Auxiliary temperature reduction units in the Greater London area

Overview of the study progress to date

Background

Recent Euro VI/6 standards have seen exhaust emissions from all road vehicles diminish significantly. The effective mandating of diesel particulate filters (DPF) at Euro V and selective catalytic reduction (SCR) at Euro VI has meant that the emissions of both particulate matter (PM) and oxides of nitrogen (NOx) from the exhausts of heavy vehicles (HGV, bus, coach) have fallen to very low levels. This does mean however, that concentrations of these pollutants measured at the road side are predominantly from other sources. For example, more than half of the PM now measured by roadside monitoring stations is derived from tyres, brakes, road wear and resuspension, rather than vehicle exhaust. These emissions are not new, but were previously masked by the exhaust pollutants.

This new area of interest has led to Transport for London (TfL) embarking on studies of non-exhaust vehicular emissions in order to better characterise and then reduce them.

One element of this work is an investigation into the Transport Refrigeration Unit (TRU) industry, where it is commonplace for refrigeration units powered by small diesel auxiliary engines to be used, mostly on semi-trailers forming part of an articulated HGV.

Scope of the study

CENEX, LowCVP and Brunel University were commissioned by TfL via the LoCITY programme[1] to conduct a study with five key aims.

- Study and report on the nature of temperature controlled transport in London
- Estimate the emissions from the temperature controlled fleet; both traction and auxiliary engines
- Review the alternative technologies currently available for temperature controlled operations
- Review potential emissions reductions from the application of best practice
- Suggest potential high level policy measures and areas for further research.

Methodology

The methodology included a desk based study of existing literature, analysis of ANPR camera data from Greater London provided by TfL, and a web-based survey of temperature controlled transport fleet operators (91 responses). This was augmented by two workshops involving senior staff from temperature controlled

[1] https://locity.org.uk/

transport operators. The study did not involve laboratory or other emissions testing. The estimates produced in the study were calculated based upon legislated limits for emissions from both traction and auxiliary engines. It is clear, and there are caveats to that effect in the report, that some empirical measurement of actual emissions performance would be necessary before any policy design would be possible.

Initial findings

It is important to understand that temperature controlled transport involves a range of commodities with an equally broad range of transport solutions. These range from consistent ambient temperature to chilled, lightly frozen, to deep frozen. One of the most challenging commodities is ice-cream, which must be maintained at -20 Celsius.

Perhaps the most useful findings within the report are the assessment of the numbers of temperature controlled vehicles in use in London, classified by vehicle size and also taking account of the proportions that are electrically driven (from the vehicle alternator) and the smaller number that are powered by diesel auxiliary engines. Of 25,500 vehicles (defined by having insulated bodies) entering Greater London annually, 15,000 visit regularly[2]. 3,500 have diesel auxiliary engines, mostly on larger vehicles. A key fact, previously unknown, is the predominance of multi-temperature truck bodies (71% of all temperature controlled). These feature both chilled and frozen compartments in the same vehicle.

A literature and stakeholder review of alternatively powered refrigeration systems is included and acknowledges the widespread use of direct drive (alternator driven) systems. Cryogenic systems are being trialled in a number of areas but are not yet ready for widespread adoption.

Some useful points on operational best practice and driver training are identified in the study, for instance, limiting of door opening times.

The estimates for air quality pollutant emissions are less robust, emphasising the need for empirical measurement of real-world emissions. The report contains the following passage that explains the reason why this is so:-

The majority of auxTRU diesel units operating in London are below the 19kW cut-off limit for compression-ignition engines in NRMM regulations. As such, there is currently no requirement for the majority of existing diesel auxTRU engines to comply with any emissions standard. There is a clear need to develop an emissions evidence base from real-world emissions testing and develop an applicable emissions factor.

[2] More than once per month taken on average across a 12 month period.

Recommendations

The study suggests a number of practical and potential policy recommendations, some of which are already being actioned and others which should be the responsibility of national government and type-approval authorities. Recommendations include:-

Recommendation	Role / Responsibility
Technology trial of alternative TRU options	TfL / Innovate UK / DEFRA / DfT
Real-world air quality measurements from TRUs	TfL / Innovate UK / DEFRA / DfT
Produce a best practice guide for operators	LoCITY / FORS
Tighter emission standards for TRUs	DEFRA / DfT
Trailer recognition scheme	DfT / DVSA
Light coloured refrigerated bodies	DfT
Consolidation centres	GLA / TfL / DfT
Preferential routes and out of hours times for low emission vehicles	GLA / London Councils / TfL

Conclusion

This study forms a useful first stage in the investigation of non-exhaust pollutant emissions from road vehicles. At the time of writing, it is envisaged that this may lead to further research with the gathering of real-world emissions data from auxiliary diesel engines in both operational and controlled situations. This would allow more accurate characterisation of this emissions source for emissions inventories.

There is also the potential for TfL to contribute to a multi-partner European research project, should the funding bid be successful, although that would be a longer term (2-3 years) project than any operator focused deliverables assigned to LoCITY.

Independent, not-for-profit, low emission vehicle and energy for transport experts

PROJECT

REPORT

Auxiliary Temperature Reduction Units in the Greater London Area

Air Quality and Climate Change Impacting Emissions from Temperature Controlled Transport

14/12/2017

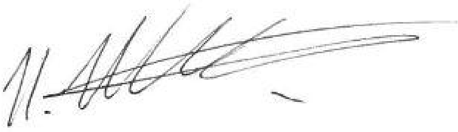
Prepared for:

Fergus Worthy

LoCITY
Palestra 11G8
197 Blackfriars Road
SE1 8NJ

FergusWorthy@tfl.gov.uk
+44 (0)20 7126 4309

Prepared by:



Nick McCarthy
Technical Specialist

Approved by:

Steve Carroll
Head of Transport

Cenex
Advanced Technology Innovation Centre
Oakwood Drive
Loughborough
Leicestershire
LE11 3QF

Registered in England No. 5371158
VAT Registered No: 933596983

Tel: 01509 635 750
Fax: 01509 635 751
Email: info@cenex.co.uk

Twitter: @CenexLCFC
Website: www.cenex.co.uk

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Document Revisions

No.	Details	Date
1	First Draft	11/08/2017
2	Updated following comment	15/10/2017
3	Final draft	04/12/2017
4	Final release	13/12/2017

Contents

1 Table of abbreviations

AuxTRU	Auxiliary Temperature Reduction Unit
AQ	Air Quality
BACT	Best Available Control Technology
BUL	Brunel University London
CARB	California Air Resources Board
CAZ	Clean Air Zone
CCZ	Congestion Charge Zone
DVLA	Driver Vehicle Licencing Authority
DVSA	Driver Vehicle Standards Authority
ETS	Electronic Tracking Systems
FORS	Freight Operator Recognition Scheme
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HC	Hydrocarbon
HGV	Heavy Goods Vehicles
HVAC	Heating Ventilation and Cooling
LEZ	Low Emission Zone
MTJD	Multi-Temperature Joint Distribution
NRMM	Non-Road Mobile Machinery
OEM	Original Equipment Manufacturer
PM	Particulate Matter
PTO	Power Take Off
TCO	Total Cost of Ownership
TfL	Transport for London
TMVD	Traditional Multi-Vehicle Distribution
TRL	Technology Readiness Level
TRU	Temperature Reduction Unit
ULEZ	Ultra-Low Emission Zone
WTW	Well to Wheel

Acknowledgement: Ms Ashika Rai and Professor Savvas Tassou of Brunel University London have provided invaluable assistance to this research. Many temperature controlled transport stakeholders have been extremely helpful in the completion of this work. They are too many to name individually, but we acknowledge that this report would not have been possible without their openness and cooperation. LowCVP have also provided invaluable insight in the completion of this project.

2 Executive summary

Key Points

- Cenex was commissioned by LoCITY to conduct research to quantify the energy usage and emissions associated with auxiliary engines for transport refrigeration units in London, and to review the alternative technologies available to mitigate emissions from these units.
- Auxiliary engines for transport refrigeration units account for around 9% (83,500 t/annum) of all well-to-wheel (WTW) CO_2 emissions from temperature controlled transport which enters London.
- The real-world air quality emissions from these units are unknown. There is a lack of effective regulatory standards covering emissions from auxiliary diesel refrigeration units and a lack of independent real-world test data.
- This report estimates that auxiliary engines for transport refrigeration units could disproportionately account for around 59% (86 t/annum) of all PM emissions from temperature controlled transport which enters London and 11% (621 t/annum) of all NOx emissions.
- If the entire London temperature controlled transport fleet were Euro 6/VI compliant then the percentage of emissions due to auxiliary engines for transport refrigeration units could account for 95% of all PM emissions and 40% of NOx emissions from the vehicles.
- It is estimated that auxiliary engines emit at least 30 times more PM and 4.5 times more NOx per kWh than the traction engines used by the temperature controlled transport fleet in London.
- Alternative cleaner technologies could be adopted at a similar or better whole life cost to incumbent technology.
- There are number of technological and political solutions which can be progressed to improve the emission performance of the temperature controlled transport fleet.

Background

Air pollution presents a major threat to public health. The total mortality burden in London from poor air quality is equivalent to 9,416 deaths per year. The economic cost of these health impacts is estimated to be up to £3.7 billion.

Auxiliary engines are frequently used to power temperature reduction units (TRUs), primarily for the distribution of chilled and frozen consumable goods. Emissions from TRUs are regulated by Non-Road Mobile Machinery (NRMM) standards. However, these standards are widely considered as insufficient to protect public health in cities. Policy development around TRUs is hindered by a lack of data on their energy usage and emissions. The draft Mayors Transport Strategy makes a commitment to providing tailored and targeted approaches to address the unique challenges faced by the individual sectors such as food. The London Environmental Strategy seeks to ensure that London's entire transport system is zero emission by 2050. These strategy documents provide a clear mandate to start understanding and reducing the contribution that auxiliary TRUs contribute to London's poor air quality.

Cenex was commissioned by LoCITY to conduct research to quantify the energy usage and emissions associated with auxiliary engines for transport refrigeration units in London, and to review the alternative technologies available to mitigate emissions from these units.

Methodology

A literature review and widespread stakeholder engagement were used to inform this study. This included two workshops, one with the temperature controlled transport (TCT) community and another with policy makers. A survey collected together 91 responses from TCT stakeholders (fleet managers, equipment providers and fleet drivers). Responses represented over 2,300 vehicles, with the TCT vehicles in those fleets representing approximately 10% of the estimated total London TCT fleet. Automatic number plate recognition (ANPR) data were also used to establish the number of TCT vehicles operating in London.

London TCT and auxTRU operation

25,500 unique TCT (defined as having insulated bodies) vehicles access London each year. 15,000 of these have regular access (defined by the number of TCT vehicles that appear in ANPR data on a quarterly basis) into London annually.

3,500 (23% of TCT fleet) vehicles with diesel powered auxiliary temperature reduction units (auxTRUs) regularly enter London annually, and 1,800 of these also travel into the CCZ. Of the TCT vehicles operating with a diesel auxTRU engine in London, 0% are in the 0-3.5t gross vehicle weight (GVW) category, and 15%, 52% and 33% are in the 3.5-12t, 12t+ and artic. categories respectively. The London auxTRU fleet comprises 16% of vehicles operating with Euro VI traction engines, 59% with Euro V, 10% Euro IV and 15% Euro III or lower.

Multi-temperature bodied vehicles (those which have different temperature zones within the same vehicle) dominate the sector, being used in 71% of all TCT vehicles. Here, supermarkets are responsible for 49% of all multi-temperature vehicles, with a further 18% being independent retailers offering similar mixed goods distribution to supermarkets. The remaining 29% are traditional single temperature distribution vehicles.

