	11.1 kW	Pre-2019	R404A
Carrier	Vector 1550	14.7 kW	Pre-2019	R452A
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

To aid any cross-referencing between the results presented here and those published in the February 2024 report, the results tables in the following chapter following the same Unit 1-6 numbering convention for the auxTRU tested in 2023. Units 7 and 8 are the auxTRUs tested in 2021.

2.2 Refrigerated van testing

A programme of work was undertaken to baseline two current Euro 6 standard diesel 3.5 tonne vans fitted with multi temperature refrigerated bodies (typical of UK supermarket delivery use). Engagement with industry contacts prior to testing highlighted two dominant conventional technologies, with the fridge either powered via an alternator or via a power take-off (PTO). One of each were tested, with "Vehicle 1" (first registered in 2022) having an alternator-driven fridge unit and "Vehicle 2" (first registered in 2019) using a PTO-driven system.

The test cycle used was a modified version of Zemo's Clean Vehicle Retrofit Accreditation Scheme (CVRAS) Van test cycle, comprising the Transport for London (TfL) urban peak driving cycle and the WLTC (Worldwide Harmonised Light Vehicles Test Cycle) legislative cycle. The full cycle thus included a wide range of typical driving conditions, from low speed, city-centre type operations through urban, regional and motorway-type conditions. For these vans, the Class 2 (low power to weight) version of WLTC was used with a maximum speed set to 90 km/h as both vans were speed limited.

The drive cycle was modified based on discussion with the expert steering group of the project, to better reflect the typical delivery process and to exercise the refrigeration units in the most representative way. Specifically, three "delivery stops" were inserted into the cycle. Two stops of 5 minutes each including 60 seconds with the doors for all fridge, freezer and ambient compartments opened. The final stop was for 10 mins with 120 seconds of doors open.

To assess the impact of operating each vehicle's fridge system, a test day was configured with repeat tests of "fridge-on" and "fridge-off" with the vehicles operating in ambient conditions of 15°C and 30°C.

In order to represent the real world operation of these vans, prior to each test the vehicle was preconditioned overnight at the required ambient temperature and the load (water-filled containers) was preconditioned in separate chambers (to 2°C and -18°C for chilled and frozen loads respectively). The start of testing commenced with the van's fridge being plugged into shore power (an external electrical power supply) to condition the body compartments for one hour, in accordance with normal industry practice. The conditioned "load" was then inserted into the van and a "cold start" test commenced with the fridge operational.

Two further "warm start" tests were conducted with intervals typically of 30 mins between tests, with the fridge operational. The fridge was then switched off and 2 additional (warm start) tests run to the same procedure but without any fridge operation.

2.2.1 Instrumentation

Thermocouples were positioned in each of the van compartments (frozen, chilled and ambient) and in the driver's cabin. The driver's cabin was controlled to a target of 20°C throughout testing.

Emissions of CO_2, NOx, particle mass (PM) and particle number (PN) were measured using legislative measurement processes and additionally in real time at 10 Hz sample rate. Applying Euro 6 processes means a 23 nm roll-off function was used to count the particles. Further detailed analyses of the particles by size (e.g. to identify ultrafine proportions) is not possible from the measurement equipment used for these tests. Further details on the 23 nm roll-off function are provided in the next section.

3. New particle emissions data from HGV auxTRU tests

The report published in 2021 presents particle mass (PM) and particle number (PN) data based on the full spectra of particle sizes measured by Cambustion. This covered particle size distributions from 5nm-1µm. For the February 2024 report, PN was reported in terms "equivalent to Euro 6 protocols", which applied a cut-off at 23 nm (excluding particles smaller than 23 nm).

Further data has now been obtained from Cambustion that allows for more detailed analyses. These new data allow for both full alignment of all the key PN results between the two test programmes and to take advantage of new software that can process PN data in ways that are fully aligned with Euro 6 protocols (these apply a "roll-off" function which includes some particles smaller than 23 nm and excludes some that are slightly larger than 23 nm). This allows for an even more robust, like-for-like comparison between the auxTRU results and reported emissions from Euro VI diesel HGV engines. The new data also provides specific numbers of particles in the "ultrafine" size range, i.e. up to 100 nm in diameter, as it is these particles that are of greatest concern from a public health perspective.

The results tables in the following sections thus provide four separate measures of Particle Number:

- "PN rate" = production rate (in number per hour) of all particle sizes measured (5nm-1µm).
- "UPN rate" = production rate of all ultrafine particles, i.e. only those up to 100 nm in diameter.
- "E6PN rate" = production rate of all particles meeting the Euro 6/VI measurement protocol size requirements.
- ">23PN rate" = production rate counting only those particles of at least 23 nm in diameter and as used as a proxy for Euro 6 equivalence for the February 2024 report. These results are not available for the two 2021 tests (Units 7 and 8).

Note that this new data on the numbers of very small particles emitted (but excluded from the earlier analyses) has no meaningful impact on the estimated Particle Mass (PM) emission rates. The drivers for PM results focus significantly more on a number of relatively large particles, which were counted fully in all previous assessments – since the mass of an individual particle is broadly proportional to the cube of its diameter, it can be estimated, for example, that each 15 nm particle would weigh only around one thousandth that of single 150 nm particle.

3.1 Chilled mode results

This section presents the particle emissions results from all the chilled tests at 2 °C load temperature.

Tables 2 and 3 show the total particle number emission production rates in each phase for the three pre-2019 units tested and the post-2019 units respectively. Figures in brackets in the UPN, E6PN and >23PN columns represent those results as a percentage of the (all measured particles) PN production rate. Cells shaded in grey indicate PN rate results previously published. Figure 1 summarises the (all phases) results at 15 °C ambient temperature.

