LowCVP
Low Carbon Vehicle Partnership

Innovate UK

Report

Development of Emissions Testing Procedures for Transport Refrigeration Units (TRUs)

The results of an Innovate UK funded project to develop a robust, representative and cost-effective methodology for measuring the energy consumption and emissions performance of refrigerated commercial vehicles.

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The LowCVP, which was established in 2003, is a public-private partnership working to accelerate a sustainable shift to lower carbon vehicles and fuels and create opportunities for UK business. Over 200 organisations are engaged from diverse backgrounds including automotive and fuel supply chains, vehicle users, academics, environment groups and others. LowCVP members have the opportunity to:

- Connect : With privileged access to information, you'll gain insight into low carbon vehicle policy development and into the policy process.
- Collaborate : You'll benefit from many opportunities to work - and network - with key UK and EU government, industry, NGO and other stakeholders.
- Influence : You'll be able to initiate proposals and help to shape future low carbon vehicle policy, programmes and regulations.

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Executive Summary

Refrigerated freight delivery vehicles are a key part of modern food distribution systems. Temperature controlled transport (TCT) is crucial to maintaining food safety standards and protecting public health. Poor air quality, however, is harmful to public health, being linked to a wide variety of cardio, respiratory and other health problems and tens of thousands of premature deaths each year in the UK. Tailpipe pollutant emissions from heavy vehicles are falling rapidly as the latest Euro VI regulations take effect and newer vehicles meeting those standards replace older, more polluting vehicles. In this context, the focus of emissions reduction efforts is starting to shift 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 fitted to many urban food delivery vehicles.

An initial piece of work led by Cenex (for Transport for London's LoCITY programme), supported by the LowCVP and Brunel University, attempted to quantify the scale of the emissions challenge from Transport Refrigeration Units (TRUs) in London[1]. Amongst that study's findings was the following conclusion:

> *"There is a clear need to develop an emissions evidence base from real-world emissions testing and develop an applicable emissions factor [for auxiliary (aux)TRUs]."*

With this identified need to improve the TRU emissions evidence base for policy makers and operators in London and the rest of the UK, the LowCVP was asked by Innovate UK to begin the process of developing and validating an emissions test protocol for conventional and alternative TRU technologies. It should be emphasised that this project was not intended (or funded) to fully develop and validate a comprehensive set of TRU test methods. Its aim was instead to make some initial investigations and take the first steps towards that wider, longer-term objective.

It was anticipated that separate protocols would be needed for auxiliary TRUs (auxTRUs) and direct-drive TRUs and the project aimed to ensure close alignment and comparability between the two as far as practicable.

A literature review identified some internationally recognized test methods of relevance to TRUs, but none were found to be wholly suited to the emissions testing of units fitted to vehicles and operating under representative conditions.

The main objectives of the pilot testing carried out as part of this project were to put the test procedures hitherto suggested by the research into practice, assess their suitability and identify potential further refinements. It was also decided that the emissions of nitrogen oxides and particulates should be measured to generate some preliminary evidence regarding in-service TRU emissions; a key evidence gap identified by the earlier, Cenex-led research.

The pilot test programme involved two modes:

- Chilled (setpoint 2 °C)
- Frozen (setpoint -20 °C)

Five phases were used for each mode:

1. Pull-down (reduce internal temperature of) empty trailer from 18°C to setpoint
2. Trailer is removed from test chamber and loaded with pre-chilled, water-filled intermediate bulk containers (IBCs) and empty cardboard boxes
3. Trailer is installed into chamber again and TRU pulls down again to setpoint
4. Trailer is run in continuous mode or stop/start mode for three hours at setpoint
5. 15-minute door opening followed by closing and pulling down again towards setpoint

At 15 kW (0 °C, 30 °C ambient) and with a 1.5 l engine, the auxTRU tested is slightly smaller and likely to be more fuel efficient, than some larger units (e.g. 18 kW and 2 l engine). The target average fuel consumption rate suggested by stakeholders of 2.5 litres per hour applies to these larger units, so a more appropriate target figure for the test unit would be 2.0 l/h.

Using the Cenex-report figures, over a typical four hour delivery cycle (that study suggests that artics typically make six deliveries per 24-hour period) from arriving at one site to the next, the TRU (if it is left running while the doors are open) would thus be in pull down mode for about two hours (during the delivery, with the doors open most of the time, and when pulling-down again for the first hour or so of the journey to the next delivery site, and in steady state mode for the remaining two hours (final stages of journey to next delivery).

Using the pull-down rates measured from both the loaded tests of about 2.7 l/h on average, and the average steady state consumption of about 1.5 l/h, the overall average on this basis would be around 2.1 l/h. This is very close to the target value of 2.0 l/h, suggesting that this simple method may well be close enough to be representative of typical TRU usage, and could potentially (subject to further testing and expert stakeholder dialogue) be used as an initial basis for a standard test protocol.

> *Average in-service fuel rate = Mean of measured loaded pull-down and steady state rates*

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

Executive Summary (continued)

If, when driven, it is assumed that TCT vehicles drive in accordance with the CVRAS HGV cycle (a test cycle representative of typical UK freight delivery vehicle operations, developed by LowCVP for the Clean Vehicle Retrofit Accreditation Scheme), which has an average speed of around 30 km/h, then the likely average NOx emissions from auxTRUs, calculated in a similar way to the fuel consumption model but considering only the driving time, and based on the pilot testing results, can be estimated to be roughly 1.6 g/km. On a Euro VI diesel HGV this would be likely to have the effect of tripling or quadrupling its overall NOx emissions, whereas on a Euro V vehicle it would add only around 10%. Particulate mass emissions would be around 0.06 g/km, some 6 times higher than a typical Euro VI HGV and particle number would be around 1.2×10^{14}per km, which is equivalent to at least 200 Euro VI HGVs. These findings indicate that emissions from auxTRUs are very likely to remain an important source of pollution in urban areas unless alternative technologies and solutions are deployed. They also seem to vindicate the need for a comprehensive, robust and representative set of test protocols to be developed, building on the initial proposals made by this study.