On average, vehicles in the TCT sector entering London operate between 14-18 hours per day, undertaking between 44,000 to 196,000 km per year (from 3.5t to articulated trucks respectively). The proportion of these miles actually driven in London is unknown. As much as 1,124 million km could be driven by the London TCT fleet per year, with diesel auxTRU TCT vehicles generating 438 million km (or 39%) of the total TCT distance driven.

Energy and emissions from temperature reduction units

The Cenex LoCITY Fleet Advice Tool, a Brunel University London TCT Energy Use and Emissions Model and publicly available emission factors were used to estimate the emissions from the main engine that propels the vehicle and the additional energy requirements (and hence emissions) of the refrigerated compartment of the vehicle. The table below presents the emission estimates for the entire London TCT fleet. Refrigeration energy is provided by two general different system, either an auxTRU or an engine alternator driven TRU unit.

Emissions (tonnes/year)	Traction engine (for motive power only)	Diesel powered auxTRU emissions	Alternator driven TRU emissions	Total emissions
WTW CO_2e	722,636	83,550	74,930	881,116
NOx	4,587	621	476	5,684
PM	55	86	6	147

The table above shows that TCT is responsible for 881,000 t WTW CO_2 annually. Refrigeration is thought to account for 18% (158,000 t) of these emissions, with emissions from auxiliary diesel refrigeration units estimated to account for 53% (83,500 t) of these. This report provides a conservative estimate that auxiliary engines for transport refrigeration units disproportionately account for around 59% (86 t/annum) of all PM emissions from temperature controlled transport which enters London and 11% (621 t/annum) of all NOx emissions. If the entire London temperature controlled transport fleet were Euro 6/VI compliant then the percentage of emissions due to auxiliary engines for transport refrigeration units could account for 95% of all PM emissions and 40% of NOx emissions. Due to a lack of real-world data there is a great deal of uncertainly within the emissions stated.

The majority of auxTRU diesel units operating in London are below the 19kW cut-off limit for compression-ignition engines in NRMM regulations. As such, there is currently no requirement for the majority of existing diesel auxTRU engines to comply with any emissions standard. There is a clear need to develop an emissions evidence base from real-world emissions testing and develop an applicable emissions factor. New NRMM Stage V emissions do come into force from 2019 onwards. In Stage V, all new NRMM engines below the 19kW range will also have to comply with emissions standards for the first time. The Stage V standard for smaller engines has a NOx limit of 7.5g/kWh and PM 0.4 g/kWh. This compares to Euro VI heavy duty truck regulation which has NOx limits of 0.46 g/kWh (94% lower) and PM limits of 0.01 g/kWh (98% lower).

There is no robust evidence base to quantify Air Quality (AQ) emissions from London TCT fleet vehicles; all AQ emissions presented in this report incorporate a very high degree of uncertainty.

Alternative technologies to reduce emissions

A review of alternative options to auxTRU units was conducted through a literature review and stakeholder consultation. Cost and emissions of alternative options were provided by suppliers to assess their performance against the incumbent technology.

Mature technology such as direct drive electric TRUs already have significant market share. Their increased uptake is limited by the need to install additional electrical infrastructure compared to diesel auxTRUs. Cryogenic refrigeration **demonstration projects** are underway and should be monitored closely as more data becomes available. Several interesting technologies are **in development**. Although not ready for implementation in the short term, energy recovery and alternative traction engine drivetrain technologies should be monitored closely as they offer the most promising potential for implementation in the near term.

An emission and cost analysis of **market ready and demonstrator technologies showed that significant WTW CO_2 (up to 80%) and air quality (up to 100%) savings could be achieved at a similar whole life cost** to the incumbent diesel auxTRU technology, with liquid nitrogen technology showing a £4 – 5k whole life cost saving. However, this assessment was based on economic and performance data provided by manufacturers, which needs to be verified through real-world trials and data collection.

Influence of best practice on TCT

Brunel University London used their TCT energy model to show the influence of operational changes on energy and emissions. This showed the following:

- Reducing average door opening times by 25% can save a fleet-average 16% of refrigeration fuel consumption - a saving of 25,000 t CO_2e per year for London.
- A modelled dark body vehicle had a 27% higher body energy requirement compared to a white body vehicle on the same duty cycle. The total CO_2e per year from the London TCT fleet could be reduced by approximately 2,000 t if all refrigerated vehicle bodies were coloured white or silver. A possible 1.3% reduction in total annual CO_2e from the TCT fleet.
- Full ATP compliance (an international insulation standard for TCT) would equate to a 1.6% total refrigerated-body emission saving of approximately 2,500 t of CO_2e per year.
- Savings in fuel consumptions would also allow air quality savings to be realised.

There is a lack of knowledge and understanding by fleets of the factors impacting efficient TCT operations and equipment designs. Further research is also required to support some of the emission saving claims presented here and for other operational changes (for example, the cost/benefit of using internal curtains in refrigerated transport is not understood).

Policy review and recommendations

A review of policies from other countries to reduce emissions from TCT revealed that California intends to introduce stationary operation time limits for all TCT units that are not zero emission at the point of use, and has emission limits for auxTRU equipment. ATP compliance is mandatory across France for all TCT vehicles. Recommendations from this report are summarised below.

Further areas of research required

This study highlighted several areas where further research and consultation are required to inform and facilitate policy.

- **Alternative TRU technology trial:** instigate a real-world trial of alternative TRU options to create a working knowledge of the technology costs, emissions and operational factors. Results should be used to inform supporting policy and any potential grant structure.
- **Air quality impacts study:** instigate a testing program to develop an evidence base for air quality emissions from diesel TRUs.
- **Trailer recognition:** the current inability to register and recognise insulated trailers would be a barrier to the implementation of schemes encouraging cleaner technology. An investigation into the solutions for this should be undertaken.
- **Curtains**: internal curtains reduce energy consumption but are heavy and have some impact on payload. The cost/benefit impact of curtains needs further research.

TCT Operational efficiency recommendations

It is recommended that the following items can be developed to form a series of measures that support increased operational efficiency of TCT:

- **Increased insulation:** Consider the implementation of ATP compliance for TCT. Review policy impacts and implementation options with TCT stakeholders.
- **TCT Stakeholder training:** Develop toolkits and guidance documents to encourage best practice operations in TCT transport.

TCT Policy recommendations

It is recommended that the following policy options are considered to encourage low emission TCT operation.

- **Preferential treatment:** Implement preferential and out of hours access for low emission TCT, review policy options with TCT and local authority stakeholders for preferential treatment of zero-emission TRUs.
- **Introduction of tighter emission standards:** review policy options for implementing more stringent emissions standards for TCT.
- **Consolidation centres:** initiate a feasibility study into consolidation centres allowing zero emission TCT delivery in to London.
- **Infrastructure grants:** develop infrastructure grants to support electrical infrastructure.

It is recommended that **independent emissions testing of auxTRUs and creating awareness through the development of stakeholder training materials and best practice guides represent quick wins that can be implemented immediately**. This should be closely followed by the provision of a real-world technology trial to inform policy and infrastructure grant funding decisions while longer term actions, such as the more detailed consideration and consultation of policy options (e.g. preferential treatment, tighter emission standards, ATP compliance etc.) are progressed.

Conclusions

The TCT stakeholders consulted were willing to acknowledge the importance of TCT's impacts on AQ and were very open to the possibility of changing their technology and/or working practices. A well evidenced and supported plan, brought forward by TfL, has excellent prospects of making long term reduction in emissions arising from the TCT sector.

Some low emission technologies are suitable for implementation in the short term, but will require support to implement quickly. Direct drive electrically powered TRUs are a mature technology already making inroads to this sector but will require funding and training for TCT stakeholders to support the conversion. Operational constraints limiting their adoption could be overcome with the installation of depot and point-of-delivery based plug-in points. Other technologies such as cryogenic refrigeration are possible longer-term solutions. A dedicated feasibility study and stakeholder consultation process should be implemented to quantify the cost implications and timeframes for the transition. Real world trials are required to provide an evidence base for the technologies. The replacement of diesel auxTRU in the CCZ and Greater London area appears possible in the future (within a 10-year timeframe) for the majority of vehicles.

There are a broad range of policy options available. These range from the short-term solutions with immediate impacts (for example driver training courses) to long-term projects requiring additional feasibility studies, stakeholder engagement and significant resources (for example freight consolidation centres and implementing stricter emission standards on auxTRUs).

A variety of possible TCT policy levers are available. There is no single operational or technological solution to the issue of emissions from TCT. A combined approach of legally enforced requirements, stakeholder training, and technology adoption will be required. Successful implementation will require clear, consistent leadership from government, education of stakeholders, support for the public and stakeholders, enforcement of policy and the creation of support infrastructure for new technologies, operational practices, and sustainable power generation.

One issue that impacted this research is the quality of the data available. TCT is not well studied in the literature and there is relatively little published real-world data. There is a clear requirement to develop an emission impact and evidence base. Although there is uncertainty in some of the underlying data, we believe this report collects together the best evidence of the London TCT fleet available at the time of writing.

3 Introduction

Air pollution presents a major threat to public health. The total mortality burden in London from poor air quality (AQ) is equivalent to 9,416 early deaths per year. The economic cost of these health impacts is estimated to be up to £3.7 billion. Transport is a major contributor to pollution in Greater London, accounting for 50% of NOx emissions in 2013. Vans and heavy goods vehicles (HGVs) are responsible for 32% of all transport NOx emissions in the capital. Road freight movement is expected to increase by 20% by 2031 to serve London's growing population and economy. Substantial action must be taken to mitigate the potential environmental impacts.

LoCITY commissioned Cenex to investigate the impact of temperature controlled transport (TCT), specifically that of auxiliary diesel engines, on greenhouse gas (GHG) and AQ emissions in London. This work was undertaken as part of the strategy to reduce London's CO_2 emissions to 60% below 1990 levels by 2025. This study also considered alternative means of reducing emissions from auxTRUs, also known as auxiliary engine transport refrigeration units.

The draft Mayors Transport Strategy makes a commitment to providing tailored and targeted approaches to address the unique challenges faced by the individual sectors such as food, and the London Environmental Strategy seeks to ensure that London's entire transport system is zero emission by 2050. These strategy documents provide a clear mandate to start understanding and reducing the contribution that auxiliary TRUs contribute to London's poor air quality.

Auxiliary engines are frequently used to power TRUs, primarily for the distribution of chilled and frozen consumable goods. Most auxiliary engines consume diesel, and therefore emit carbon dioxide and relatively high levels of Particulate Matter (PM) and NOx. Poorly maintained refrigeration units might also leak hydrofluorocarbon (HFC) refrigerants, known as F-gases, which have a very high global warming potential. Emissions from TRUs are regulated by the Non-Road Mobile Machinery (NRMM) standards; however, as discussed later in the report many compression-ignition TRUs operating in London are below 19 kW output and so fall outside the scope of current regulations. These standards are not sufficiently strict to encourage uptake of alternatives to auxiliary diesel engines. Policy development for TRUs is hindered by a lack of data on energy use and emissions.

Research commissioned by Dearman estimated that a diesel trailer refrigerator engine emits six times more NOx and 29 times more PM than a Euro VI HGV engine. The Dearman estimate of emissions was based on a comparison of regulatory limits; no independent 'real-world' research has been published to support these claims [1]. Brunel University London (BUL) published a study in 2009 [2] which reported typical fuel consumption for auxTRUs in litres per hour, from which carbon dioxide emissions figures can be derived, but did not estimate the regulated pollutant emissions from auxiliary engines for TRUs. It was noted in the Brunel report that there is a lack of in-field data on energy consumption. The report also outlined the alternative technologies that could reduce energy use and emissions. Several companies are developing low or zero emission TRUs, but there is a lack of independent evidence of their technology readiness levels, the potential financial and environmental costs and benefits.