Figure 1. PN rates, chilled mode tests at 15 °C

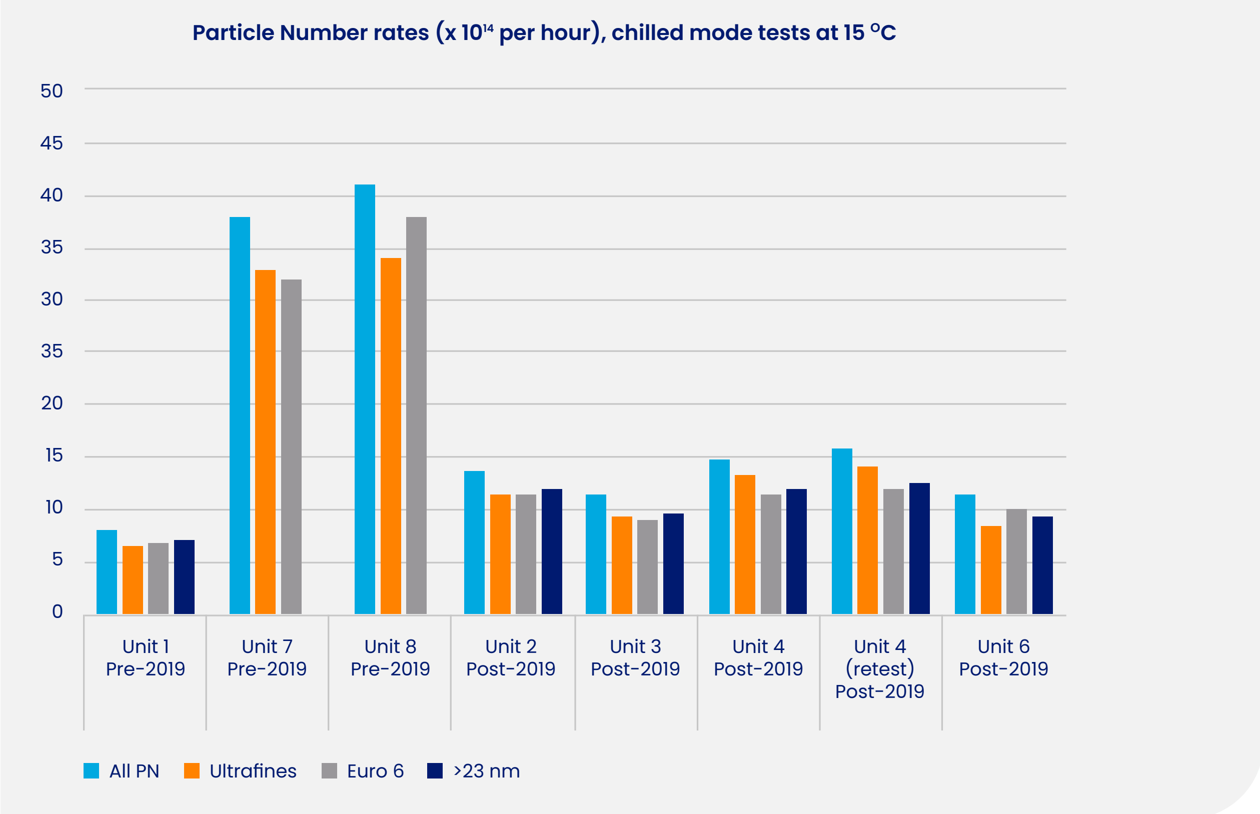


Table 2. Chilled mode particle number emissions results, pre-2019 units

Phase	Ambient °C	Duration mins	PN rate x 10^{14} per hour	UPN rate x 10^{14} per hour	E6PN rate x 10^{14} per hour	>23PN rate x 10^{14} per hour
Unit 1: pre-2019						
3 Pull-Down 1	15	30	8	7 (83%)	6 (79%)	7 (82%)
4 Steady State	15	180	8	7 (80%)	7 (86%)	7 (89%)
5 Doors Open	15	30	8	6 (80%)	7 (86%)	7 (89%)
6 Pull-Down 2	15	7	8	6 (81%)	7 (86%)	7 (89%)
All	**15**	**247**	**8**	**7 (80%)**	**7 (85%)**	**7 (88%)**
Unit 7: pre-2019						
3 Pull-Down 1	15	56	40	34 (87%)	33 (83%)	
4 Steady State	15	180	38	33 (87%)	32 (84%)	
5 Doors Open	15	30	39	33 (85%)	33 (85%)	
6 Pull-Down 2	15	42	39	33 (85%)	33 (85%)	
All	**15**	**308**	**38**	**33 (86%)**	**32 (84%)**	
3 Pull-Down 1	5	2	45	40 (90%)	35 (78%)	
4 Steady State	5	180	46	40 (87%)	39 (84%)	
5 Doors Open	5	30	41	36 (88%)	34 (83%)	
6 Pull-Down 2	5	19	40	32 (89%)	30 (82%)	
All	**5**	**231**	**45**	**39 (87%)**	**38 (84%)**	
Unit 8: pre-2019						
3 Pull-Down 1	15	21	49	40 (83%)	42 (87%)	
4 Steady State	15	180	41	34 (83%)	37 (91%)	
5 Doors Open	15	30	39	32 (83%)	36 (93%)	
6 Pull-Down 2	15	5	39	32 (83%)	36 (93%)	
All	**15**	**236**	**41**	**34 (83%)**	**38 (91%)**	
3 Pull-Down 1	5	36	33	28 (85%)	28 (86%)	
4 Steady State	5	180	28	24 (83%)	25 (88%)	
5 Doors Open	5	30	27	23 (84%)	24 (87%)	
6 Pull-Down 2	5	7	21	17 (82%)	19 (89%)	
All	**5**	**253**	**29**	**24 (84%)**	**25 (87%)**	

Table 3. Chilled mode particle number emissions results, post-2019 units

Phase	Ambient °C	Duration mins	PN rate x 10^{14} per hour	UPN rate x 10^{14} per hour	E6PN rate x 10^{14} per hour	>23PN rate x 10^{14} per hour
Unit 2: post-2019						
3 Pull-Down 1	15	30	13	10 (83%)	11 (85%)	12 (88%)
4 Steady State	15	180	14	12 (84%)	11 (83%)	12 (87%)
5 Doors Open	15	30	16	13 (81%)	13 (86%)	14 (89%)
6 Pull-Down 2	15	22	14	11 (85%)	11 (84%)	12 (87%)
All	**15**	**262**	**14**	**12 (84%)**	**12 (84%)**	**12 (87%)**
Unit 3: post-2019						
3 Pull-Down 1	15	28	11	10 (84%)	9 (78%)	9 (82%)
4 Steady State	15	180	11	10 (84%)	9 (82%)	10 (86%)
5 Doors Open	15	30	12	10 (83%)	10 (84%)	11 (89%)
6 Pull-Down 2	15	11	12	10 (83%)	10 (84%)	11 (88%)
All	**15**	**249**	**11**	**10 (84%)**	**9 (82%)**	**10 (86%)**
Unit 4: post-2019						
3 Pull-Down 1	15	21	25	23 (92%)	19 (75%)	20 (79%)
4 Steady State	15	180	13	12 (89%)	10 (77%)	10 (81%)
5 Doors Open	15	30	20	18 (90%)	16 (80%)	17 (84%)
6 Pull-Down 2	15	5	16	14 (87%)	13 (82%)	13 (85%)
All	**15**	**236**	**15**	**13 (90%)**	**12 (77%)**	**12 (81%)**
Unit 4: post-2019 (re-test)						
3 Pull-Down 1	15	36	18	16 (90%)	13 (74%)	14 (77%)
4 Steady State	15	180	16	14 (89%)	12 (76%)	12 (80%)
5 Doors Open	15	30	15	13 (88%)	12 (79%)	13 (82%)
6 Pull-Down 2	15	7	15	13 (88%)	12 (80%)	13 (83%)
All	**15**	**253**	**16**	**14 (89%)**	**12 (76%)**	**13 (80%)**