The net result of the literature review, expert stakeholder engagement and pilot testing of an auxTRU is that an initial test protocol has been developed and, to the extent possible within the limitations of this preliminary study, validated against average in-service conditions.

A more detailed equivalent test protocol, applicable to vehicles with direct-drive TRUs (and involving an appropriate mix of pull down and steady state operation of the TRU) has been proposed and a series of recommendations made for further work to validate it and use it to evaluate the emissions of various conventional and alternative TRU technologies.

1 Introduction

1.1 Background

Refrigerated freight delivery vehicles are a key part of modern food distribution systems. Temperature controlled transport (TCT) is crucial to maintaining food safety standards and protecting public health. Poor air quality, however, is harmful to public health, being linked to a wide variety of cardio, respiratory and other health problems and tens of thousands of premature deaths each year in the UK. Tailpipe pollutant emissions from heavy vehicles are falling rapidly as the latest Euro VI regulations take effect and newer vehicles meeting those standards replace older, more polluting vehicles. In this context, the focus of emissions reduction efforts is starting to shift 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 fitted to many urban food delivery vehicles.

An initial piece of work led by Cenex (for Transport for London's LoCITY programme), supported by the LowCVP and Brunel University, attempted to quantify the scale of the emissions challenge from Transport Refrigeration Units (TRUs) in London[2]. Amongst that study's findings was the following conclusion:

> *"There is a clear need to develop an emissions evidence base from real-world emissions testing and develop an applicable emissions factor [for auxiliary (aux)TRUs]."*

With this identified need to improve the TRU emissions evidence base for policy makers and operators in London and the rest of the UK, the LowCVP was asked by Innovate UK to begin the process of developing and validating an emissions test protocol for conventional and alternative TRU technologies. It should be emphasised that this project was not intended (or funded) to fully develop and validate a comprehensive set of TRU test methods. Its aim was instead to make some initial investigations and take the first steps towards that wider, longer-term objective.

1.2 Objectives

The stated objectives of this project were:

- To review existing TRU test approaches, assess their applicability and feasibility for whole vehicle tests, and propose a robust, representative and cost-effective methodology.
- To build upon the findings of the Cenex/LoCITY report, consult with key stakeholders in the process and make use of their input.
- To trial/validate the proposed methodology through pilot testing of at least one auxTRU.
- To scope out the most important next steps needed as part of any follow-on activity; e.g. to finalize the test protocol and use it to baseline the (GHG and AQ) emissions performance of current, conventional TRUs and assess the emissions-saving potential of new and alternative technologies.

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

Furthermore, it was anticipated that separate protocols would be needed for auxTRUs and direct-drive TRUs, but the project aimed to ensure close alignment and comparability between the two as far as practicable, particularly in drive/duty cycles. To be representative of real-world conditions, it was also recognized that the procedures would ultimately need to be able to cover both single and multi-temperature units (frozen, chilled and controlled ambient), fitted to any size of commercial vehicle, including vans.

1.3 Methodology

The project was taken forward in five main phases, over a period of around six months:

- **Phase 1 - Evidence gathering and preliminary ideas development.** This included a review of internationally recognised test methodologies of relevance, including the European NRMM (non-road mobile machinery) regulations, the ATP standards (an agreement on the International Carriage of Perishable Foodstuffs and on the special equipment to be used for such carriage), and the American AHRI (Air-Conditioning, Heating & Refrigeration Institute) standard for the performance rating of TRUs. These methodologies, and others identified during the research, were evaluated for their suitability for whole vehicle TRU testing and emissions measurement and from them an initial set of proposals developed.
- **Phase 2 - Hardware assessment.** This was an initial hardware familiarization exercise for LowCVP to develop its understanding of how TRUs operate, their performance and capabilities, focussing particularly on energy use and how it varies according to factors such as ambient temperature, door openings etc, facilitating subsequent wider engagement with the industry.
- **Phase 3 - Refinement of ideas with key expert stakeholders.** This further developed and refined the preliminary ideas, using the experience and expertise of key individuals and LowCVP member organisations. This was achieved via a dedicated expert workshop and further engagement via email/phone, with broad, cross-sector input from operators, technology developers, researchers, policy makers and NGOs. At the end of this phase, an initial draft test methodology and a short, pilot test programme to assess/validate it had been agreed.
- **Phase 4 - Pilot testing and validation.** Sufficient resources were allocated to pilot test one auxiliary TRU, fitted to an HGV, in accordance with the proposed methodology and to either validate it or identify areas for its further refinement. This testing was on a conventional, diesel auxTRU, so that the results could also be used to start to baseline the emissions performance of current technologies (a key evidence gap identified by the Cenex/LoCITY work).
- **Phase 5 - Reporting and next steps planning.** This stage brought together, in the form of this report, the ideas, evidence and results gathered into a consensus position and set of initial proposals for a TRU emissions testing protocol. As well as highlighting any remaining gaps in the evidence base or proposals, it also makes recommendations as to the next steps needed in any follow-on research, particularly the gathering of baseline performance data from the current TRU fleet and quantifying the emissions saving potential of the alternative technologies available.