There are two main types of temperature distribution in a TCT vehicle.

- **Traditional Multi-Vehicle Distribution (TMVD)** has a single set temperature in each vehicle and typically delivers only one product per vehicle.
- **Multi-Temperature Joint Distribution (MTJD)** uses a single vehicle with separated temperature zones. This allows delivery of goods that must be transported at differing temperatures. There can be as many as five separate temperature compartments in MTJD,

but two sections (one chilled and one frozen) is far more common. The UK, and London in particular, has a reputation for being at the forefront of MTJD.

This choice of delivery style has a significant impact on the energy required to achieve the desired set temperature in refrigerated compartment(s).

This report brings together existing information with new research based on consultation with TCT stakeholders operating in the greater London area. The newly-gathered data is used to inform high-level emission models of the London TCT fleet vehicles, quantify the energy use and emissions associated with auxiliary engines for TRUs in London, and review the alternative technologies available to mitigate emissions from these units.

3.1 The auxTRU

A typical diesel-powered auxTRU unit is shown below in Figure 1.

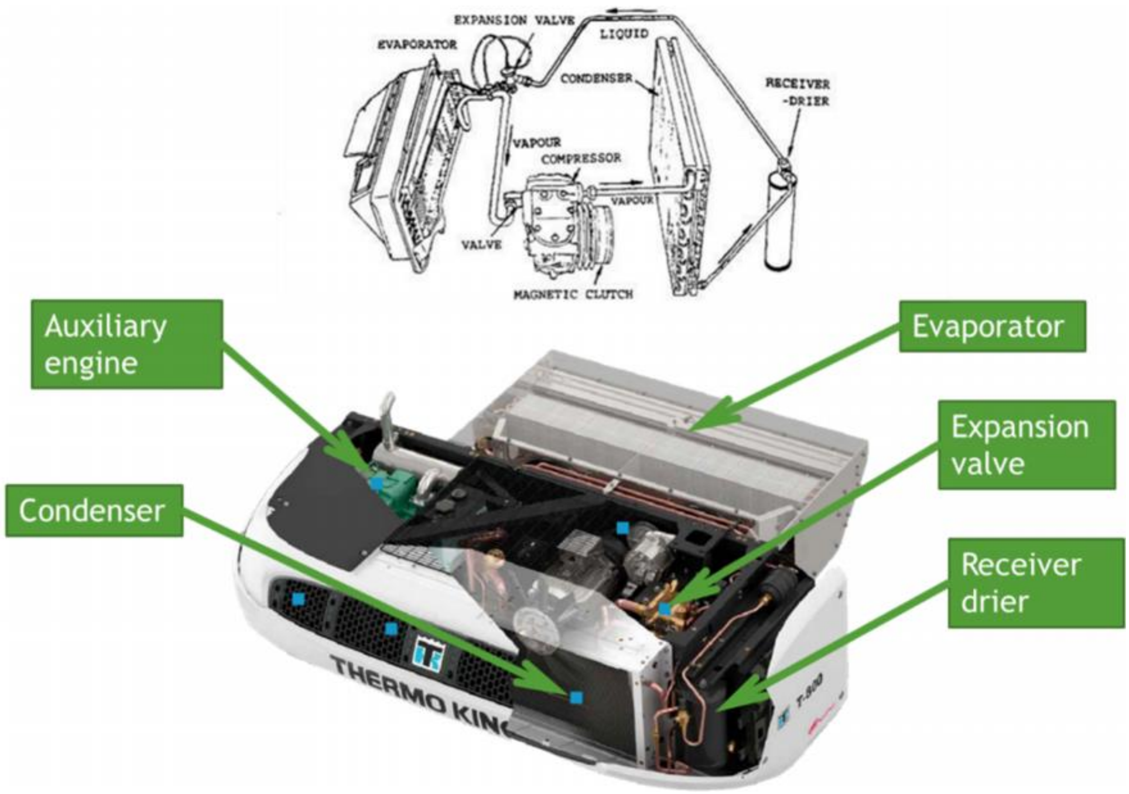


Figure 1: Typical diesel auxTRU unit (source: Thermo King)

Figure 1 shows a generic auxTRU and some of the key components. Typically, a diesel-powered auxiliary engine operates a refrigerant loop where (like a domestic fridge or freezer) a working fluid (known as a refrigerant) is pumped around a circuit. The refrigerant is first compressed in the condenser and then relieved through an expansion valve into an evaporator where it undergoes a pressure drop. Fluid expansion in this pressure drop creates a cooling effect which is then used to cool air which is blown into the vehicle body to maintain a low temperature. Many auxTRUs can also run from electrical power when at the depot [3]. Connecting the TRU to an electricity supply in this way is referred to as cold ironing.

3.2 Temperature controlled transport

TCT is a critical component in modern life, providing safe and reliable medical, food and drink. A variety of sizes of vehicle provide TCT delivery. In this study, vehicles were segregated into four broad categories based on their GVW as shown in Figure 2 below. The four vehicle categories used were;

- Less than 3.5t (<3.5t);
- Between 3.5t and 12t (3.5-12t);
- Rigid body vehicles greater than 12t (12t+); and
- Articulated vehicles (artics.)

Figure 2: Example vehicles in study weight classes

4 Methodology

Key Points
Methodology: A literature review and widespread stakeholder engagement were used to inform this study. This included two workshops, one with the TCT community and another with policy makers. A survey collected together 91 responses from TCT stakeholders (fleet managers, equipment providers and fleet drivers). Fleet manager responses represented 2,319 vehicles. The TCT vehicles in those fleets represented approximately 10% of the estimated total London TCT fleet. **Next Steps**: The data captured were analysed to generate representative values for items such as London vehicle duty cycles, transported product types, vehicle refrigerated compartment fuel duty cycles and an estimated size of the greater London TCT fleet. These representative values became the assumed values entered in to a vehicle duty cycle fuel consumption model and refrigeration duty cycle fuel consumption model. The results of two models are reported later in this report.

4.1 Study areas

The projects main study areas are shown in the table below.

Work Package Title	Purpose & Content
London TCT and auxTRU operations	Study and report on typical London TCT operations
Energy and emissions	Estimate the emissions from the London TCT fleet traction and auxTRU engines
Alternative technologies	Review the alternative technologies available to improve emissions from diesel auxTRU units
Application of best practice	Review potential emission improvements available from the application of TCT best practice
Policy	Suggest high level policy recommendations and areas for further research which can be implemented to reduce the emissions from TCT in London

Table 1: Project study areas

4.2 Data and information sources

The sections below outline the main data sources utilised in the study, with further explanation and detail given in the main report where required.

4.2.1 Literature review and definition of requirements

Full details of the literature review can be found in the references/bibliography section at the end of this report. The reference section is used as supporting evidence throughout this study. A key output of the literature review was gaining an understanding of the factors that influenced the energy requirements of TCT operations. These factors are presented in Table 2 and summarised as Thermodynamic (physical characteristics of TCT) or Behavioural factors (operational factors of TCT). Characterising these factors for the London TCT fleet were the main focus of the research, surveys, and the stakeholder workshop.

Thermodynamic factors	Operational / behavioural factors
Size of refrigerated compartment (internal length, height, width)	Number of deliveries per time unit (hour/day/week)
Thermal conductivity and thermal mass of refrigerated compartment walls	Number of door openings per delivery
Manufacturer of refrigerated compartment, year and model number	Duration of door-opening events
Internal layer, external layer and insulation material type and thickness	Pre-chilling of refrigerated compartment prior to loading
Ambient temperature (yearly average for this study – meteorological data)	Shut down duration after last delivery
Desired temperature	Refrigerant type and estimated leak rate
Desired temperature tolerance	Cleaning/ maintenance regime (frosting and heat exchangers)
Duration desired temperature is required	Logistics style (TMVD or MTJD)
Mass and type of goods loaded (thermal mass)	Engine details (size, manufacturer, year, model number, efficiency)
Temperature of mass at time of loading	Fuel consumption estimate
Power requirement at set temperature (watts)	Vehicle type/size
Air flow rate (m^3/hr and m/s) if known	Representative telemetry data
Diesel engine efficiency	Vehicle utilisation (hrs/day, days/week, weeks/year)
Diesel engine size	Typical drive cycles (e.g. trunking, rural, urban)
Diesel engine manufacturer and model number	Number of delivery drops
Size of door opening	Total distance driven per year
Average speed	Average speed
External colour of refrigeration compartment	

Table 2: Thermodynamic and operational factors identified by literature review

4.2.2 Questionnaire

A survey was conducted of the auxTRU TCT fleet operating in the Greater London area to determine their typical technical and operational characteristics. This was achieved through a combination of online (Survey Monkey) questionnaires and hard copy paper surveys sent to targeted stakeholders. The survey was publicised through an industry newsletter (Cold Chain News) and disseminated through the BUL network of contacts, the Cenex mailing list, LowCVP events and the LoCITY website and newsletter.

The online survey consisted of 123 separate questions, though key stakeholders who completed the survey would not have visibility of all questions. The survey questions varied depending on the responder's job title (whether driver, fleet manager, servicer/builder, manufacturer of refrigeration equipment or vehicle manufacture).

The primary focus of the questionnaire was on stakeholders using one or more diesel auxTRUs that operated in the London region. Figure 3 shows the respondents' job roles and the number of vehicles represented in the responses.

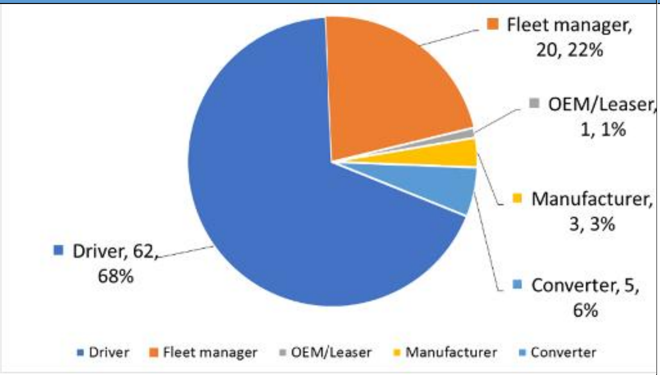
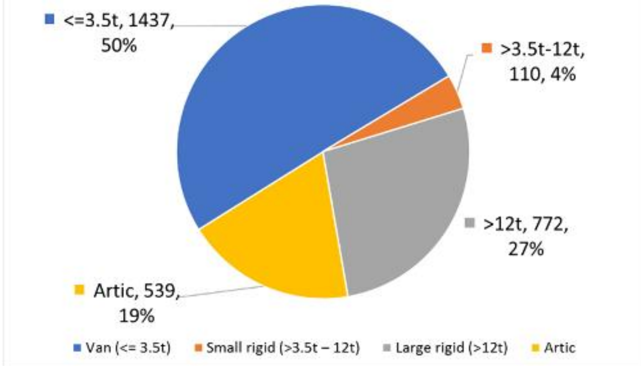
Job roles represented by survey respondents	Vehicles represented by survey respondents
	

Figure 3: Job roles and number of vehicles represented in stakeholder survey

The questionnaire had a total of 91 responses. The fleet managers survey reported 2,319 vehicles representing approximately 10% of the total London TCT fleet.

4.2.3 ANPR data

LoCITY provided anonymised data captured from the London Automatic Number Plate Recognition (ANPR) software connected to the capital's network of closed-circuit television cameras. This data was captured in two distinct regions of London; 1) Greater London (all London) and, 2) The Congestion Charge Zone (CCZ).

The ANPR data provided by LoCITY did not include any personal details and describes vehicles based on their registered GVW and vehicle type.