Phase	Ambient °C	Duration mins	PN rate x 10^{14} per hour	UPN rate x 10^{14} per hour	E6PN rate x 10^{14} per hour	>23PN rate x 10^{14} per hour
Unit 6: post-2019						
3 Pull-Down 1	30	101	13	9 (67%)	12 (91%)	11 (85%)
4 Steady State	30	180	14	9 (65%)	12 (88%)	11 (81%)
5 Doors Open	30	30	17	10 (60%)	15 (91%)	14 (83%)
6 Pull-Down 2	30	43	15	10 (65%)	13 (88%)	12 (80%)
All	**30**	**354**	**14**	**9 (65%)**	**13 (89%)**	**12 (82%)**
3 Pull-Down 1	15	61	11	8 (73%)	10 (90%)	9 (82%)
4 Steady State	15	180	11	8 (76%)	10 (88%)	9 (80%)
5 Doors Open	15	30	14	10 (68%)	13 (91%)	12 (82%)
6 Pull-Down 2	15	15	13	9 (72%)	11 (89%)	10 (80%)
All	**15**	**286**	**11**	**8 (74%)**	**10 (89%)**	**9 (80%)**
3 Pull-Down 1	5	51	9	7 (74%)	8 (90%)	8 (88%)
4 Steady State	5	180	11	8 (75%)	10 (89%)	9 (87%)
5 Doors Open	5	30	12	9 (74%)	11 (87%)	11 (85%)
6 Pull-Down 2	5	7	13	9 (71%)	12 (90%)	11 (88%)
All	**5**	**268**	**11**	**8 (75%)**	**9 (89%)**	**9 (87%)**

3.2 Frozen mode result

This section presents the particle emissions results from all the frozen mode tests.

Tables 4 and 5 show the total particle number emission production rates in each phase for the three pre-2019 units tested and the post-2019 units respectively. Figures in brackets in the UPN, E6PN and >23PN columns represent those results as a percentage of the (all measured particles) PN production rate. Cells shaded in grey indicate PN rate results previously published.

Figure 2 summarises the (all phases) results at 15 °C ambient temperature.

Figure 2. PN rates, frozen mode tests at 15 °C

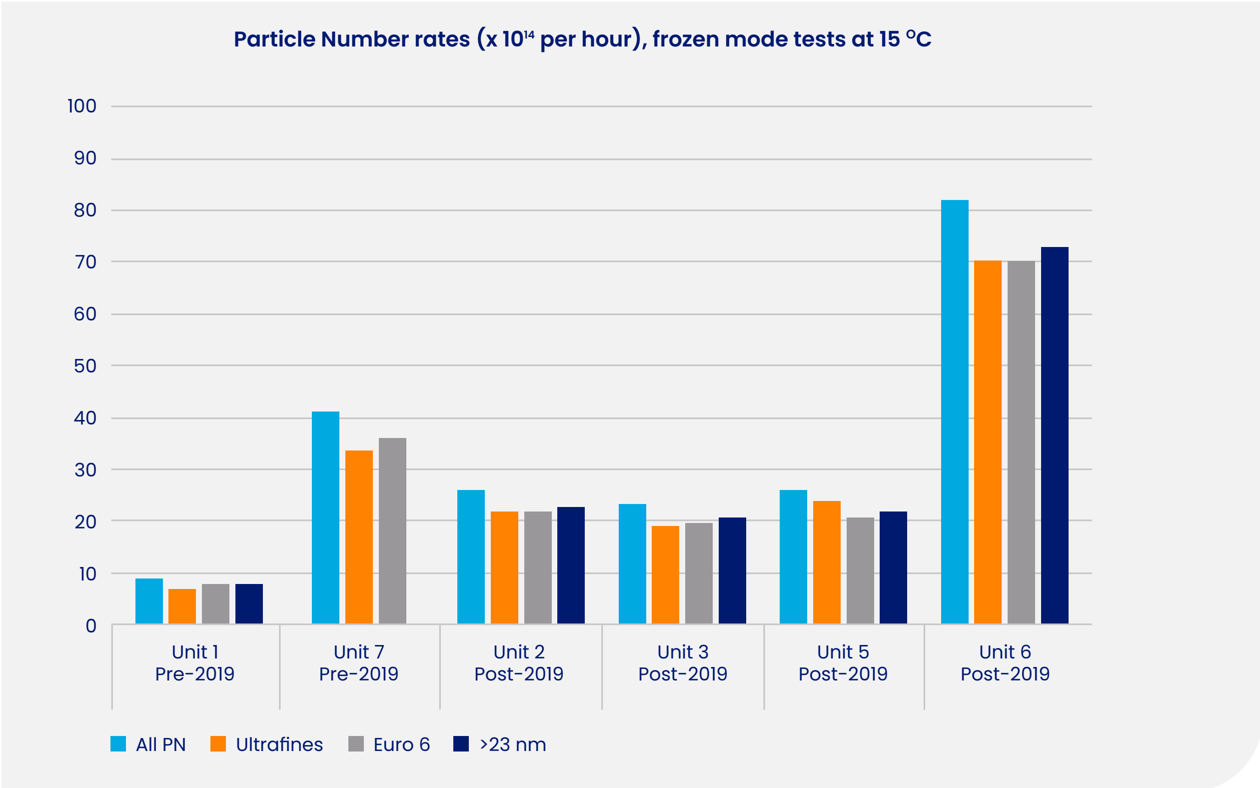


Table 4. Frozen mode particle number emissions results, pre-2019 units

Phase	Ambient °C	Duration mins	PN rate x 10^{14} per hour	UPN rate x 10^{14} per hour	E6PN rate x 10^{14} per hour	>23PN rate x 10^{14} per hour
Unit 1: pre-2019						
3 Pull-Down 1	15	119	12	9 (81%)	10 (86%)	11 (89%)
4 Steady State	15	180	5	4 (73%)	5 (89%)	5 (91%)
5 Doors Open	15	30	12	9 (77%)	11 (87%)	11 (90%)
6 Pull-Down 2	15	25	14	11 (76%)	13 (88%)	13 (90%)
All	**15**	**354**	**9**	**7 (77%)**	**8 (87%)**	**8 (90%)**
Unit 7: pre-2019						
3 Pull-Down 1	15	91	56	46 (83%)	49 (87%)	
4 Steady State	15	180	26	22 (83%)	23 (87%)	
5 Doors Open	15	30	57	47 (83%)	49 (87%)	
6 Pull-Down 2	15	43	61	51 (84%)	53 (87%)	
All	**15**	**344**	**41**	**34 (83%)**	**36 (87%)**	
3 Pull-Down 1	5	124	53	44 (82%)	43 (81%)	
4 Steady State	5	180	19	16 (82%)	15 (81%)	
5 Doors Open	5	30	66	54 (81%)	55 (82%)	
6 Pull-Down 2	5	32	63	51 (81%)	52 (82%)	
All	**5**	**366**	**38**	**31 (82%)**	**31 (81%)**	
Unit 8: pre-2019						
3 Pull-Down 1	5	120	57	51 (91%)	44 (78%)	
4 Steady State	5	180	41	35 (87%)	33 (82%)	
5 Doors Open	5	30	52	47 (91%)	41 (78%)	
6 Pull-Down 2	5	22	45	41 (90%)	36 (80%)	
All	**5**	**352**	**47**	**42 (89%)**	**38 (80%)**	