1.4 Report Structure

This report provides the findings/conclusions of phases one, two and three together in the following Chapter (Two). This is followed (Chapter Three) by a description of the pilot testing and its results (phase four). The report ends with a Chapter (Four) summarizing the overall conclusions of this project and setting out LowCVP's recommended next steps (phase five).

2 Development of pilot test protocol

2.1 Literature review

The review identified some internationally recognized test methods of relevance to TRUs, but none were found to be wholly suited to the emissions testing of units fitted to vehicles and operating under representative conditions.

The following standards were reviewed:

- EU Non-Road Mobile Machinery (NRMM) Regulations 2016/1628 & 2017/654
- ANSI/AHRI Standard 1111: Performance Rating of Mechanical TRUs
- ATP Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be used for such Carriage

The NRMM regulations currently apply only to engines with maximum net power in excess of 19 kW, which means most if not all TRUs are exempt. From January 2019, however, all engines will be in scope, meaning auxTRUs placed on the European market after that date will have to meet certain emissions requirements. The assessment of those emissions for NRMM, however, is limited to an engine only test (i.e. irrespective of the application of that engine) and involves steady state testing over a range of fixed combinations of engine speed and torque, with the results weighted to come up with overall emissions values in g/kWh. Without a direct link to the end-use application of the engine, the NRMM Regulation's test methods are thus useful in setting overall limits on emissions performance whenever the engine is running but cannot provide meaningful in-service emissions data. They would also, of course, be irrelevant to the assessment of TRUs powered directly by the vehicle's engine.

ANSI/AHRI 1111 was developed by the Air-Conditioning, Heating & Refrigeration Institute (AHRI) and issued/approved by the American National Standards Institute (ANSI) in October 2013. It involves testing under steady state conditions to ascertain the Net Refrigerating Capacity of the TRU (in W). There is no measurement of emissions and no quantification of performance under anything other than fixed, steady state conditions. The procedures also rely on the use of calibrated calorimeter boxes, rather than fitting the TRUs to a vehicle.

The agreement on the International Carriage of Perishable Foodstuffs and on the special equipment to be used for such carriage, known as the ATP agreement (after its French initials) was drawn up by the United Nations Economic Committee for Europe in 1970-71. ATP provides a multilateral agreement between Signatory Countries (Contracting Parties) for overland cross-border carriage of perishable foodstuffs, facilitating international traffic and trade by setting common standards. Amongst its requirements, ATP defines a series of tests both to ensure TRUs meet the standards required of them and that the insulated boxes to which they are fitted, and in which the foodstuffs are to be transported, are fit for the purpose. The TRU tests are very similar to the AHRI Standard in that they assess only the overall cooling capacity and involve no measurement of emissions. They do, however, allow for the testing of whole vehicles and include the measurement of fuel consumption, though this is only under full load conditions. The tests to measure the insulation performance of the load box are, however, of some potential relevance, as data derived by that method could be used to normalize between different vehicles (with different load box characteristics) so that the results from the TRUs fitted to each vehicle can be based on those TRUs having performed equivalent work.

2.2 Expert stakeholder input

After further desk-based research, discussions with experts and a hardware familiarization exercise, an expert workshop was convened by LowCVP. Hosted by Millbrook, this workshop (and subsequent discussions with some individuals unable to attend) engaged expertise from a wide range of organizations; test houses, TRU suppliers, body builders, technologists, researchers and policy makers. The objectives were:

- To **propose a robust, representative and cost-effective methodology**, at least for the testing of auxTRUs initially.
- To **agree some KPI's** to use to assess if the proposed methodology is broadly representative, e.g. l/h fuel consumption.
- To agree a basic framework for developing a comparable test for alternator-driven or power take off-driven (alt/PTO) TRUs (if the above isn't already).
- To **plan pilot testing** on at least one auxTRU.
- To **scope out the major next steps** needed as part of any follow-on activity; e.g. to finalize the test protocol and use it to baseline the (GHG and AQ) emissions performance of current, conventional TRUs and assess the emissions-saving potential of new and alternative technologies.

The major issues identified in the initial stages of the project, as set out in the text boxes shown in the following sections, were reviewed and used to frame the discussions.

In response to Box 1, covering some issues identified regarding existing test methods and the need for simple but representative test conditions, experts pointed out that there are partial load (CEN) and steady state conditions tests (BS EN 16440-1:2015) in existence but agreed none attempt to replicate the full range of representative, in-service conditions (a mix of full load, part-load and stopped conditions).

It was also suggested that ATP-based testing is appropriate for measuring the overall insulation performance, and furthermore existing ATP certification could potentially be used without further testing, particularly FRC rated vehicles/trailers (those certified to carry frozen foodstuffs), as their thermal performance was likely to be close to the 0.4 W/m2/K requirement – performance significantly beyond that was unlikely. However, it was also noted that ATP certification is based on the load box, without a TRU fitted, so overall thermal performance would tend to be more variable once TRU fitment/integration had taken place, limiting this opportunity to cut down on overall testing and expense. Insulation properties also tend to degrade over time, so recently certified trailers may perform better than ones certified two or three years ago.

A water load, experts agreed, would be better than just air, but this would still not be adequately representative of typical loads. The consensus view was that empty cardboard boxes would be a better option, as these would affect air circulation within the load bay appropriately and provide for more stable and repeatable conditions.