ANPR data were reported over a period of 12 months and quarterly and showed the specification of each unique vehicle entering London in the reporting period. The quarterly figures were far smaller than the annual figure and showed a high degree of seasonality. It was assumed that annual figures were influenced by large numbers of single trips into the area of data capture. Therefore the quarterly figures were assumed more representative of regular traffic entering the two identified regions (CCZ and all London).

4.3 Stakeholder workshops

In May 2017, a day-long workshop was held for a variety of TCT stakeholders. Preliminary data from the survey and interview process were presented, discussed and refined. Workshop attendees were from a wide cross-section of the London TCT community, including fleet managers, TCT industry bodies, TRU equipment manufacturers, vehicle servicers and converters, refrigeration and heating ventilation and cooling (HVAC) engineers, academics, F-gas distribution companies and TCT drivers. A second workshop was held in July 2017 for representatives of various government departments to discuss the policy options for TCT in both London and the UK.

4.3.1 Stakeholder interviews

The topics raised in the literature review, summarised in Table 2, were used as a framework for 12 interviews and discussions with TCT stakeholders. Further interviews were conducted throughout the project as supporting information was required.

5 London TCT and auxTRU operation

Key Points

Methodology: ANPR data, questionnaires, a stakeholder workshop and a series of stakeholder interviews were used to gather data to describe the way TCT vehicles are used and configured in London. Where conflicting data were received across the different data collection methods, we endeavoured to provide an average industry opinion.

Key Results:

- 25,500 unique TCT (defined as having insulated bodies) vehicles accessed London during 2016. 15,000 of these regular entered (defined as number of unique vehicles entering each quarter) London annually, 8,000 (53%) of these also travelled into the CCZ.
- 3,500 (23% of TCT vehicles) vehicles with diesel powered auxTRUs entered London, and 1,800 of these also travelled into the CCZ. Of the TCT vehicles operating with a diesel auxTRU engine in London, 0% were in the 0-3.5t weight category, 15%, 52% and 33% were in the 3.5-12t, 12t+ and artic. categories respectively.
- The London auxTRU fleet comprised of 16% Euro VI traction engines, 59% with Euro V, 10% Euro IV and 15% Euro III or lower.
- Multi-temperature vehicles dominate the sector, used in 71% of all TCT vehicles. Here, supermarkets were responsible for 49% of all multi-temperature vehicles, with a further 18% being independent retailers offering similar mixed goods distribution. The remaining 29% were traditional single temperature distribution vehicles.
- On average vehicles in the TCT sector entering London operate 14-18 hours per day, undertaking between 44,000 to 196,000 km per year (from 3.5t to articulated trucks respectively).
- As much as 1,124 million km could be driven by the London TCT fleet per year, with diesel auxTRU TCT vehicles generating 438 million km (or 39%) of the total TCT distance driven.
- Across the different weight categories studied (3.5t to articulated trucks) the rated power output of diesel auxTRUs ranged from 3.3kW to 15kW, the number of door openings per delivery ranged from 2 to 5, the average time the door was open ranged from 2.5 to 15 minutes and the time the vehicle's temperature had to be controlled ranged from between 10 and 24 hours per day.

Next Steps: The London TCT vehicle and usage characteristics established in this section were taken forward as a basis to understand the energy requirement, emissions and total cost of ownership (TCO) from TCT transport, in section 6 and section 7 of this report.

5.1 Number of TCT and auxTRUs operating in London

5.1.1 ANPR data

ANPR data for vehicles operating in London during 2016 to 2017 were provided by Transport for London (TfL).

ANPR data were cross referenced with DVLA data to determine the number of vehicles with insulated bodies operating in London. This was combined with TCT industry estimates of the percentage of insulated vehicles which have a diesel auxTRU fitted and used to estimate the total London auxTRU fleet. Testimonials from fleets at the stakeholder workshop suggested that between vehicle converters not registering insulated vehicles, and the DVLA not updating records, or delays in updating records, the ANPR data was likely to underestimate the number insulated vehicles operating in London.

5.1.2 ANPR data extrapolation for semi-trailers

ANPR did not recognise insulated trailers and therefore could not be used to identify the number of artics used in combination with an insulated trailer. We estimated the number of insulated semi-trailers (which would form an articulated combination) by extrapolating the percentage of insulated vehicles to total vehicles in the other vehicle classes, which was then verified with TCT industry contacts. There was no consensus on the 'correct number' to use, but the estimation provided a broadly sensible mid-point based on the responses received. There was a very high degree of uncertainly around the extrapolated value.

Throughout the remainder of this report ANPR data includes the extrapolation made here and an artic is defined as an articulated combination with insulated semi-trailer.

Number of insulated vehicles operating in London per annum

The data showed there were approximately 25,500 unique insulated vehicles (registered in or after 1990) entering London in 2016-17, with approximately 13,000 (51%) of those being 3.5 tonnes GVW (or less) rigid panel vans.

The table below shows the number of unique vehicles that entered London per annum and per quarter. The quarterly average number of vehicles provided a more representative number for estimating total TCT emissions and distances travelled. We assumed these represented vehicles which regularly enter London[1]. The table also shows the number of TCT vehicles entering the CCZ. On average, approximately 54% of vehicles entering London also entered the CCZ.

Quarter / GVW	Vehicles in London				Vehicles in the CCZ			
	<=3.5t	3.5t-12t	12t+	Artic.	<=3.5t	3.5t-12t	12t+	Artic.
Per year	13,043	3,310	5,976	3,130	7,224	1,958	3,457	1,058
Q1	7,321	2,054	3,745	1,565	3,993	1,199	2,176	529
Q2	7,714	2,083	3,669		4,269	1,199	2,132	
Q3	7,666	2,088	3,744		4,179	1,192	2,153	
Q4	9,007	2,255	4,064		4,929	1,355	2,338	

Table 3: ANPR Insulated vehicles total and quarterly averages

Number of diesel auxTRU vehicles in London per annum

On average TCT stakeholders (e.g. convertors and fleets) estimated the number of insulated vehicles operating in London that had a diesel-powered auxTRU installed to be 0% of the <3.5t, 25% for the 3.5 – 12t, 50% for the 12t+ and 75% for the artics. A low penetration of diesel auxTRUs were applied to the smaller vehicles segments as these are better suited to direct drive (alternator driven) TRUs.

Table 4 below shows the resulting number of vehicles operating in London and the CCZ which have diesel auxTRU units.

[1] The number of artics entering London was reduced by 50% to account for seasonal variation as TCT stakeholders considered that the number of semi-trailers used in the Christmas period was significantly greater than the annual mean number of insulated trailers in use.

Vehicle GVW	<=3.5t	3.5-12t	12t+	Artic.	Row Total
Insulated vehicles in London (Q3)	7,666 (51%)	2,088 (14%)	3,744 (25%)	1,565 (10%)	**15,063 (100%)**
Diesel auxTRU vehicles in London (Q3)	0 (0%)	522 (15%)	1,872 (52%)	1,174 (33%)	**3,568 (100%)**
Insulated vehicles in CCZ (Q3)	4,179 (52%)	1,192 (15%)	2,153 (27%)	529 (7%)	**8,053 (100%)**
Diesel auxTRU vehicles in CCZ (Q3)	0 (0%)	298 (17%)	1077 (61%)	397 (22%)	**1,771 (100%)**

Table 4: Estimated number of diesel auxTRUs

There are around 3,600 unique auxTRU vehicles that regularly enter Greater London on an annual basis, of these 1,771 (54%) also enter the CCZ. The vehicles comprise approximately 0% in the <3.5t GVW category, 15% 3.5-12t, 52% > 12t and 33% being artics pulling trailers with auxTRU units.

5.2 TCT vehicle Euro standard compliance

The ANPR data were used to identify the age of the vehicles operating in London. This age profile was then used to identify their likely Euro emission standard compliance. There is overlap allowed between the end of one set of Euro standards, vehicle registration dates and the commencement of new emission standards. Therefore, the Euro standard data can only be considered broadly correct.

The London auxTRU fleet comprised of 16% of vehicles operating with Euro VI traction engines, 59% with Euro V, 10% Euro IV and 15% Euro III or lower. As stated previously, it is not possible to calculate Euro standard exactly from the year of registration of the vehicles. This, and the fact some companies may elect to operate older vehicles and pay the daily charge in the London Low Emission Zone (LEZ), may explain why 15% of the vehicles appear to be below the minimum Euro IV standard for the LEZ. A breakdown of vehicles by Euro standard is shown in Appendix A1.

5.3 London TCT duty cycle

This section brings together information from the stakeholder questionnaires and workshops to estimate the typical duty cycle and usage behaviour of the London TCT fleet.

5.3.1 Goods and temperature distribution

TCT stakeholders were asked to report on the type of goods they delivered and the type of temperature distribution they operated. Fleet managers who operate both multi-temperature joint distribution (MTJD) and traditional multi-vehicle distribution (TMVD) vehicles, or who have vehicles that operate in both configurations were reported as 'MTJD + TMVD'. The fleet managers' survey results showed that 95% of fleets operate at least some MTJD vehicles, with 48% operating MTJD exclusively. There was only one company (Ocado) that reported a significant number of TMVD vehicles (1,200 across two fleets). However, we recorded these as MTJD as their chilled delivery vehicles use insulated delivery boxes (unlike most of the companies that responded) utilising phase change inserts (typically dry-ice or solid CO_2) for frozen goods. A more typical use of TMVD is delivery of single product (e.g. ready meals, fresh vegetables, or frozen fish).

Table 5 below shows the distribution of goods delivered and onboard temperature management type (single or multi) across the London TCT fleet. The information is a blend of survey results and the TCT industry stakeholder opinions.

Estimates of London TCT fleet - combined results (survey and industry opinion)				
	<=3.5t	3.5t-12t	12t+	Artic.
Total MTJD (multi-temperature)	58%	78%	93%	78%
Total TMVD (single temperature)	40%	20%	5%	20%
% Other	2%	2%	2%	2%

Table 5: Combined estimate of London TCT product and temperature characteristics

MTJD delivery dominates the sector, used in 77% of all TCT vehicles. In this sector, supermarkets were thought to be responsible for 49% of all MTJD vehicles, with a further 18% being independent retailers offering similar mixed goods distribution to supermarkets. 21% is TMVD. The remaining 2% represents temperature distribution which were reported as 'other' in the questionnaire, it is unclear what this was and may represent vehicles which are regularly configured to be either MTJD or TMVD.

A further breakdown of the temperature type by different TCT sectors is provided in Appendix A2.

5.3.2 London TCT fleet duty cycles

London TCT fleet operating hours and annual mileage

Table 6 presents the operating time and mileage undertaken by the TCT vehicles. Fleet managers were unable to clarify how many miles each vehicle undertook in London, therefore the information below represents the annual mileage of TCT vehicles which enter the Greater London area, with the limitation that not all the mileage was actually undertaken within Greater London.

Vehicle type/size	<=3.5t	3.5-12t	12t+	Artic.
Daily operating time (hours)	13.4	14.5	14.1	17.5
Operating days per annum	222	276	282	301
Average speed (km/hr)	15.1	13.9	25.3	37.3
Annual distance travelled per vehicle (km)	44,919	55,627	100,598	196,477
London TCT fleet annual distance travelled (000 km)	344,218	114,983	357,826	307,487
London diesel auxTRU fleet annual distance travelled (000 km)	0	28,745	178,913	230,664

Table 6: Estimated km per year for London TCT fleet

The values in Table 6 indicate that as much as 1,124 million km could be driven by the TCT vehicle fleet that enter London each year, with diesel auxTRU TCT vehicles generating 438 million km (or 39%) of the total TCT distance driven. On average the TCT fleet operate between 14 hours (for vans) and 18 hours (for artics) each day. These estimates were influenced by larger supermarket and retailer fleets operating multiple shifts per vehicle. Smaller, independent traders are less likely to run vehicles for 14 hours a day.