Table 5. Frozen mode particle emissions results, post-2019 units

Phase	Ambient °C	Duration mins	PN rate x 10^{14} per hour	UPN rate x 10^{14} per hour	E6PN rate x 10^{14} per hour	>23PN rate x 10^{14} per hour
Unit 2: post-2019						
3 Pull-Down 1	15	107	41	35 (84%)	35 (84%)	37 (88%)
4 Steady State	15	180	16	14 (83%)	14 (85%)	14 (88%)
5 Doors Open	15	30	22	18 (81%)	19 (86%)	21 (89%)
6 Pull-Down 2	15	27	33	27 (84%)	28 (85%)	28 (88%)
All	**15**	**344**	**26**	**22 (84%)**	**22 (85%)**	**23 (88%)**
Unit 3: post-2019						
3 Pull-Down 1	15	86	41	35 (84%)	34 (84%)	36 (88%)
4 Steady State	15	180	14	11 (83%)	11 (85%)	12 (88%)
5 Doors Open	15	30	21	17 (80%)	18 (86%)	19 (89%)
6 Pull-Down 2	15	29	32	26 (82%)	27 (85%)	28 (89%)
All	**15**	**325**	**23**	**19 (83%)**	**20 (85%)**	**20 (88%)**
Unit 5: post-2019						
3 Pull-Down 1	15	80	42	39 (93%)	33 (79%)	35 (83%)
4 Steady State	15	180	14	13 (92%)	11 (79%)	11 (83%)
5 Doors Open	15	30	19	18 (91%)	15 (80%)	16 (83%)
6 Pull-Down 2	15	74	40	37 (91%)	32 (80%)	34 (84%)
All	**15**	**364**	**26**	**24 (92%)**	**21 (79%)**	**22 (83%)**
3 Pull-Down 1	5	52	40	38 (94%)	31 (77%)	33 (81%)
4 Steady State	5	180	15	14 (93%)	12 (77%)	12 (81%)
5 Doors Open	5	30	9	9 (93%)	7 (76%)	7 (80%)
6 Pull-Down 2	5	28	18	17 (92%)	14 (77%)	15 (81%)
All	**5**	**290**	**19**	**18 (93%)**	**15 (77%)**	**16 (81%)**

Phase	Ambient °C	Duration mins	PN rate x 10^{14} per hour	UPN rate x 10^{14} per hour	E6PN rate x 10^{14} per hour	>23PN rate x 10^{14} per hour
Unit 6: post-2019						
3 Pull-Down 1	30	327	120	92 (79%)	100 (89%)	110 (91%)
4 Steady State	30	180	68	54 (80%)	59 (87%)	60 (89%)
5 Doors Open	30	30	120	91 (75%)	110 (90%)	110 (91%)
6 Pull-Down 2	30	46	120	95 (79%)	110 (87%)	110 (89%)
All	**30**	**584**	**100**	**81 (79%)**	**90 (88%)**	**92 (90%)**
3 Pull-Down 1	15	123	120	100 (85%)	100 (84%)	110 (88%)
4 Steady State	15	180	51	44 (86%)	44 (86%)	46 (90%)
5 Doors Open	15	30	78	64 (82%)	68 (88%)	71 (91%)
6 Pull-Down 2	15	35	100	88 (86%)	90 (87%)	94 (91%)
All	**15**	**368**	**82**	**70 (85%)**	**70 (85%)**	**73 (89%)**
3 Pull-Down 1	5	111	120	68 (56%)	75 (62%)	72 (60%)
4 Steady State	5	180	47	27 (57%)	29 (61%)	28 (58%)
5 Doors Open	5	30	110	64 (58%)	66 (60%)	64 (58%)
6 Pull-Down 2	5	6	100	61 (58%)	63 (60%)	61 (58%)
All	**5**	**327**	**79**	**45 (57%)**	**48 (61%)**	**47 (59%)**

3.3 Multi-temperature mode results

This section presents the particle emissions results from all the three tests carried out under multi-temperature conditions (chilled and frozen load compartments operating).

Table 6 shows the total particle number emission production rates in each phase for the single, post-2019 unit tested under these conditions. Figures in brackets in the UPN, E6PN and >23PN columns represent those results as a percentage of the (all measured particles) PN production rate. Cells shaded in grey indicate PN rate results previously published.

Figure 3 summarises the (all phases) results at all three ambient temperatures (5, 15 and 30 °C).