BOX 1 - SOME ISSUES IDENTIFIED…

- Existing tests tend to be unit-only, not whole vehicle, and tend to measure absolute performance capability, rather than typical daily duty cycle, e.g. NRMM, AHRI.
- ATP has whole vehicle test, but no measure of emissions included and fuel consumption relates to full-load (pull-down) operation only. **So no existing test fully suitable**.
- One element of ATP assesses the overall **insulation performance**, which could be useful to correct/control for different TRU technologies being fitted to different vehicles.
- Testing should be in a **temperature-controlled chamber** - too many variables outside, e.g. wind, cloud cover.
- The load bay should have a load in it, as fresh air only would be insufficiently representative of real-world conditions. Water-filled IBCs could be used, with weight/volume of water set to be fixed proportion of load volume? 20%? 50%? So fixed ratio of air:water by volume.

It would be best to not use curtains within the load bay by default. Part of the wider benefits of a test process would be to quantify the potential savings from such voluntary interventions, e.g. curtains, better insulation, fewer door openings, use of electric standby etc.

Most multi-temperature units have movable bulkheads to change the proportions of frozen, chilled and ambient load bay volumes. The test process should specify a standard set of proportions and set the bulkhead positions accordingly.

Issues regarding the test process and duration (Box 2) generated some debate over whether the figures of 14-16 hours were representative, particularly for refrigerated vans, but the consensus nevertheless was that the test process should not include a full pull-down element (from ambient to setpoint). Instead it should focus on the emissions performance over the course of a vehicle's daily activities away from its depot.

The door-opening proposals (on a door area and time open basis) were felt to be a reasonable starting point, and the amount of time/door area specified should vary by vehicle size, with large vehicles generally having fewer door openings, but for a longer time and small vehicles having frequent but short duration openings.

The test should recommend a white load box but accept any vehicle with at least a white roof.

BOX 2 - SOME MORE ISSUES…

- **Should we try to include pull-down emissions or just focus on steady state?** Earlier work suggest TRUs typically used 14-16 hours per day, so assumption is that pull-down is negligible part of overall duty cycle.
- **How steady should state steady be?** We think we should simulate door openings, but how? Relate door openings to door area and time open, e.g. $5m^2$ door open for 60s, $3m^2$ door open for 100s, $2m^2$ door open for 150s? Or have heater inside load box set to input x kWh every y minutes?
- **What duration should the test have** to allow for fair mix of stop/start, low/high speed operation? 2 hours? 4 hours?
- **Should we do all testing on a rolling-road to simulate engine load, or can TRUs be tested with vehicle stationary?** Current thinking is that auxTRUs could be with stationary vehicle (but fans set at vehicle front to stimulate air flow), alternator & PTO TRUs would have to be on dyno to get representative emissions.

Discussions around details of the test procedure (Box 3) arrived at the consensus view that, for auxTRUs, the air flow around the vehicle should be minimized (e.g. less than 5 m/s) to aid repeatability, so not related to vehicle speed.

Ideally, experts agreed, testing should be at two ambient temperatures - 11°C & 25°C but testing at 18°C would be appropriate if time/costs only permitted one temperature.

Experts reported that the TRU itself could weigh 500 kg or more, so its mass would need to be factored in to the measurement of the base vehicle's emissions and fuel consumption.

The TRU's set temperature(s) may need to be adjusted during the stabilization phase to achieve the actual target load-space temperatures.

BOX 3 - A FIRST STAB AT A PROCEDURE

- For both auxTRUs and alt/ptoTRUs, base testing around the LOWCVP HGV cycle (or Van cycle for <3.5t vehicles) developed for the Clean Vehicle Retrofit Accreditation Scheme. This will facilitate like-for-like comparisons.
- For all testing, derive overall insulation properties of load box (or compartments for multi-temp units) via ATP insulation test or equivalent thereof. Use to standardize results to same load box. Chamber set to 18°C, load box loaded and TRU set to -20°C for frozen (or +2°C for chilled).
- For auxTRUs:
    - Stationary vehicle, traction engine off
    - External fans set to average speed of city driving phase. Once steady state internal temperatures achieved, start sampling emissions and fuel consumption. Apply simulated door-openings at representative frequency.
    - Repeat for urban and extra-urban cycle fan speeds.
- For alt/pto TRUs:
    - Vehicle on chassis dyno, drive CVRAS cycle (fan speed automatically varied continuously to equal driving speed). Sample emissions throughout, with simulated door-openings at representative frequency, process results separately for the City, urban and extra urban phases.
    - Repeat but with TRU switched off. Deduct emissions from above results to calculate TRU contribution in each phase.

The following suggestions were made by the expert stakeholders regarding pilot testing:

- Use an FRC certified trailer with an auxTRU.
- Test at a single load-bay temperature initially to develop confidence in the methodology before attempting multi-temp conditions.
- Access to dedicated TRU expertise during the pilot testing would be vital to maintain industry credibility.
- A trailer TRU would typically consume about 2.5 litres per hour of diesel over the course of a typical day's running, so the test protocol could be considered broadly representative if it required a similar rate. Experts further suggested that 18t rigid vehicle auxTRUs would consume around 1.5 litres per hour, and van altTRU systems would typically reduce the vehicles' fuel consumption by about 2-3 mpg.

For any follow-on test programme, to baseline the existing TRU fleet, experts suggested that three different TRUs in each vehicle segment (vans, rigids and artics) would be sufficient to generate representative and scalable data to model the UK vehicle parc's emissions.

2.3 Protocol used for pilot testing

With the above expert consensus suggestions as a starting point, detailed discussions were then held with the expert test house appointed to carry out the pilot testing (Cambridge Refrigeration Technology Ltd, CRT) to plan a series of tests compatible with the time and budgetary constraints of the project.