London TCT fleet duty cycles

Duty cycles for the vehicle groups were broken up into four categories.

- **Urban** built-up city centre driving.
- **Regional** typically depot based utilising the main road network to travel between multiple urban areas.
- **Trunking** a majority of motorway driving.
- **Mixed** a combination of the other three duty cycles too finely mixed to segregate out effectively.

The resultant representative driving cycles are shown in Table 7 below.

Vehicle type/size	<=3.5t	3.5t-12t	>12t	Artic.
Mean fleet size (number of vehicles)	90	7	48	34
Survey % Urban	99%	25%	63%	5%
Survey % Mixed	1%	75%	38%	35%
Survey % Regional	0%	0%	0%	6%
Survey % Trunking	0%	0%	0%	53%

Table 7: Fleet survey results for duty cycle of 'average' fleet

Table 12 lists the mean number of vehicles reported in each weight category, not all fleet managers reported a typical duty cycle for their fleets, including some very large retailers. Despite limitations in the number of responses, the resultant information suggests that larger vehicles (articulated and large rigid vehicles) tend to be used most for trunking, regional and mixed operations. Vans are used mostly for urban operations. This is in line with expectations from the freight sector.

Further characteristics of the London TCT fleet are reported in Appendix A3.

6 Energy and emissions from temperature reduction units

Key Points
Methodology: The Cenex LoCITY Fleet Advice Tool, the BUL TCT diesel auxTRU model and publically available emission factors were used to estimate the emissions from both the main engine that propels the vehicle and the additional energy requirements and emissions of the refrigerated compartment of the vehicle.

Key Results: In the greater London area, emissions (t/year) from the TCT fleet are made up of the following:

Traction engine (for providing motive power only):

- 722,636 t WTW CO_2e;
- 4,587 t of NOx; and
- 55 t of PM.

Diesel-powered auxTRUs emit;

- 83,550 t of CO_2e;
- *621 t of NOx (simple estimate factored from compliance limits); and
- 86 t of PM.

Alternator driven TRUs emit;

- 74,930 t of WTW CO_2e; and
- *476 t of NOx (simple estimate factored from increase in traction engine fuel use); and
- *6 t of PM (simple estimate factored from increase in traction engine fuel use).

Of the total WTW CO_2e emissions for the London fleet 82%, 9% and 9% are emitted to supply motive power, diesel auxTRU units and direct drive TRUs respectively. Refrigerant leakage, at a rate of 5% PA, contributes an average of 0.02% towards total CO_2e emissions.

This report estimates that auxiliary engines for transport refrigeration units disproportionately account for around 59% (86 t/annum) of all PM emissions from temperature controlled transport which enters London and 11% (621 t/annum) of all NOx emissions.

AuxTRUs are used on just 23% of the TCT fleet but they account for 57% of NO_X and 87% of PM emissions from the temperature control systems on the TCT vehicle fleet. The remainder being alternator/PTO driven cooling, or static cooling (e.g. ice packs, phase change materials etc.).

If the entire London temperature controlled transport fleet were Euro 6/VI compliant then the percentage of emissions due to auxiliary engines for transport refrigeration units could account for 95% of all PM emissions and 40% of NOx emissions.

When comparing current auxTRU NRMM stage III emission limits to the vehicle Euro standard limits (weighted by the distribution of Euro standards through the London fleet), the London auxTRU units emit 30 times more PM and 4.5 times more NOx per kWh. However, all AQ emission estimates are likely to be optimistic because ***there is currently no requirement for the majority of existing diesel auxTRU engines to comply with any emissions levels.*** This is because the majority of auxTRU diesel units operating in London are below the 19 kW cut-off limit for compression-ignition NRMM compliance.

T***here was no robust evidence base to estimate AQ emissions from London TCT fleet vehicles.*** All AQ emissions presented in this report incorporated a very high degree of uncertainty.

TCT emissions were dominated by supermarket MTJD vehicles, with 50-60% of all emissions coming from this sector.

With total CO_2e estimates at 881,000 t/year for TCT goods delivery, there was evidence to suggest the contribution of the London TCT fleet to GHG emissions has been underestimated in the past.

This section of the report estimates the fuel consumption and resultant emissions of the London TCT fleet.

6.1 Methodology

The total emissions reported were made up of the following three constituent parts.

- **Vehicle only emissions** these represent the emissions generated from fuel used to provide motive power only. WTW CO_2e was estimated by establishing the fuel consumption over the vehicles' average duty cycle reported in section 5.3.2 using the Cenex developed LoCITY Fleet Advice Tool model. Air quality emissions were estimated by entering the average vehicle speed, duty cycle and Euro standard of the vehicles into the COPERT (v10 2014) emission factor tool [6].
- **AuxTRU only emissions** these represent the diesel consumed to provide TCT refrigeration power from the auxTRU units. BUL developed a model of TCT energy requirements [7]. This energy model included the factors highlighted in Section 4.2.1, and was used to estimate the emissions resulting from the cooling requirements of TCT. A brief description of the Brunel Model is presented in Appendix B. **GHG emissions** are presented on a WTW CO_2e basis and include CH_4, N_20 and R404a. Refrigerant gasses such as R404a are extremely potent greenhouse gases. This report assumes all refrigerant gas used by the London TCT fleet is R404a and experiences a 5% leak rate per year (based on average manufacturers' estimates across all vehicle segments). **Air quality** emissions are presented on a tailpipe basis. Whilst the model provides an estimate of fuel consumption, the other emissions (non-CO_2 GHGs and air quality emissions) were estimated by assuming the engine is compliant and emits the allowable emission for the minimum regulated compression ignition engine size of 19kW under NRMM Stage III regulations.
- **Direct drive TCT system emissions** these represent the emissions of fuel burnt in the traction engine which is used to provide refrigeration power in alternator connected systems. Direct drive (PTO and alternator) TRUs are typically described as emitting 50% less [8] CO_2 pollution (compared to a diesel auxTRU) by the manufacturers. The test conditions under which these claims are made are unclear, and there was a lack of real-world evidence in the public domain to substantiate them. With no independent evidence for the impact of alternator powered TRUs for the London TCT duty cycle vehicles, this assessment uses the 50% fuel saving and CO_2 emission improvements from manufacturers' claims. Since in direct drive systems emissions result from increased use of the traction engine, the total AQ emissions from the direct drive systems were estimated by assuming AQ emissions increase proportionally to CO_2 emissions. **It should be noted this is a very simplistic and high-level assumption.**

6.2 Emissions results

The results of the emission modelling are shown in Table 8 below. The figures shown in *grey italics** were not included in the BUL modelling work due to low confidence levels. Cenex have provided indicative estimates here for completeness.

	Emissions London TCT fleet				
	<=3.5t	3.5t-12t	>12t	Artic.	Sub total
CO2e Traction engine (t/year)	95,124	63,600	253,371	310,541	722,636
CO2e AuxTRU (t/year)	0	8,958	31,958	42,634	83,550
CO2e Alternator (t/year)	38,407	13,437	15,979	7,106	74,930
CO2e Total CO2e (t/year)	133,531	85,996	301,308	360,281	**881,116**
NOx Traction engine (t/year)	234	352	2188	1813	4,587
NOx AuxTRU (t/year)					*621**
NOx Alternator (t/year)					*476**
NOx Total (t/year)	372	239	1,388	9,706	**5,684**
PM Traction engine (t/year)	3	3	15	33	55
PM AuxTRU (t/year)	0	8	27	51	86
PM Alternator (t/year)					*6**
PM Total (t/year)	3	11	42	84	**147**

Table 8: Emissions model summary

In summary it is estimated that the London TCT fleet contributes 881,100 t WTW CO_2e, 5,700 t NOx, 147 t PM annually, this breaks down as the following.

Traction engine (for providing motive power only):

- 722,636 t WTW CO_2e;
- 4,587 t of NOx; and
- 55 t of PM.

Diesel-powered auxTRUs emit;

- 83,550 t of CO_2e;
- *621 t of NOx (simple estimate factored from compliance limits[2]); and
- 86 t of PM.

Alternator driven TRUs emit;

- 74,930 t of WTW CO_2e; and
- *476 t of NOx (simple estimate factored from increase in traction engine fuel use); and
- *6 t of PM (simple estimate factored from increase in traction engine fuel use).

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[2] Assuming 80% of (NOx + HC) limit consists of NOx.

Of the total WTW CO_2e emissions for the London fleet 82%, 9% and 9% are emitted to supply motive power, diesel auxTRU units and direct drive TRUs respectively. Refrigerant leakage, at a rate of 5% PA, contributes an average of 0.02% towards total CO_2e emissions.

This report estimates that auxiliary engines for transport refrigeration units disproportionately account for around 59% (86 t/annum) of all PM emissions from temperature controlled transport which enters London and 11% (621 t/annum) of all NOx emissions. If the entire London temperature controlled transport fleet were Euro 6/VI compliant then the percentage of emissions due to auxiliary engines for transport refrigeration units could account for 95% of all PM emissions and 40% of NOx emissions.

AuxTRUs are used on just 23% of the TCT fleet but could account for 57% of NO_X and 94% of PM emissions from the temperature control systems on the TCT vehicle fleet.

All TRUs in the van (3.5t) fleet were assumed to be drivetrain connected, hence there are no auxTRU emissions associated with this segment.

The assumption that auxTRUs comply with NRMM regulations should be considered an extremely optimistic scenario. The majority of auxTRU diesel units operating in London are below the 19kW cut-off limit for compression-ignition NRMM. As such, there is currently no requirement for the vast majority of existing diesel auxTRU engines to comply with any emissions levels. There is a clear need to develop an emissions evidence base from real-world emission testing.

NRMM Stage V regulations come into force from 2019 onwards. All new NRMM engines below the 19 kW range will have to comply with emissions standards for the first time. The Stage V standard has a NOx limit of 7.5g/kWh and a PM limit of 0.4 g/kWh. This compares to a Euro VI diesel truck which has NOx limits of 0.46 g/kWh (94% lower) and PM limits of 0.01 g/kWh (98% lower).

When comparing current auxTRU NRMM stage III emission limits to the Euro limits (weighted by the distribution of Euro standards through the London fleet), the auxTRU units emit 30 times more PM and 4.5 times more NOx (note: the 7.5g/kWh NRMM limit is a joint NOx+HC, we have therefore assumed 80% of this is NOx – which is representative of the ratio in Euro and NRMM emission standard where NOx and HC limits are separated).

TCT emissions are dominated by the Supermarket MTJD vehicles, with 50-60% of all emissions coming from this sector. A further 15 – 20% come from the general mixed MTJD sector, which deliver broadly similar goods to those delivered in the Supermarket category, but these are delivered by independent (i.e. non-supermarket) organisations. A full breakdown of emission by market segment is provided in Appendix A3.

To place these TCT fleet emission values in context, previous research by James and James [12] quote London as generating 41M t/year of CO_2e, with the cold chain reported as contributing approximately 1% (410,000 t/year) of the total [13,14], lower than the value of 881,000t/year reported in this study. The previously-reported cold chain emission estimates include initial temperature reduction during manufacture, rail, shipping, and road freight as well as cold temperature maintained at the point of sale. Therefore, the study evidence suggests that the 1% value for the entire London cold chain underestimates the contribution of the London TCT fleet to GHG emissions.