Figure 3. PN rates, multi-temp tests at various ambient temperatures

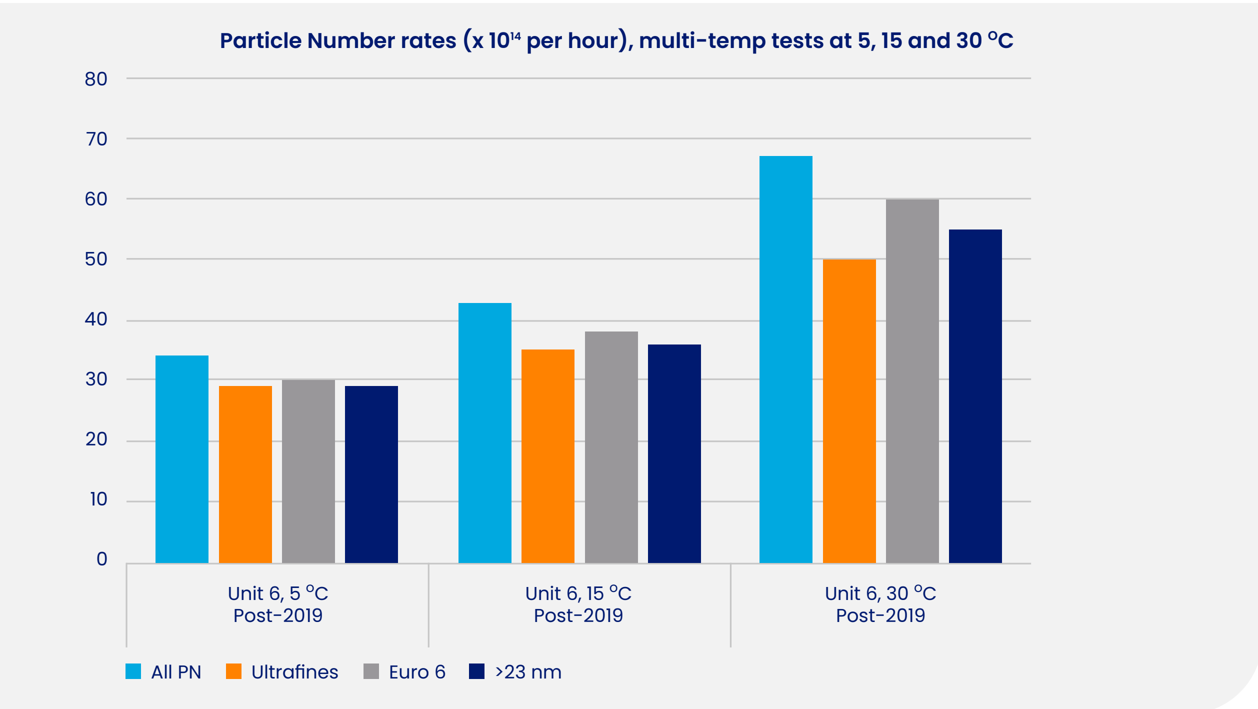


Table 6. Multi-temp mode particle emissions results

Phase	Ambient °C	Duration mins	PN rate x 10^{14} per hour	UPN rate x 10^{14} per hour	E6PN rate x 10^{14} per hour	>23PN rate x 10^{14} per hour
Unit 6: post-2019						
3 Pull-Down 1	30	256	84	64 (76%)	76 (91%)	70 (83%)
4 Steady State	30	180	40	31 (78%)	35 (87%)	32 (79%)
5 Doors Open	30	30	50	31 (62%)	46 (91%)	41 (82%)
6 Pull-Down 2	30	57	84	61 (72%)	76 (90%)	69 (82%)
All	**30**	**523**	**67**	**50 (75%)**	**60 (90%)**	**55 (82%)**
3 Pull-Down 1	15	73	77	62 (81%)	69 (90%)	65 (85%)
4 Steady State	15	180	23	19 (84%)	20 (87%)	19 (82%)
5 Doors Open	15	30	76	61 (81%)	67 (89%)	64 (84%)
6 Pull-Down 2	15	21	51	43 (85%)	44 (87%)	42 (82%)
All	**15**	**304**	**43**	**35 (82%)**	**38 (89%)**	**36 (84%)**
3 Pull-Down 1	5	40	74	61 (82%)	66 (90%)	64 (87%)
4 Steady State	5	180	19	16 (85%)	16 (86%)	16 (82%)
5 Doors Open	5	30	74	64 (86%)	64 (87%)	62 (84%)
6 Pull-Down 2	5	11	30	25 (84%)	26 (87%)	25 (84%)
All	**5**	**261**	**34**	**29 (84%)**	**30 (88%)**	**29 (84%)**

4. Ultrafine particle emissions discussion

A primary objective of acquiring the above new data was to be able to better characterise the overall particle emissions results, including generating data on exactly what proportion of the previously published numbers of particles being emitted had diameters no greater than 100 nm, commonly referred to as ultrafine particles.

The results indicate that this proportion was found to vary, in an overall range from 57-93%, with an average of 82%. All but a handful of tests produced ultrafine proportions in the range 75-90%.

No consistent patterns are evident from the data in terms of any differences in ultrafine percentages between pre and post-2019 units, nor any consistent effects from raising ambient temperature or between chilled, frozen and multi-temp modes. As noted in the February 2024 report, one of the post-2019 units tested (the only one tested in chilled, frozen and multi-temp modes) produced notably higher levels of PM and PN emissions than other units of similar age in directly comparable tests, but it is not possible to be certain as to the cause, e.g. whether by poor design or (perhaps more likely) some internal maintenance or fault condition.

It is thus reasonable to assume, with a high degree of confidence, that the great majority of particles emitted by diesel auxTRUs are ultrafines (PN0.1) and that only around 10-25% of the particles emitted are larger than 100 nm in diameter.

Note that particle mass (PM) measurements will tend to be dominated by these smaller numbers of larger particles – each doubling in particle diameter translates to something like an 8-fold increase in particle mass.

4.1 Comparisons to Euro VI HGV emissions discussion

A secondary objective from acquiring the new data was to provide for a more precise comparison with published Euro VI emissions data by aligning fully with Euro 6/VI particle number measurement protocols (23 nm roll-off) rather than simply estimating an equivalence using a 23 nm cut-off.

While there were found to be some small differences between the results from these two alternative PN measures, both produced an overall average of 82% coverage, compared to the full PN results (of all particles 5-1000 nm). The difference between these metrics within any one individual test did not exceed 9% and was less than ±5% in all but a few cases.

It is thus possible to conclude that the comparisons with Euro VI emissions data published in the February 2024 report (based on equivalence estimates) remain valid, with no evidence found here to suggest more closely aligning with regulatory measurement protocols for particle number would have altered its key findings.

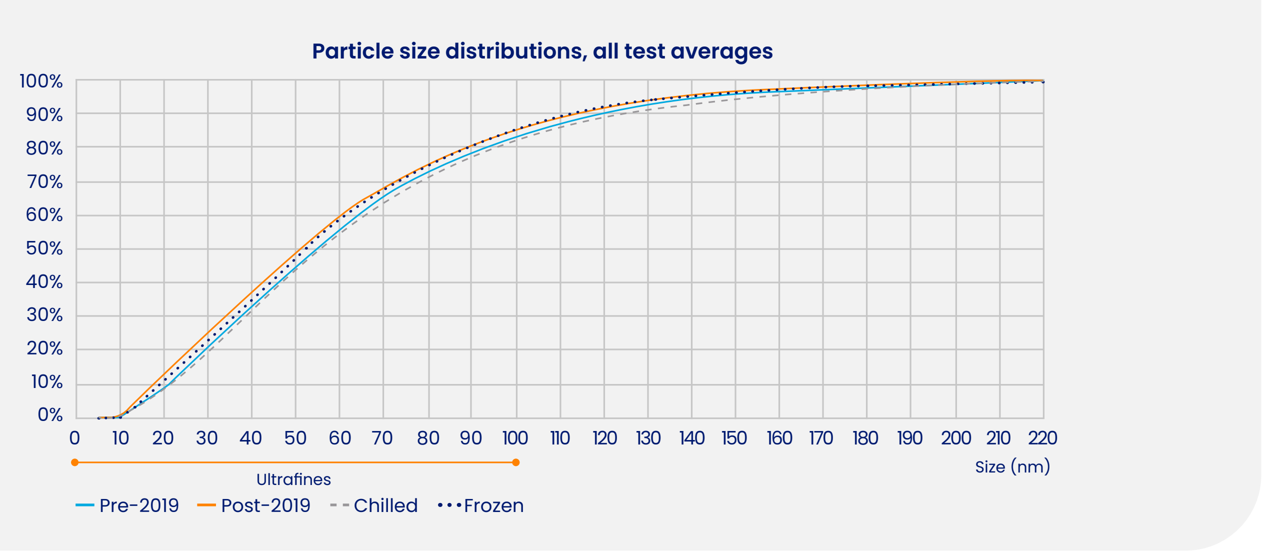
Note that for PN, these comparisons are based on the numbers of particles exceeding the Euro 6/VI roll-off diameter of 23 nm. Since they are not measured as part of the Euro 6/VI type approval procedures, comparisons based on smaller particle sizes (added into the overall picture by this report) are not possible.

4.2 Particle size distribution discussion

As the preceding sections describe, the measured proportion of ultrafine emissions and the measured proportion of particles that meet the Euro VI size specifications were both found, by coincidence, to be 82% on average across all the tests. This suggests that around 18% of the particles emitted typically by auxTRUs are smaller than 23 nm or so in diameter and a further 18% are larger than 100 nm, leaving the remaining majority (64%) meeting both the Euro VI measurement specification and being ultrafine particles.

Very few differences were found between the size distributions of emitted particles when comparing between pre-2019 and post-2019 units, or between chilled and frozen-mode tests, as illustrated by Figure 4. Very few particles larger than 250 nm in diameter were emitted, across all the tests carried out (98-100% were smaller than 250 nm).