The main objectives of this pilot testing were to put the test procedures hitherto suggested by the research into practice, assess their suitability and identify potential further refinements. It was also decided that, whilst not strictly necessary for test procedure validation, the emissions of nitrogen oxides and particulates should be measured so as not to waste the opportunity presented to generate some preliminary evidence regarding in-service TRU emissions; a key evidence gap identified by the earlier, Cenex-led research for TfL/LoCITY. Cambustion Ltd were appointed to work alongside CRT to provide this emissions-measuring capability and data.

It was also agreed that the emissions performance and fuel consumption should be measured under pull-down (temperature-reducing) conditions, not necessarily as part of the final proposed test procedure but to ensure data would be available for all parts of the TRU's duty cycle. The only other significant variation from the procedures suggested above was to use a combination of empty cardboard boxes and water-filled intermediate bulk containers (IBCs) as the trailer's load (Figure 1). This was felt to be a likely 'best of both worlds' solution in that it would generate a representative air flow within the load box and have an overall thermal mass reasonably representative of typical loads.

The trailer was fitted with an array of thermocouples for accurate measurement of temperatures at various locations and the auxTRU (a conventional diesel unit rated at approximately 15 kW maximum net power and manufactured in 2017) was inspected and checked prior to testing to ensure it was operating satisfactorily.

The TRU's fuel consumption was measured via the continuous monitoring of weighing scales with a diesel fuel container mounted on them.

The air flow around the trailer while in the environmental test chamber was maintained at between 1 and 2 m/s, and the ambient temperature within the chamber maintained at 18 °C.

The overall pilot test programme involved two modes:

- Chilled (setpoint 2 °C)
- Frozen (setpoint -20 °C)

Five phases were used for each mode:

1. Pull-down empty trailer from 18°C to setpoint
2. Trailer is removed from test chamber and loaded with pre-chilled, water-filled IBCs and empty cardboard boxes
3. Trailer is installed into chamber again and TRU pulls down again to setpoint
4. Trailer is run in continuous mode (chilled) or stop/start mode (frozen) for three hours at setpoint
5. 15-minute door opening followed by closing and TRU pulling down again towards setpoint

Note that due to logistical constraints at the test site, the trailer had to be removed from the chamber for loading. The outside ambient temperatures were, at the time of testing, a few degrees above the temperature in the chamber. 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 second 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 TRU vehicle operators.

At 15 kW (maximum net power at 0 °C, 30 °C ambient) and with a 1.5 l diesel engine, the auxTRU tested is slightly smaller and, therefore, likely to be more fuel efficient, than some larger units (e.g. 18 kW and 2 l engine). The target average fuel consumption rate suggested by stakeholders of 2.5 litres per hour applies to these larger units, so a more appropriate target figure for the tested unit would be nearer 2.0 l/h.

The following Chapter presents a summary of the key findings from the pilot testing.

Figure 1. Combination of empty cardboard boxes and water-filled IBCs used for pilot testing.

3 Results of pilot testing

The following sections present the results of the pilot tests, firstly covering the measured fuel consumptions, useful for validation purposes and further refinement of the test procedures to ensure they are representative of in-service conditions, and then reporting the NOx and particulate emissions, useful in building the evidence base.

The temperatures achieved in the test chamber, trailer and at the TRU cold air inlet are shown in Figure 2, for both the chilled and frozen tests. The figures also illustrate the four key operational phases tested; pull-down (empty) at the start, then after a pause to allow for loading of the trailer, pull-down (loaded), then immediately into steady state (temperature maintaining) and finishing with a door opening phase.