7 Alternative technologies to reduce emissions

Key Points
Methodology: Alternative options to auxTRU units were reviewed through a literature survey and a stakeholder consultation. Cost and emissions of alternative options were provided by suppliers to assess their performance against the incumbent technology. **Key Results**: • Several interesting technologies are in development. Although not ready for implementation in the short term, energy recovery and alternative traction engine drivetrain technologies should be monitored closely as they offer promising potential for implementation. • Direct drive electric TRUs already have significant market share. Their increased uptake is limited by the need to install additional electrical infrastructure compared to diesel auxTRUs. • Cryogenic refrigeration demonstration projects are underway and should be monitored closely as more data becomes available. • The emission and TCO analysis of technologies for the circa. 18t GVW range showed that significant WTW CO_2e (up to 80%) and air quality (up to 100%) savings could be achieved at a similar TCO to incumbent diesel technology auxTRUs. However, this assessment was based on economic and performance data provided by manufacturers and needs to be verified through real-world trials and data collection. • Total additional infrastructure upgrade cost for site based electrification of the existing diesel auxTRU fleet (excluding articulated TCT trailers) was estimated at £15.8M. The total refuelling infrastructure cost of converting the existing diesel auxTRU fleet (for the 18t+ section, excluding articulated TCT trailers) to cryogenics was estimated at between £58M to £127M this breaks down to between £0.7M and £1.7M per station – with each station servicing around 40 trucks/day. • A detailed feasibility study would be needed to verify the infrastructure cost estimates before further action. **Next Steps**: Having established an understanding of the alternative technologies available, operational factors impacting TCT fuel use and emission profiles are considered.

7.1 Alternative technologies to diesel auxTRUs

In this section of the report possible alternative technologies are highlighted that may contribute to the reduction of total (GHG and AQ) emissions of the London TCT fleet. The characteristics of the main alternative technologies are summarised in Table 9.

Viability colour key:	**Suitable**	**Suitable for some applications**	**Not suitable**

Development	**Viable in the short to medium term?**
Direct-drive electric TRUs: electric motor driven TRUs that are powered through an alternator system, batteries or power take off shaft.	**Yes:** direct-drive electric TRUs already have significant market share. Implementation is limited by the need to install additional infrastructure at delivery and depot sites to maintain refrigerated compartment temperatures when the traction engine is switched off. There is no perceived advantage for the customer to provide infrastructure for third party delivery vehicles.
Eutectic and other phase change materials: a change in state (solid, liquid, gas) or crystalline structure of matter requires energy. Phase change materials are cooled by high efficiency, low emission refrigeration equipment and act as a refrigerated mass to maintain low temperatures. Examples include Solid CO_2 and Ice (H_2O).	**Yes:** suitable for some routes and applications. Combines well with insulated storage boxes for smaller deliveries. Can reduce the total weight or volume available for frozen goods.
Alternative refrigerants: a wide variety of alternative refrigerant gases have been developed over the years to mitigate damage to the upper atmosphere. Examples include: • Low GWP HFC • Other organic fluorocarbons	**Yes:** extensive research has demonstrated the viability of a wide range of low global warming potential (GWP) refrigerant gases. Commercial uptake has been slow however due to the changes to refrigeration systems and operations they require, such as the need for additional training for TCT refrigeration equipment design engineers in the use of flammable gases.
Alternative fuels & powertrains for direct drive TRUs: a wide variety of alternative fuels and novel powertrains are being explored by most, if not all HGV manufacturers. Examples include drop in fuels, biofuels, CNG/LNG, and electrification (battery, plug in hybrid and fuel cell).	**Yes:** demonstration projects for most if not all alterative drivetrains for traction engines are underway. It is recommended that alternative traction engine drivetrain development be monitored closely, especially when considered in combination with direct drive electric TRUs.

Development	Viable in the short to medium term?
Cryogenic fluids: cryogenic fluids provide high efficiency, low emission refrigeration. Examples include: • Liquid Nitrogen (LiN) • Dearman engine	**Yes**: demonstration projects are underway and should be monitored closely as more data becomes available. Infrastructure and delivery requirements hinder total system cost and life-cycle CO_2 emissions effectiveness. Technology best suited to larger vehicles (18t+).
Air cycle refrigeration: air cycle refrigeration utilises air as the refrigerant fluid. Examples include: • Bernoulli heat pump • Stirling cycle	**No**: no evidence found for successful implementation in road based TCT. Air cycle systems tend to be extremely large and operate at very low temperatures. They have been used in heavy duty transport systems (shipping and long haul aircraft) but are not suited to smaller, road haulage based, TCT.
Electrocaloric materials: electrocaloric materials undergo a temperature change when under an applied electric field. These include: • Peltier effect thermo-electric • Magneto thermo materials (e.g., Ni-Mn-In-Co alloys)	**No:** although extremely efficient, and able to hold temperatures with a high degree of stability, these materials are extremely expensive and heavy. As such they are currently only suited to laboratory use or highly specialised, temperature critical transport of premium goods
Energy recovery: energy recovery systems capture energy that is typically discarded in conventional power systems. This includes high temperature exhaust gases with thermo-electric materials, or regenerative braking systems	**No**: additional weight and complexity of energy recovery systems has yet to be justified in mobile refrigeration units. This is an active topic of research and should be monitored over the next few years.
Sorption cycle refrigeration: low grade heat sources are used to induce phase changes in a refrigerant.	**No**: smallest unit available at the time of writing is 35kW for static refrigeration

Table 9: Summary of TCT emissions reduction technologies

7.2 Alternative TRU options for London

Based on Table 9, three alternative technology options are considered viable, or at least may be viable with in a relatively short time frame (zero to five years) for TCT in the Greater London area:

- Electrically driven refrigeration.
- Cryogenic gases and liquids.
- Solid or semi solid (gel) phase change and eutectic materials.

Alternative fuels and refrigerants have also been identified as suitable for implementation in the London TCT fleet. However, the primary focus of this report is the reduction and replacement of diesel powered auxTRUs with low or zero emission alternatives. Therefore, we focus this section on the three alternatives listed above. Each of these technologies is briefly introduced, with an assessment of its maturity, and its suitability for each of the four weight categories. Maturity level is defined in terms of technology readiness level (TRL) as defined by the European Commission [15], and is shown in Table 10.

Technology Readiness Level	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Validated in lab
TRL 5	Validated in relevant environment
TRL 6	Demonstrated in relevant environment
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Proven and manufactured in operational environment

Table 10: Technology readiness levels

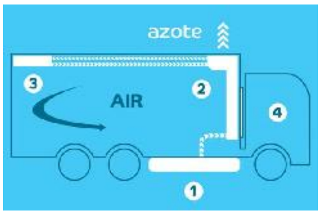
7.2.1 Alternator drive TRUs

<table>
<tr><td colspan="3">Alternator drive TRU</td></tr>
<tr><td colspan="3">
Electric temperature reduction units (also called alternator units, PTO units or direct drive units). These devices use an electric motor to drive the refrigeration unit. PTO units can be powered by an additional on-board battery for brief periods of time, a direct drive connected to the alternator, or a power take off drive shaft. They can be plugged in during depot stops or delivery stops which makes it possible to have zero emission and near silent running deliveries. The emission performance of these units should be superior to auxTRUs as they use the traction engine for power.</td></tr>
<tr><td colspan="3">Technology readiness level: 9</td></tr>
<tr><td colspan="3">Suppliers: Frigoblock, Carrier-Transicold, Zanotti, Hubbard</td></tr>
<tr><td colspan="3">Operational experience: extensively used. Near 100% dominance in 3.5t and smaller vehicles, and significant market share in other weight categories [8]. For example, Frigoblock were active participants in this study and claim 50% market share for the 12t+ category. Limited adoption in articulated trailers due to infrastructure requirements. Large TCT trailers are required to maintain low temperatures for up to 24 hours a day, while the traction engine may be switched off during deliveries.</td></tr>
<tr><td rowspan="4">Applicability classes: (weight or power)</td><td>2-5 kW (van)</td><td>Yes</td></tr>
<tr><td>5 – 10 kW (small truck)</td><td>Yes</td></tr>
<tr><td>8-12kW (large truck)</td><td>Yes</td></tr>
<tr><td>12-19kW (Artic.)</td><td>Yes</td></tr>
<tr><td colspan="3">System costs: premium product with additional cost compared to diesel auxTRUs. Prolonged delivery durations and time at depot without running the main propulsion engine results in additional infrastructure costs to power to the unit for fleets that require refrigerated temperature at depot.</td></tr>
</table>

Table 11: Summary characteristics of electric TRUs

7.2.2 *Cryogenic fluids*

Cryogenic fluids



Cryogenic fluids are created using grid-powered compressor units in dedicated manufacturing units (which can be small enough to install in larger fleet depots if it is cost effective). The cold fluid is stored in thermally insulated and pressurised containers on the vehicle and then using heat exchangers provides cooling to the refrigerated compartment. The post refrigeration gas is then vented to atmosphere. The Dearman unit is a true auxTRU with gas pumping power derived from a dedicated Dearman engine that is driven by the post refrigeration expansion of the liquid Nitrogen. The Air Liquide and Carrier Transicold systems utilise alternator driven pumps to ensure uniform flow of the cryogenic fluid through the heat exchanger and venting systems. Cryogenic TRUs and associated fuel storage tanks are heavier than diesel TRUs and reduce the payload of the vehicle.

Technology readiness level: 7-9

Suppliers: Dearman, Air Liquide, Carrier-Transicold

Operational experience: Dearman and Air Liquide have completed demonstration projects for the technology. The Carrier Transicold system (CO_2 based) is in its first demonstration trial with Tesco. Dearman have produced reports [16] which make the case for the Dearman system.

Applicability classes: (weight or power)	2-5 kW (van)	No
	5 – 10 kW (small truck)	No
	8-12kW (large truck)	18t and upwards
	12-19kW (Artic.)	yes

Table 12: summary characteristics of cryogenic TCT

7.2.3 Phase change (eutectic) materials

Eutectic phase change

Eutectic and other phase change units are cooled to a low temperature between deliveries. In some cases, this operation is carried out by the on-board refrigeration unit in the delivery van. It is recommended that the refrigeration of the eutectic is carried out in a static industrial freezer with increased efficiency; preferably one that is powered by renewable energy sources. The eutectic materials undergo a change of state at key temperatures that requires a significant amount of energy (i.e. heat) to reverse. It is this phase change that makes the eutectic TCT system viable. It is possible to run for short durations using only eutectics, though they are more typically used as a support for an existing on-board refrigeration unit. Eutectic plates are extremely heavy and can reduce the maximum pay load of a delivery vehicle significantly.

Technology readiness level: 9

Suppliers: Hubbard, Eisetechnik, Thermal-Master, OzeFreeze, Sunamp

Operational experience: The technology is often criticised for the additional weight of the eutectic, and for the shift limits imposed by eutectic materials (which typically can only operate for a maximum of 10 hours before requiring prolonged refrigeration). Many eutectic beam systems rely on initial temperature draw-down being carried out in the vehicle, in which case onboard or depot based refrigeration must be used to chill the eutectic materials (typically overnight). Eutectic and other phase change systems have been used for decades in the TCT sector[13,2,17]. Ocado currently use consumable solid CO_2 packs in insulated boxes to provide localised temperature control in their TMVD fleet. Phase change materials are typically limited to single shift duty cycles, as it can take up to 12 hours for the phase change material to be adequately cooled before the next delivery cycle can take place. This can be mitigated by operating multiple systems (for example alternator driven TRUs and phase change materials working together), as practiced by Ocado and several pharmaceutical TCT delivery fleets.

Applicability classes: (weight or power)		
	2-5 kW (van)	No
	5 – 10 kW (small truck)	Yes
	8-12kW (large truck)	Yes
	12-19kW (Artic.)	No

Table 13: summary characteristics of phase change materials

7.3 Economic assessment of typical TCT vehicle and alternative technology

All identified technology providers were asked to submit economic and fuel consumption information for their various mainstream and alternative TCT solutions. The resultant TCO model (based on the manufacturers' data alone) is reported in Table 14 below. All six technologies were based on a representative 18 t vehicle over a 7-year ownership period, to facilitate a like-for-like comparison.