Figure 4. Particle size distributions



5. Estimating environmental impacts of HGV auxTRUs

The following sections describe how the new data on PN emissions effects the estimates of the likely contribution to emissions of air pollutants from auxTRU published in the February 2024 report. As a reminder, the basic approach to modelling these overall impacts involves the equation:

I = N x H x R

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

The February 2024 report based most of its overall particle number estimates on results from testing in 2023 that only counted particles of 23 nm in diameter or greater (to be equivalent to Euro 6 measurement protocols). The new data has generated results for all particles in the size range 5- 1000 nm, allowing the original estimates to be revised upwards (by about 10% on average). The new data also allows for the first time, estimation of the total number of ultrafine particles emitted from diesel auxTRUs in the UK (PN0.1). The new PN analyses do not in any way affect the original estimates for NOx, fuel consumption or GHG emissions nor, for the reasons explained earlier, PM estimates.

5.1 Particle number emission production rates

Table 7 presents the modelled hourly rates, at three ambient temperatures, based on the test results. The three PN rates quoted relate to all particles, ultrafine particles and Euro 6-specification particles.

Table 7. Modelled average particle number production rates (x 10^{14} per hour)

	5 °C			15 °C			30 °C		
Chilled/Frozen/Multi-Temp	C	F	MT	C	F	MT	C	F	MT
Pre-2019 units									
All particles (5-1000 nm)	25	31	28	30	36	33	44	50	47
Ultrafine particles (up to 100 nm)	21	25	23	25	30	27	36	41	39
Euro 6 particles (23 nm roll-off)	21	25	23	25	30	27	36	41	39
Post-2019 units									
All particles (5-1000 nm)	8	31	16	13	36	21	27	50	35
Ultrafine particles (up to 100 nm)	7	25	13	11	30	17	22	41	29
Euro 6 particles (23 nm roll-off)	7	25	13	11	30	17	22	41	29

5.2 New and revised total auxTRU emissions estimates for UK

Combining the above new "R" figures with the "N" and "H" numbers used in the February 2024 report allows for new and revised low, high and central scenario estimates to be made for the particle number emissions impacts of diesel auxTRUs in the UK. Table 8 shows the results of these calculations. The figures for ultrafines and Euro 6 particles are identical (both assumed to be 82% of the all particles numbers), so have been combined into one number in the table for brevity.

Table 8. AuxTRU particle number emissions estimates for the UK (x 10^{21} per year)

	Pre-2019 units	Post-2019 units	All diesel auxTRU
Low numbers and low hours scenario (lower bound estimates)			
All particles (5-1000 nm)	120	78	198
Ultrafine-only and Euro 6-only particles	98	64	162
High numbers and high hours scenario (upper bound estimates)			
All particles (5-1000 nm)	330	215	544
Ultrafine-only and Euro 6-only particles	270	176	446
Central scenario (central estimate)			
All particles (5-1000 nm)	214	139	353
Ultrafine-only and Euro 6-only particles	175	114	289

6. Results of diesel refrigerated van tests

The following sections present the results of the programme of tests on two conventional, diesel- engine refrigerated vans used for home-delivery purposes by UK supermarket chains, with the fridge units powered either by an alternator or via a power take-off (PTO).

The testing was carried out to provide an initial indication of how such vans may impact the environment, in direct comparison to otherwise identical but unrefrigerated vans. It is therefore the differences in measured emissions production and fuel consumption rates between the fridge-on and fridge-off tests in otherwise identical conditions of ambient temperature and warm engine start that are of interest.

The following results tables thus show these differences, using the convention that any positive differences indicate the emissions/fuel consumption in the fridge-on condition were higher than with the fridge-off. Negative numbers are used if the emissions were lower with the fridge-on. Results are presented for CO_2, NOx emissions and particle emissions.

With just one of each fridge type (alternator and PTO-driven) being tested, direct comparisons between the two may not be properly representative of the wider populations. In the tests, Vehicle 2's fridge (PTO-driven) struggled to achieve the target compartment temperatures, especially with a high ambient temperature of 30 °C. The reasons for this are not known but some possible explanations include:

- High internal heat transfer from the ambient compartment to the chilled and frozen compartments
- Poor external insulation
- Poor test set-up, e.g. lack of air flow over unit
- Poor fridge efficiency, e.g. due to low refrigerant levels
- Under-powered fridge

6.1 CO_2 emissions and fuel consumption impacts

Table 9 summarises the impacts of fridge-on operation, compared to fridge-off, for tailpipe CO_2 emissions. Both vehicles showed generally lower impacts of fridge operation at higher average vehicle speeds. Vehicle 1 showed consistently higher emissions at the higher ambient temperature, but this situation was reversed for Vehicle 2 (fridge impacts were lower at the higher ambient temperature). It is thought likely that its fridge was operating at or near to its maximum capacity at both ambient temperatures, so this apparent reduction in CO_2 impacts should not be interpreted as suggesting that raising the ambient temperature somehow reduced the fridge's fuel demand. This is supported by data from the fridge-off tests which showed the vehicle's CO_2 emissions increasing with ambient temperature.

Table 9. CO_2 impacts of fridge operation

Chamber Temp	In-Vehicle Temps (fridge-on) °C		CO_2 impacts by test phase (average speed), g/km				
°C	Chilled	Frozen	Very Low	Low	Medium	High	Whole Cycle
Vehicle 1: Alternator driven fridge unit							
15	+10	-15	34	27	13	9	16
30	?	?	37	45	20	14	22
Vehicle 2: PTO driven fridge unit							
15	+4	-9	98	98	43	29	51
30	+9	+4	60	72	30	18	33

Averaging across the four tests and compensating for the poor performance of Vehicle 2's fridge at high ambient temperatures, the vans emitted typically about 20-40 g/km more CO_2 with the fridge-on than with the fridge-off. This is equivalent to about 0.75-1.5 litres per 100 km additional fuel consumption (8-15% increase).

6.2 NOx emissions impacts

Table 10 shows the NOx impacts of fridge operation. In some cases, NOx emissions were reduced by use of the fridge. This is likely to be due to the fridge's additional energy demand and fuel consumption leading to higher exhaust temperatures, thus improving the effectiveness of the vehicles' Euro 6 aftertreatment systems. At higher vehicle speeds, this effect would be reduced and this, too, is reflected in the results. Overall, averaging across the whole test cycle for two fridges and two ambient temperatures, NOx emissions impacts were negligible.

Table 10. NOx impacts of fridge operation

Chamber Temp	In-Vehicle Temps (fridge-on) °C		NOx impacts by test phase (average speed), mg/km				
°C	Chilled	Frozen	Very Low	Low	Medium	High	Whole Cycle
Vehicle 1: Alternator driven fridge unit							
15	+10	-15	-17	0	11	0	-1
30	?	?	67	22	-8	4	14
Vehicle 2: PTO driven fridge unit							
15	+4	-9	-15	-46	-16	9	-6
30	+9	+4	-19	-37	0	24	5

6.3 Particle emission impacts

Table 11 shows the impacts of fridge operation on the number of particles emitted. Only Vehicle 2 results are shown because Vehicle 1 was, soon after testing had been completed, found to have a faulty Diesel Particulate Filter (DPF) system. When tested, this vehicle did produce unusually high levels of particle emissions, which indicated a fault was likely. Vehicle 2's results were in line with what would normally be expected of Euro 6 vans. For this vehicle, PN emissions reduced on average by about 0.5 x 10^8 (about 20%). There was found to be negligible overall impact on particle mass (PM) emissions.