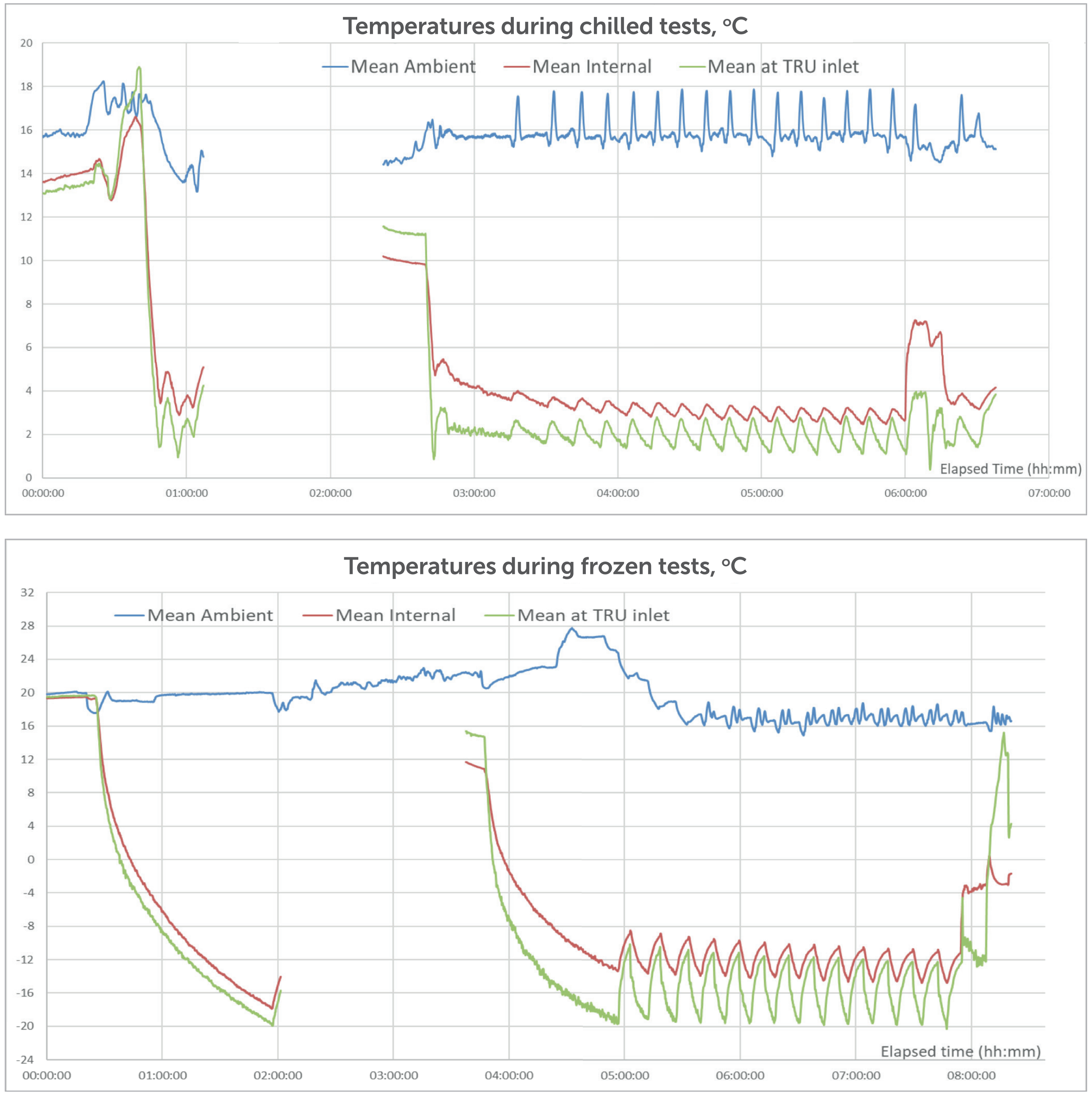

Figure 2. Temperatures during chilled and frozen tests

3.1 Fuel consumption results

The measured average fuel consumptions, in l/h, during each of the four test phases in which the TRU was operating (i.e. excluding the loading phase) are shown in Table 1.

Table 1. Fuel consumption results

Test Mode	Phase	Start Temp (°C)	End Temp (°C)	Duration (mins)	Fuel used (Litres)	Flow rate (l/h)
Chilled	Pulldown (empty)	16	3	36	1.55	2.58
	Pulldown (loaded)	10	4	22	0.71	1.94
	Steady state (continuous)	4	3	180	4.96	1.65
	Door opening	3	4	30	0.87	1.74
	All phases	**16**	**4**	**268**	**8.09**	**1.81**
Frozen	Pull-down (empty)	20	-18	92	5.18	3.38
	Pull-down (loaded)	11	-13	72	4.03	3.36
	Steady state (start/stop)	-13	-12	178	3.94	1.33
	Door opening	-12	-3	25	1.24	2.97
	All phases	**20**	**-3**	**367**	**14.49**	**2.37**
Both modes	**All phases**			**635**	**22.58**	**2.13**

The results from the empty pull-down tests show reasonable consistency between the two modes and indicate that when operating at full capacity, the TRU unit tested consumes just under 3.4 litres of diesel per hour. The somewhat higher fuel consumption figure for the frozen empty pull-downs is likely the result of higher ambient chamber temperatures during those tests (19 °C vs 16 °C for the chilled tests). There was, however, found to be a big difference in fuel consumption between the two modes for the loaded pull-down phase. In chilled mode, the TRU only had to achieve a temperature reduction of 6 °C, whereas in frozen mode it was a 24 °C reduction. More energy (fuel) is needed during the temperature-reduction phase as the temperature difference between inside and outside of the load box increases, which may well explain some of these differences. The ambient chamber temperatures were also notably warmer during the frozen loaded pull-down test than the chilled equivalent (24 °C vs 16 °C). Another factor influencing these findings is likely to be the time delay (lag) between the temperatures being monitored achieving the set point and the (earlier) modulation of the TRU itself, so some of the time classified as 'pull-down' may actually be 'steady state' for the TRU.

The fuel consumption figures under steady state conditions demonstrate, firstly, that less fuel is needed to maintain the set temperature points than is consumed to get down to those points in the first place and, secondly, that despite the set point being considerably lower in the frozen tests than when chilled, in (frozen) stop-start mode the TRU still managed to consume fuel at a lower overall rate than when run continuously (under chilled conditions). It should be noted, however, that the mean internal temperatures did vary more under the stop-start condition (cycling between about -10 °C and -14 °C) than when the unit was run continuously (though still apparently modulating between high and low speed) during the chilled tests (2.6 °C – 3.2 °C), implying that stop-start operation may not be suited to precise control of temperature.

The door opening tests also show differences in fuel consumption between the chilled and frozen modes. When chilled, the results seem to indicate that opening the doors for 15 minutes only marginally increased fuel consumption, from around 1.65 l/h to 1.74 l/h. During the 15 minute door-open period, the mean internal temperature rose to around 7 °C, and was brought back down to 3 °C within just four minutes of the doors being closed again. In frozen mode, the results were more in line with expectations, in that the TRU's fuel consumption during and immediately after the door opening event (3.0 l/h) was quite similar to that seen during the loaded pull-down (3.4 l/h). During the door-open period the mean internal temperature increased from -11 °C to 0 °C. Time constraints meant there were only another ten minutes of running permissible after closing the doors again, by which time the TRU had only managed to get the internal temperature down to -3 °C.