	Diesel auxTRU	PTO	Alternator TRU	Liquid Nitrogen (LiN) + Dearman engine	LiN
Estimated TCO over 7 years	£41,600	£49,200	£40,400	£36,100	£37,400
Estimated tonnes of CO_2e per year (Including R404a)	16	8	12	3	5

Table 14: TRU alternative technology TCO and CO_2e comparison

The CO_2e emissions provided by the manufacturer of the diesel auxTRU unit were approximately 95% of the values estimated from the Brunel Model and the London duty cycle developed in this document (16t per year and 16.8 t per year respectively). This provides further confidence in the BUL model results.

The emission and TCO analysis showed that significant WTW CO_2e (up to 80%) and air quality (up to 100%) savings could be achieved at a similar TCO to the incumbent diesel auxTRU technology, with liquid nitrogen technology showing a £4 – 5k TCO saving. However, this assessment was based on economic and performance data provided by manufacturers, which needs to be verified through real-world trials and data collection. The conditions these costings were supplied under has been provided to TfL in a confidential appendix.

7.3.1 Infrastructure costs

Infrastructure costs were not factored into the TCO assessment above. A high-level assessment of the likely infrastructure costs for various technologies were considered. Appendix C offers more detail on these infrastructure estimates. The main conclusions of the infrastructure assessment are presented below:

- The total infrastructure cost of electrification to allow the existing diesel auxTRU fleet (excluding articulated trailers) to operate on alternator connected systems is estimated at £15.8M. This equates to an average cost of approximately £6.8k per vehicle. Extensive grid reinforcement for the electrification of TCT across greater London is likely and would be a major project requiring extensive planning and management. Typically, grid reinforcement, planning permission, manufacture and commissioning for a single secondary-substation can take around six months.
- The infrastructure cost of converting to cryogenics (for the 18t+ section, and excluding articulated trailers) of the existing diesel auxTRU fleet is estimated at between £0.7M and £1.7M per station – with each station servicing around 40 trucks/day. This results in a cost of approximately £30,000 per truck. It is estimated that 76 stations would be required to support 100% fleet conversion, resulting in a total capital cost requirement of £58M to £127M.

A detailed feasibility study is recommended to verify these high-level estimates. No economic information was provided by suppliers or manufacturers of eutectic or other phase change materials for TCT operation.

7.4 Alternative technologies for diesel auxTRU conclusions

Direct drive electric TRU systems (whether connected to the main traction engine through an alternator, power take-off system or some other means) are the most versatile and mature technology for replacing diesel auxTRUs. TCT duty cycles that require cooling whilst the main traction engine is switched off may require additional infrastructure to connect the TRU to an electricity supply while the engine is not running (known as cold ironing). This need for grid based power can be mitigated by onboard battery systems or phase change materials, increasing the time that the refrigerated compartment can maintain its temperature without the main traction engine running. Articulated trailer TCT is considered the most problematic in terms of adopting direct drive electric TRU systems due to the prolonged loading and unloading times that can be required, a factor that can be compounded by the need to switch off the main traction engine during deliveries to reduce noise pollution.

If funding for cold ironing infrastructure at loading bays, depots and the point of delivery is made available, then direct drive electric TRU systems could replace the majority of diesel auxTRUs in London in the short term.

Cryogenic refrigeration may have a role to play in larger vehicles where direct drive electric TRU systems and the required cold ironing infrastructure cannot be installed cost effectively. At the time of writing the economics and practicability for cryogenic refrigeration are uncertain. However, if policy changed to deter diesel auxTRUs then a niche may open in locations where cold ironing infrastructure cannot be installed.

Eutectic plates and other phase change systems are unlikely to be a standalone replacement for diesel auxTRU vehicles operating typical London TCT duty cycles. Ocado and others have shown that operational use of phase change systems, combined with insulated delivery boxes, can increase the versatility of more traditional TCT vehicles. It is likely that similar benefits could be realised with cryogenic and direct drive electric TRU systems.

Subject to further analysis, the replacement of diesel auxTRUs in the CCZ and Greater London area may be possible within a 10-year time frame for the majority of vehicles. Providing incentives for infrastructure provision, and demonstration projects are facilitated. AuxTRUs vehicles are typically replaced after 7-years. Direct drive electric TRUs should be the first-choice technology to replace diesel auxTRUs, but will require funding and training for TCT stakeholders to support the conversion. Additional cold ironing facilities, and phase change or cryogenic technologies where cold ironing is not suitable, will be required. A dedicated feasibility study and stakeholder consultation process should be implemented as soon as possible to quantify the cost implications and timeframes for the transition.

A summary table of operational and economic suitability of TRU technologies for the various weight classes reported in this study is presented in Table 15 below.

Key:								
White	Not capable of performing the London TCT duty cycle				Not cost competitive			
Amber	Operational compromises may be required				Uncertain cost benefit			
Green	Capable of performing the London TCT duty cycle				Cost competitive option			
	Operational suitability				Economic suitability			
GVW / Technology	<=3.5	3.5-12t	12t+	Artic.	<=3.5	3.5-12t	12t+	Artic.
Diesel auxTRU								
Direct drive TRU (PTO or alternator)								
Cryogenics								
Phase change materials								

Table 15: Economic and operational suitability of alternative auxTRU technologies

8 Influence of best practice in TCT

Key Points
Methodology: A literature review and analysis with the BUL model was completed to assess a wide variety of TCT operational issues which could be better managed to improve the efficiency and emission performance of TCT operations in general. **Key Results**: • There is a lack of knowledge and understanding by stakeholders of some of the factors impacting efficient TCT operations and equipment designs. • TCT operator training has the potential to offer significant emissions savings. • Reducing average door opening times by 25% can save a fleet-average 16% of refrigeration fuel consumption – a saving of 25,000 t CO_2e per year. • Independent research is required to validate the perceived risks, productivity, and emission impact of curtains on refrigerated compartments. • A dark body vehicle has a 27% higher transmission load compared to the white body vehicle on the same duty cycle. • Cooling requirement of stationary vehicles increase by 20% when exposed to sunlight for several hours. • The total CO_2e per year from the London TCT fleet can be reduced by approximately 2,000 t if all refrigerated vehicle bodies are coloured white or silver. This is a possible 1.3% reduction in total annual CO_2e from the TCT fleet. • Full ATP compliance equates to a 1.6% total refrigerated-body emission saving of approximately 2,500 t of CO_2e per year. • Static refrigerants are typically recorded as having 25% annual refrigerant leakage rates. • Estimated emissions due to refrigerant leakage are 91 t/year CO_2e, based on the manufacturers' reported 5% annual leakage rate. Stakeholder engagement revealed that 5% may be a significant underestimate of real-world refrigerant leakage rates – if the actual annual leakage rate was 20% (as was stated by one operator), emissions would increase to 362 t/year CO_2e. • There is a lack of independent evidence to support some of the emission savings claims made for operational changes. Further research is recommended. **Next Steps**: policy and further work recommendations are presented in the final section.

In this section, operational factors that can have significant impact on the fuel use and emissions of TCT are considered in more depth.

There are a variety of external and operational factors that can greatly influence the amount of energy needed to maintain the low temperatures required for safe delivery of TCT goods. These include:

- **Infiltration Load:** any source of high temperature entering the refrigerated compartment.
- **Precooling load:** ideally goods should only be loaded into the vehicle at, or below, the temperature they are to be transported.
- **Product load:** the mass of goods being transported, once at the desired temperature for transport, acts as a cold store. The removal of this mass of cold at each delivery has an impact on the energy required to cool the remaining goods.
- **Transmission load:** the ambient air temperature, air speed and incident sunlight on the surface of the vehicle all impact the energy required to maintain the refrigerated compartment at the desired temperature.

8.1 Door opening

Infiltration time – the time where ambient air and other sources of heat (such as ambient temperature goods) can enter the refrigerated body of the vehicle – is a critical factor of the total cooling power required. TCT vehicles can undergo dozens of door-opening events. Results from the fleet survey showed a typical average open-door duration of 2.5 minutes. Based on the BUL model, Table 16 below shows the reduction in fuel consumption due to reducing the door opening time by 25% for the different vehicle classes over their typical London duty cycle.

	<=3.5t	3.5-12t	12t+	Artic.
25% reduction in door open duration: refrigeration fuel saving	17.8%	14.3%	14.5%	16.7%

Table 16: Refrigeration fuel savings by reduced door opening times

Reducing average door opening times by 25% yielded significant reduction in the energy required to maintain the desired temperature. A fleet-average reduction of 16% across the London TCT fleet equates to a saving of 25,000 t of CO_2e per year.

Detailed telemetry data on TCT door opening times supplied to Cenex (from a fleet of double shifted vans with similar operating cycles) showed the average door opening duration was 8 minutes and 45 seconds. 80% of drivers operated with an average door opening time of 5 minutes and 30 seconds. The remaining 20% were far higher than this, with some drivers leaving the door open for 20+ minutes at a time. This indicates that in some cases average door opening duration could be reduced by over 25% simply through training all drivers to minimize door opening times.

8.2 Curtains for refrigerated compartments

Study research suggested that curtains over the refrigerant compartment doorway can make a significant reduction in the infiltration load. Curtain systems have existed for many years, but these have not been popular with drivers. Face to face interviews with fleet managers during the study revealed several key issues around the use of curtains:

- A typical curtain system for a small vehicle weighs approximately 20 kg. This is more than one standard delivery in the smaller supermarket/mixed delivery sector. If curtains were applied to

cenex

the entire fleet, additional vehicles and drivers would have to be employed to make up the short fall.

- We found no evidence that this would be cost effective regarding fuel savings or emission savings either way.
- Drivers will remove curtains to facilitate speedier delivery times. Most fleet managers are willing to turn a blind eye to this as there is a perceived increased productivity and therefore profitability.
- In larger vehicles where the weight of the curtains is less of a factor, there is anecdotal evidence that visions strips in curtains become damaged and constitute a possible hazard.

The lack of hard evidence for the emission and fuel efficiency savings for curtains on refrigerated vehicles means that it was not possible to recommend their increased uptake. Independent research is required to validate the perceived risks, productivity, and emission impact of such curtains.

8.3 Refrigerant emissions and regulations

Many refrigerants used in TCT have a significant global warming potential, and therefore any leakages would be harmful to the environment. For example, the organic refrigerant R404a, used in over 90% of TCT vehicles in the UK, has a GWP nearly 4,000 times higher than CO_2.

Like all fluorine based organic compounds, R404a usage is controlled by F-gas regulations [18] (2014 EU F-Gas Regulation (517/2014)), and it is only supplied and disposed of by qualified and registered companies. F-gas regulations require the complete replacement and disposal of all F-gas in the system once a leak has been detected and repaired. This means there is no perceived benefit to fleet managers to identify and repair minor leaks of the refrigerant at the earliest opportunity. The 5% leakage rate reported is based on average manufacturers' estimates across all vehicle segments. In the absence of independent studies, it is possible that refrigerant leakage rates are being under reported by the industry. One manufacturer consulted during the study indicated that 20% leakage rates were typical for smaller units, and static refrigeration units are typically recorded as having 25% annual leakage rates [19].

The table below shows the impact the various leakage rates of R404a on total London TCT fleet CO_2e emissions.