Table 11. Particle emission impacts of fridge operation

Chamber Temp	In-Vehicle Temps (fridge-on) °C		PN impacts by test phase (average speed), # x 10^8/km				
°C	Chilled	Frozen	Very Low	Low	Medium	High	Whole Cycle
Vehicle 2: PTO driven fridge unit							
15	+4	-9	-0.4	0.1	0.1	-0.3	-0.2
30	+9	+4	-1.1	-1.3	-0.8	-0.3	-0.7

Given the apparent DPF issues with Vehicle 1, it is impossible to estimate with any confidence what a realistic and representative average value for PN impacts of refrigerated vans might be. Further testing may be needed to confirm the true picture, but on the evidence currently available, we think it likely that a refrigerated van with a properly functioning Euro 6 DPF system would be unlikely to increase PN emissions (when fridge-on versus fridge-off) and may well actually reduce them slightly. As with the NOx results, this would be consistent with fridge operation causing slightly higher exhaust system temperatures and so enhancing aftertreatment system effectiveness.

7. Estimating environmental impacts of diesel refrigerated vans

Following a similar approach to that used for estimating HGV auxTRU impacts, the above test results can be combined with estimates relating to the numbers and typical usage of refrigerated vans to derive overall UK environmental impact estimates. With emissions impacts measured in per km terms, however, the equation for doing so is amended to:

I = N x D x R

- I is the annual total impact being estimated,
- N is the number of refrigerated vans in use,
- D is the distance (km) driven in fridge-on conditions per annum and
- R the relevant annual average per km fuel consumption or emission production rate (from the test programmes described above).

In the same way as the HGV auxTRU estimates above do not include emissions or fuel use from the HGV itself, the van estimates only include the impacts of the fridge. The "R" values are as presented above, referring only to the change in emissions when the fridge is on compared to when it is off.

Official statistics on the numbers of refrigerated vans in the UK are not collected. In 2021, the Cold Chain Federation estimated[5] the UK population of such vehicles to be around 25,000 while Cenex suggested[6] the total number of refrigerated vehicles in the UK is around 100,000 and cited a 2015 report that estimated the figure at 84,000. Zemo's estimates of the numbers of refrigerated HGVs (with and without auxTRU) lie in the range 55,000 - 65,000. Combining these various estimates further supports the view that there are around 25,000-35,000 refrigerated vans in use in the UK.

The market survey carried out in an earlier phase of this research, combined with discussions with various industry expert stakeholders, suggest that refrigerated vans typically cover from around 100 km per day in city-centre operations up to around 350 km per day in more rural locations. Using 150 – 250 km as a reasonable central range and assuming 6 days per week operation, this implies typical annual distances covered of around 45,000 – 75,000 km.

The emissions test results found that the refrigerated vans emitted about 20-40 g/km more CO_2 than when the fridges were switched off, equivalent to about 0.75 – 1.5 l/100 km of additional fuel consumption. NOx emissions impacts were found to be sufficiently small as to be negligible. Particle emission (PM and PN) impacts could not be quantified with a high degree of confidence in the test programme but, pending any evidence to the contrary, are also thought likely to be negligible.

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

[6] Refrigerated Transport Insights: A ZERO White Paper, Cenex, 2021.

Table 12. Estimates of UK CO_2 and fuel consumption impacts of refrigerated vans

	Low range	Central estimate	High range
Number of refrigerated vans	25,000	30,000	35,000
Annual km driven with fridge-on (per van)	45,000	60,000	75,000
CO_2 emission impacts per km (g)	20	30	40
Fuel consumption impacts per 100 km (litres)	0.75	1.10	1.50
Total CO_2 impact (kilo-tonnes)	**23**	**54**	**105**
Total fuel consumption impacts (million litres)	**8**	**20**	**39**

Table 12 provides the resultant estimates for the UK refrigerated van population. The central estimate is that such vans are emit an additional 54 kt of tailpipe CO_2 emissions, relative to those vans operating without a fridge unit, and consume around 20 million litres of extra fuel. For context, this equates to about 0.3% of the 7,400 million litres of fuel burnt annually by vans across the UK.

8. Overall discussion on the combined environmental impacts of diesel refrigerated vans and HGV auxTRUs

With the above-described refrigerated van test results and the updated HGV auxTRU emissions, we can now start to fully characterise the environmental impacts of the full UK cold chain transport sector assessed to date. The following sections provide these characterisations, firstly at an individual vehicle level and then at an overall UK fleet level. Note that the UK fleet of rigid (and some articulated) refrigerated HGVs equipped with TRUs powered by the vehicles' main propulsion engine (akin to the refrigerated vans) has not yet been assessed and is excluded from the following preliminary analyses.

8.1 Environmental impacts of individual refrigerated vehicles

Table 13 and Table 14 show the indicated typical fuel consumption impacts and tailpipe GHG, NOx and particle emissions impacts, based on the test results described in this and earlier Zemo reports, of a large, single-deck articulated refrigerated HGV (with pre-2019 or post-2019 diesel auxTRU) and a refrigerated diesel van (with its TRU powered by the main propulsion engine). Each vehicle is assumed to be carrying a multi-temperature load at 15 °C ambient temperature. To reflect the very different uses and tasks performed by each vehicle, within the overall cold chain transport system, the results are also presented in normalised format based on the overall volume of refrigerated load space available in each (assumed to be 87 m³ for artics and 5 m³ for vans).

The tables also separately list the emissions associated with driving the vehicle from those arising directly from the refrigeration task. To calculate the driving emissions for the refrigerated HGV, which have not been measured as part of this Zemo testing programme, other Zemo test programme sources have been used, with an assumed average driving speed of 30 km/h on mostly urban and/or city-centre roads. Euro 6/VI engines are assumed for the main propulsion of each vehicle.
The PN estimates also include provision for the smallest particles (outside of the 23 nm roll-off function), excluded from Zemo's standard (Euro 6/VI) test protocols.