3.1.1 Implications for design of TRU test protocol

The Cenex-led study for TfL/LoCITY used a combination of survey data and specialist expertise to develop a set of usage profiles for varying sizes of refrigerated vehicles. For artics, such as that used in the pilot testing, that work suggests that a typical operation involves 50% frozen and 50% chilled (in multi-compartment trailers) and that over a 24-hour period, the trailer doors would typically be open for around six to seven hours, and for around one hour in total per delivery, with an undefined but likely only short period in between each opening.

The most simplistic way of modelling this typical TRU usage would be to assume the unit can only ever be in one of two conditions; either it is in pull-down mode, reducing the load-box temperature as quickly as possible, or it is in one or other of its steady state, temperature-maintaining modes (continuous or start/stop). The testing indicated that when the doors have been opened for a period of an hour or so (as was the case when the trailer was being loaded), it takes the TRU about 25 minutes to pull-down to chilled and about 75 minutes to do so to frozen; so, very roughly, one hour for a 50:50 chilled: frozen mix.

Using the Cenex-report figures, over a typical four hour delivery cycle (that study suggests that artics typically make six deliveries per 24-hour period) from arriving at one site to the next, the TRU (if it is left running while the doors are open) would thus be in pull down mode for about two hours (during the delivery, with the doors open most of the time, and when pulling-down again for the first hour or so of the journey to the next delivery site, and in steady state mode for the remaining two hours (final stages of journey to next delivery). With this 50:50 split between pull-down and steady state, the overall average fuel consumption can be calculated as simply the average of the two measured values.

Using the pull-down rates measured from the chilled and frozen loaded tests of about 2.7 l/h on average, and the average steady state (temperature-maintaining) consumption of about 1.5 l/h, the overall average on this basis would be around 2.1 l/h. This is very close to the target value of 2.0 l/h, suggesting that this simple method may well be close enough to be representative of typical TRU usage, and could potentially (subject to further testing and expert stakeholder dialogue) be used as an initial basis of a standard test protocol;

Average in-service fuel consumption = Mean of the measured loaded pull down and steady state rates

3.2 Pollutant emissions results

The NOx, particle mass (both in grammes per hour) and particulate number (per hour) results from each phase of the pilot tests are shown in Table 2.

Table 2. Pollutant emissions results

Test Mode	Phase	NOx (g/h)	PM (g/h)	PN (Num/h)
Chilled	Pull-down (empty)	52	2.34	4.2×10^{15}
	Pull-down (loaded)	56	1.61	3.3×10^{15}
	Steady state (continuous)	58	1.58	3.4×10^{15}
	Door opening	58	1.69	3.4×10^{15}
	All phases	**55**	**1.92**	**3.5×10^{15}**
Frozen	Pull-down (empty)	56	3.71	6.4×10^{15}
	Pull-down (loaded)	56	3.53	5.9×10^{15}
	Steady state (start/stop)	27	1.54	2.7×10^{15}
	Door opening	48	2.38	4.5×10^{15}
	All phases	**41**	**2.53**	**4.4×10^{15}**
Both modes	**All phases**	**47**	**2.27**	**4.0×10^{15}**

There is good consistency in these data between the different modes when the engine is working hard to reduce the load-box temperature (pull-downs and door openings). Under the start/stop conditions, the engine is on less than about 50% of the time, and the overall average emissions reflect this. Particulate mass and number both seem to be quite well correlated with fuel consumption in that those emissions were notably higher during the frozen pull-down and door opening tests than during the equivalent chilled tests, as was the fuel consumption. NOx emissions seem to be more consistently around 50-60 g/hr during these tests, so (unsurprisingly) less well correlated to fuel consumption.

3.2.1 Implications for TRU emissions evidence base

In the absence of any data on in-service TRU emissions but to make some initial estimates of emissions from the TCT fleet in London, the study led by Cenex for TfL/LoCITY relied on the untested assumption that auxTRUs would just meet the g/kWh emissions limits set by Stage V of the NRMM regulations coming into force for <19 kW engines in January 2019 (7.5 g/kWh for NOx and 0.4 g/kWh for PM). The 7.5 g/kWh figure is actually a combined limit for both NOx and hydrocarbons (HC); Cenex assumed 80% of this (6.0 g/kWh) would be NOx. The pilot testing results from a 15kW TRU suggest that when working in temperature-reducing mode (as opposed to temperature-maintaining) and assuming the unit is operating at around 15 kW continuously, the unit produces around 4.0 g/kWh of NOx and 0.25 g/kWh of PM, implying the initial estimates may have been overly pessimistic by around 50-60%.

Alternative g/kWh estimates can be made based on fuel consumption. Assuming a diesel TRU engine operates at 40% efficiency (as might be expected for such an engine), then its engine out kWh will be about 0.4 x the energy content of the fuel it consumes. In chilled, pull-down loaded mode, the unit tested consumed 1.94 l/h of diesel fuel, equivalent to about 19 kWh/h. The expected engine-out power would be 40% of this, i.e. roughly 8 kWh/h. NOx emissions of 56 g/h would thus be broadly equivalent to 7 g/kWh under these conditions and 1.6 g/h PM would be 0.2 g/kWh. In frozen, pull-down loaded mode the fuel consumption rose to 3.36 l/h, equivalent to 13 kWh/h engine-out power. Under these conditions, NOx emissions of 56 g/h can be estimated to be equivalent to 4.3 g/kWh and PM of 3.53 g/h would be equivalent to 0.27 g/kWh. These estimates further support the notion that the Cenex assumptions of 6 g/kWh for NOx and 0.4 g/kWh for PM may be slightly pessimistic.