Table 13. Summary of environmental impacts – refrigerated HGV

Impact type	Units	Driving	With pre- 2019 AuxTRU	With post- 2019 AuxTRU	Total (pre 2019)	Total (post-2019)	% added (pre- 2019)	% added (post-2019)
Fuel consumption	l/hr	16.6	2.0	1.7	18.6	18.3	12%	10%
	l/hr/m³	0.2	0.02	0.02	0.21	0.21		
CO_2 emissions	Kg/hr	43.5	5.0	4.3	48.5	47.8	11%	10%
	Kg/hr/m³	0.50	0.06	0.05	0.56	0.55		
NOx emissions	g/hr	11	42	29	53	40	400%	276%
	g/hr/m³	0.12	0.48	0.33	0.60	0.45		
$PM_{2.5}$ emissions	g/hr	0.3	0.9	0.7	1.2	1.0	300%	233%
	g/hr/m³	0.003	0.010	0.008	0.014	0.011		
PN emissions	#x10^{11}/hr	100	33,000	21,000	33,100	21,100	33,000%	21,000%
	#x10^{11}/hr/m³	1	379	241	380	243		

While fuel consumption and CO_2 emissions impacts are broadly similar proportionately, at about 10-13% added in each case (reflecting the additional energy required for refrigeration), these tables show starkly the differences in pollutant emissions impacts between a diesel auxTRU (pre or post- 2019) and a van TRU powered by the van's own Euro 6/VI main engine.

Table 14. Summary of environmental impacts – refrigerated van

Impact type	Units	Driving	TRU	Total	% added
Fuel consumption	l/hr	3.1	0.4	3.5	13%
	l/hr/m³	0.62	0.08	0.70	
CO_2 emissions	Kg/hr	7.8	1.0	8.8	13%
	Kg/hr/m³	1.55	0.20	1.76	
NOx emissions	g/hr	0.9	±0	0.9	±0%
	g/hr/m³	0.19	±0	0.19	
$PM_{2.5}$ emissions	g/hr	0.007	±0	0.007	±0%
	g/hr/m³	0.001	±0	0.001	
PN emissions	#x10^{11}/hr	0.07	±0	0.07	±0%
	#x10^{11}/hr/m³	0.01	±0	0.01	

8.2 Environmental impacts of the UK refrigerated vehicle fleet

Table 15 combines our central estimates of the overall environmental impacts of the UK's diesel auxTRUs (50:50 split between pre-2019 and post-2019 assumed), the tractor units pulling those refrigerated trailers (all assumed to be Euro VI) and the UK's fleet of refrigerated vans (also all assumed to be Euro 6/VI). Driving emissions for the refrigerated HGVs have been estimated based on the results of Zemo HGV tests across a mix of long-haul, regional, urban and city-centre drive cycles and an assumed average annual mileage of 100,000 km per HGV (known to be broadly representative of the UK average for articulated HGVs).

Table 15. UK fleet central estimates for all refrigerated vans and HGVs with diesel auxTRUs

	Refrigerated HGVs		Refrigerated Vans		All refrigerated vehicles		Total impacts	% from refrigeration
	Driving	AuxTRUs	Driving	AuxTRUs	Driving	AuxTRUs		
Fuel (Ml)	1,700	235	186	20	1,885	255	2,140	12%
CO_2 (ktonnes)	4,534	590	466	54	5,000	644	5,644	11%
NOx (tonnes)	777	4,400	56	0	833	4,400	5,233	84%
$PM_{2.5}$ (tonnes)	43.5	126	0.4	0	44.0	126	170	74%
PN (#x10^{21})	1.5	353	0.0003	0	1.5	353	355	99.6%

This table further demonstrates how overall pollutant emissions of NOx and particulates are dominated by the HGV auxTRU sector, with Euro 6/VI van engines (and their aftertreatment systems) being much more effective at emissions control than the unfiltered and less stringently regulated auxTRUs.

Normalising by fuel consumption, HGV Euro VI engines in combination with auxTRUs produce about:

- 2,700 mg of NOx per litre of fuel burnt, compared to 270 mg/l for a refrigerated Euro 6/VI van.
- 88 mg of $PM_{2.5}$ per litre of fuel burnt, compared to 2 mg/l for a refrigerated Euro 6/VI van.
- 1,800 x 10^{11} particles per litre of fuel burnt, compared to 0.02 x 10^{11} for a refrigerated Euro 6/VI van.

9. Conclusions

9.1 New auxTRU data

New data from the programme of baseline testing of diesel auxTRU systems has been analysed to further strengthen the evidence base (specifically in relation to particle number emissions) 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.

No consistent patterns are evident from the data in terms of any differences in ultrafine percentages between pre and post-2019 units, nor any consistent effects from raising ambient temperature or between chilled, frozen and multi-temp modes.

It is reasonable to assume, with a high degree of confidence, that the great majority (range 75-90%) of particles emitted by diesel auxTRUs would likely be of 100 nm in diameter or less and therefore fall into the definition of ultrafine particles, those of greatest concern from a public health perspective.

A secondary objective from acquiring the new data was to provide for a more precise comparison with published Euro VI emissions data by aligning fully with Euro 6/VI particle number measurement protocols (23 nm roll-off) rather than simply estimating an equivalence using a 23 nm cut-off.

While there were found to be some small differences between the results from these two alternative PN measures, both produced an overall average of 82% coverage, compared to the full PN results (of all particles 5-1000 nm).

It is thus possible to conclude that the comparisons with Euro VI emissions data published in the February 2024 report (based on equivalence estimates) remain valid, with no evidence found here to suggest more closely aligning with regulatory measurement protocols for particle number would have altered its key findings.

These new data allow for our earlier overall estimates of particle number (PN) emissions from UK auxTRU to be revised upwards, from a central estimate of 330 x 10^{21} to 353 x 10^{21} (range 198-554 x 10^{21}). This upward revision is to account for some ultrafine particles below 23 nm in aerodynamic diameter, that were excluded from some of the earlier test results (to reflect standard Euro 6/VI measurement protocols).

9.2 Diesel refrigerated vans

A short programme of tests has assessed the emissions and fuel consumption impacts of two diesel-powered refrigerated vans. The results indicate that the fridge units fitted to such vehicles (powered via the van's main Euro 6 propulsion engine) consume about 0.75-1.5 litres of fuel per 100 km driven and generate an extra 20-40 g/km of tailpipe CO_2 emissions. The results further indicate that such fridge units have minimal impact on overall NOx emissions and are unlikely to significantly and adversely impact particulate emissions.

Combining the test results with estimates of the numbers of refrigerated vans in use in the UK and their typical annual mileages has generated a central estimate that such vehicles emit an additional 54 kt of tailpipe CO_2 emissions, relative to those vans operating without a fridge unit, and consume around 20 million litres of extra fuel (about 0.3% of all fuel burnt annually by vans).

9.3 Additional UK fleet environmental impact estimates

A preliminary characterisation of the environmental impacts of the UK cold chain transport sector (covering refrigerated vans and articulated HGVs with diesel auxTRUs only) has been made, utilising the results of Zemo's auxTRU and refrigerated van test programmes alongside wider HGV testing data. The results further demonstrate how overall cold chain transport pollutant emissions of NOx and particulates are dominated by the HGV auxTRU sector, with Euro 6/VI van engines (and their aftertreatment systems) being much more effective at emissions control than the unfiltered and less stringently regulated auxTRUs.

Zemo Partnership
Accelerating Transport to Zero Emissions

Zemo Partnership
3 Birdcage Walk, London, SW1H 9JJ

T: +44 (0)20 3832 6070
E: Hello@Zemo.org.uk
Visit: Zemo.org.uk

@Zemo_org
Zemo
Zemo YouTube Channel