However, the Cenex study did not consider PN; while there is no Stage V NRMM limit for engines below 19 kW, for those just above this threshold the limit is 0.01×10^{14} per kWh, whereas the pilot testing suggests current auxTRUs emit around 400 times that number. The Stage V NOx and PM limits for these larger engines are 4.7 g/kWh and 0.015 g/kWh respectively. This again indicates that while current auxTRUs may be compliant with forthcoming legislation, their particulate emissions are likely to be considerably higher than is permitted by engines only slightly larger, whereas their NOx emissions are likely to be broadly similar to such engines.

If, when driven, it is assumed that TCT vehicles drive in accordance with the CVRAS HGV cycle, which has an average speed of around 30 km/h, then the likely average NOx emissions from auxTRUs, calculated in a similar way to the fuel consumption model but considering only the driving time, can be estimated to be roughly 1.6 g/km. On a Euro VI diesel HGV this would be likely to have the effect of tripling or quadrupling its overall NOx emissions, whereas on a Euro V vehicle it would add only around 10%. Particulate emissions would be around 0.06 g/km, some 6 times higher than a typical Euro VI HGV and PN would be around 1.2×10^{14}, which is equivalent to at least 200 Euro VI HGVs.

It should also be noted that all the emissions measurements during the pilot testing described in this report were carried out while the vehicle was indoors, so any additional heat loads from solar radiation were minimized. On the open road, especially during sunny, summer days, this extra heat load could be quite considerable and lead to additional TRU fuel consumption and emissions.

4 Conclusions and next steps recommendations

4.1 Conclusions

1. The net result of the literature review, expert stakeholder engagement and pilot testing of an auxTRU is that an initial test protocol has been developed and, to the extent possible within the limitations of this preliminary study, validated against average in-service conditions.
2. To be valid, the test protocol needs to have an appropriate mix of pull-down (temperature-reducing) and steady state (temperature-maintaining) operation of the TRU.
3. The following test process, while subject to further refinement and detailing, is currently thought to be broadly suitable for TRU testing (both auxTRUs and alternator/PTO units):
    a. Load vehicle or trailer with a defined mix of water-filled IBCs and cardboard boxes
    b. Place vehicle/trailer in environmental test chamber (with chassis dyno if alt/PTO TRU being tested) and control ambient temperature to be at desired level (11 °C, 18 °C or 25 °C)
    c. Run TRU to achieve specified steady state temperature conditions in load box at appropriate chilled and/or frozen setpoint(s)
    d. Switch off TRU/vehicle and open cargo doors for a set period (e.g. 1 hour for an artic, 30 mins for rigids >3.5t and 5 minutes for vans up to 3.5t)
    e. Close doors, switch TRU/vehicle back on. If an alt/PTO TRU under test, begin first drive cycle (CVRAS HGV or CVRAS van as appropriate). Begin measuring fuel/energy consumption and emissions.
        i. For articulated vehicles with auxTRU: Run for three hours, then switch off TRU and open doors for 30 minutes, then close doors, switch TRU back on and run for further 60 minutes.
        ii. For articulated vehicles with alt/PTO TRU: Run vehicle for three complete drive cycles, with sufficient idling time in between each (about 14 minutes) to bring test time up to three hours, then switch off, open doors for 30 minutes, then close doors, switch back on and run one further drive cycle, add sufficient idling time at end (about nine minutes) to bring total test time up to 4.5 hours.
        iii. For rigid vehicles > 3.5t with auxTRU: Run for 51 minutes, then switch off TRU and open doors for 14 minutes, then close doors, switch on TRU and run for another 51 minutes, then switch off and open doors for another 14 minutes, then close doors and run TRU for a further 51 minutes.
        iv. For rigid vehicles > 3.5t with an alt/PTO TRU: Proceed as per iii but run vehicle on drive cycle during each 51-minute period. Switch off vehicle and TRU during door opening periods.
        v. For vans up to 3.5t: Proceed as per iii or iv above but leave TRU/vehicle running throughout, including while doors are open.
    f. Calculate the overall average fuel/energy consumptions and emissions as totals measured during the test period divided by four (artics) or three (rigids and vans) (for per hour metrics) or by the total distance driven (for per km metrics).

4.2 Next steps recommendations

The test process suggested above has been developed from the combined evidence gathered by the Cenex-led study (on typical usage patterns) and this study (expert engagement and pilot testing). This evidence base is still immature and very limited in its scope (e.g. London-only data) and coverage (e.g. pilot testing of just one auxTRU and at one ambient temperature). A follow-on programme of work is therefore suggested, to strengthen the evidence base and validate the test process over a wider range of applications. The basic elements of such a programme could include:

- Further expert engagement, e.g. by convening another expert workshop.
- Further pilot testing and protocol validation, e.g. of different vehicle sizes, to cover dyno-based testing of alt/PTO TRUs and to develop protocols for multi-temperature vehicles.
- Development and validation of a methodology to normalize results from TRUs fitted to vehicles with very different insulation properties.
- Baseline testing of a wider range of existing TRU technologies and evaluation of alternative TRU technologies to assess their emissions saving potential.

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The LowCVP, which was established in 2003, is a public-private partnership working to accelerate a sustainable shift to lower carbon vehicles and fuels and create opportunities for UK business. Over 200 organisations are engaged from diverse backgrounds including automotive and fuel supply chains, vehicle users, academics, environment groups and others. LowCVP members have the opportunity to:

- Connect : With privileged access to information, you'll gain insight into low carbon vehicle policy development and into the policy process.
- Collaborate : You'll benefit from many opportunities to work - and network - with key UK and EU government, industry, NGO and other stakeholders.
- Influence : You'll be able to initiate proposals and help to shape future low carbon vehicle policy, programmes and regulations.