Leak rate of CO_2e from R404a TCT fleet	0-3.5t CO_2e (t)	3.5-12t CO_2e (t)	12+t CO_2e (t)	Artic. CO_2e (t)	Total London TCT fleet R404a CO_2e (t)
5%	26.0	18.3	44.6	1.5	91
10%	52.0	36.7	89.3	3.0	181
15%	78.0	55.1	134.0	4.4	272
20%	104.0	73.5	178.6	6.0	362

Table 17: Sensitivity analysis of R404a leakage rate

As can be seen in Table 17, the existing 5% leakage rate estimate of 91 t/year CO_2e would increase to increases up to 362 t/year CO_2e if the average leakage rate is 20% per year.

8.4 ATP

The "Accord relatif aux Transports internationaux de denrées Périssables et aux engins spéciaux à utiliser pour ces transports" (ATP) is an international standard focused on maintaining the integrity of temperature critical goods that are traded and transported across international borders. A given vehicle may be ATP approved for frozen goods for a period of six years. It would then have to be re-tested and, likely, it would only be deemed suitable for the carriage of chilled goods (2°C or higher) for the next three years.

Stakeholders estimated that only 40% of the UK TCT fleet is ATP compliant. Based on the modelling completed by BUL for this report, it has been assumed that non-ATP-compliant TCT vehicles have an average insulation thickness of 75mm. ATP-compliant vehicles need an equivalent of 100mm thickness of insulation. Based on this estimate, the model developed for this study estimates that there is potential to save 2.3% of total fuel consumption (and associated emissions) by increasing insulation to ATP standards. Over the entire TCT fleet, full ATP compliance would equate to a 1.6% total refrigerated-body emission saving of approximately 2,500 t of CO_2e per year.

8.5 Vehicle body colour

Incident solar radiation increases the refrigeration load of a trailer's body. The solar radiation value can vary considerably depending on the absorption and emissivity values of the exterior colour of the body, the ambient temperature, and the insulation properties. Previous work has found the cooling requirement of stationary vehicles to increase by 20% when exposed to sunlight for several hours. When estimating the energy requirement for 'transition load' (the base load of the refrigerated compartment and the materials it is made from, without considering operational requirements) the body colour is of key importance. Figure 4 shows that an 18t rigid dark body vehicle has a 27% higher transmission load compared to the white body vehicle on the same duty cycle.

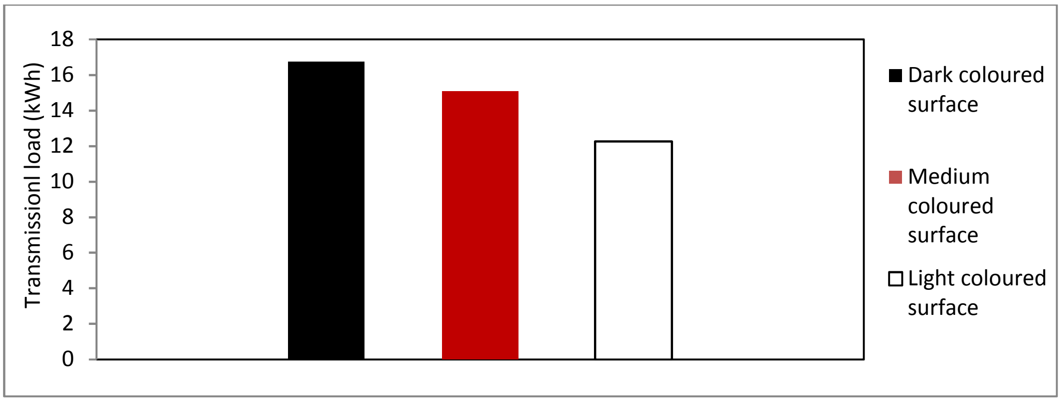


Figure 4: Transmission load (kWh) encountered by an 18t vehicle on delivery rounds

This means that on an average day, for a dark bodied vehicle, the refrigeration unit must consume an additional 0.15 litres of fuel per hour, and therefore emits an additional 0.4 kg CO_2e per hour.

Based on this analysis, the total CO_2e per year from the London TCT fleet could be reduced by approximately 2,000 t if all refrigerated vehicle bodies were coloured white or silver. This is a possible 1.3% reduction in total annual CO_2e from the TCT fleet.

8.6 Operational procedures and training

There are a wide variety of daily work practices and planning techniques that can significantly reduce the total emissions per unit of delivered goods.

- **Consolidation centres:** consolidation centres are independent, centralised distribution centres that can be used by several different suppliers.
- **Stakeholder training in TCT:** there is a lack of basic knowledge and understanding of some of the factors impacting efficient TCT operations and equipment designs.

Consolidation centres are case specific in terms of their usefulness, but have reported significant CO_2e reductions when successful. Maximising the load in individual vehicles can reduce the total number of vehicles on the road. Combining deliveries between companies can reduce the number of vehicles traveling the same delivery routes. Large centralised distribution centres can invest in the most efficient refrigeration equipment. Taken together these factors could combine to reduce the total distance travelled and energy required to deliver a given unit of goods at a given temperature.

TCT fleet manager, purchasing officer and driver training has the potential to offer significant emissions savings. Minimal upfront costs can lead to significant fuel savings if the evidence can be made available to persuade TCT fleets of the cost-benefits of changes to their existing fleet operations. Cemafroid offer a broad range of refrigeration and the environment training courses and report benefits to companies that implement their policies [20]. However, there is a lack of independent evidence to support some of the claims made for operational changes.

8.7 Influence of best practice conclusions

Energy calculations by BUL showed that infiltration loads, resulting from door opening events, was one of the highest sources of additional energy requirements on the refrigeration unit. Vehicle body colour and improved vehicle insulation (for example up to the level that is ATP compliant) were other factors with a demonstrable impact on the total energy requirement, and therefore total emission from refrigeration equipment. TCT stakeholders, from delivery drivers to purchasing officers, appear to be unaware or indifferent to the impact of these additional demands on the refrigeration system. Additional training for TCT stakeholders on these issues is recommended.

To persuade TCT stakeholders that these issues are significant sources of emissions, and add to costs due to additional fuel use, there is a need for a rigorous independent testing. It is recommended that a real-world study of London TCT vehicles be undertaken to quantify the emissions and operational impacts of TCT best practice. This study could then form the basis of a training course and guidance on TCT best practice in the Greater London area.

9 Policy assessment

Key Points
Methodology: a literature review of successful policy implementation in exemplar countries was completed. The findings of a policy workshop event held with representatives of a variety of UK government departments (TfL, local authorities, DEFRA, HMT) are incorporated into this section. **Key Results**: • California intends to introduce stationary operation time limits for all TCT units that are not zero emission at the point of use. ATP compliance is mandatory across France for all TCT vehicles. • A variety of possible TCT policy levers are available in London and the UK. • A combined approach of legally enforced requirements, stakeholder training, and technology adoption are all likely to be required. **Next Steps**: Significant steps to reduce TCT emissions in London can be achieved through a combination of policy and stakeholder initiatives, but will require investment. Priority areas for further investigation and action are: • **Technology trial of alternative TRU options** to provide real-world evidence of costs and benefits. • **Real-world AQ measurements from TRUs** to provide real-world evidence of air quality impacts from TRUs. • **TCT best practice guide production** develop toolkits and guidance documents to encourage best practice operations in TCT transport. • **Tighter emission standards for TRUs** review policy options to ensure whole vehicle TCT transport adheres to the latest emission standards (e.g. Euro VI/6, stage V NRMM). • **Trailer recognition** investigation into solutions for trailer recognition is required. • **Light coloured refrigerated bodies** review policy with TCT stakeholders and implement policy to encourage light coloured bodies. • **Consolidation centres** initiate a feasibility study for consolidation centres for London TCT deliveries. • **Preferential routes and out of hours times for low emission TCT** review policy options with TCT stakeholders and implement if possible.

LoCITY requested that this report include a review of possible policy solutions to reduce emissions from the London and wider UK TCT fleet. A key part of that research was a policy workshop event held with representatives of a variety of UK government departments on July 11th, 2017.

9.1 Examples from around the world

The UK is considered a world leader in TCT technology due to the extensive use of MTJD in London. This results in improved efficiency, reduced total journeys and reduced overall demand on TCT energy requirements. Other countries have developed, or are in the process of developing, their own solutions and policies to improve GHG and AQ emissions from TCT vehicles. This section presents examples of TCT policy from two countries that are viewed as exemplars in controlling emissions from TCT.

9.1.1 California

Existing legislation in California is targeted at two broad weight categories for heavy goods vehicles: those below 11 tonnes, and those above 11 tonnes. Californian standards are focused on activities such as the fitting of PM filters and the use of aerodynamic features on vehicles and permitted idle times during loading and unloading [20]. Such programmes have multiple exceptions and are worded so that the BACT (best available control technology) [21] legislative requirements can be applied. Californian emissions legislation works in parallel with federal legislation on emissions [22]. California has a stated aim to have 100,000 zero emission freight vehicles by 2030, and TCT transport is part of that vision. The primary policy tools used to implement this are as follows:

- TRU engines must meet in-use performance standards by the end of the 7th year after the engine model year or TRU manufacture year. The existing compliance with 2010 new engine emissions standards must now be met by all HGVs on the road.
- All TRUs and TRU generator sets must eventually meet the Ultra-Low-Emission TRU In-Use Performance Standard
- All California-based TRUs and TRU generator sets must be registered in an equipment registration (ARBER) system

The Californian authorities have focused on distribution centres and loading bay dwell times for owned and leased TCT trucks and trailers. This is a topic of interest for the Californian market as it is perceived that distribution centres and loading bays for larger supermarkets are often close to residential and entertainment areas, and so create pollution hotspots adjacent to the public, an issue that is compounded by TCT freight using public car parks when distribution centres and loading bays are full.

The Californian authorities operate three schemes which specifically target TRUs, these are (1) The Low Carbon Transportation/Air Quality Improvement Program, (2) Proposition 1B: Goods Movement Emission Reduction Program, and (3) The Carl Moyer Program.

They also provide infrastructure support for increased electrification of TRUs, including cold-ironing of the vehicles during loading, unloading and related waiting periods.

Plans include the introduction of stationary operation time limits for all TCT units that are not zero emissions at the point of use. By 2030 it is predicted that the phased implementation of stationary waiting times will be as low as 15 minutes for fossil fuel powered TCT. By 2050 California Air Recourses Board have stated that all TCT will operate in a fully zero emission mode at all times. Enforcement proposals are largely focused on the obligatory registration of all TCT vehicles (ARBER system) and the use of electronic tracking systems (ETS) to measure location and compliance with zero emission requirements.

The Californian authorities are still in a fact finding and policy creation phase when it comes to the issue of addressing TCT emissions. The proposed date to present findings, and make final policy decisions, is by the end of 2019. If California successfully implement the currently proposed TCT policies with ETS based enforcement, they will quickly become the world leader in reduced and zero emission TCT.

9.1.2 France

ATP compliance is mandatory across France for all TCT vehicles (except those that *"…transport less than 80 km without reloading, i.e. without opening the doors*" [23]). This means that the majority of TCT vehicles in France are more heavily insulated than their UK equivalent, and will no longer be used for TCT duties once their insulation can no longer meet the ATP standards.

9.2 Policy suggestions

A variety of possible TCT policy levers are available. There is no single operational or technological solution to the issue of emissions from TCT. A combined approach of legally enforced requirements, stakeholder training, and technology adoption will be required. Successful implementation will require clear, consistent leadership from government, education of stakeholders, enforcement of policy and the creation of support infrastructure for new technologies, operational practices, and sustainable power generation.

Based on the discussions presented throughout this report and the results of the stakeholder and policy workshops, the following recommendations are made.

Further areas of research required

This study has highlighted several areas that require further research and consultation before implementation. These areas are summarised below, along with an indication of whether their implementation should be the responsibility of local or national government):

- **Alternative TRU technology trial (responsibility: Local or National government):** instigate a real-world trial of alternative TRU options (similar to the Low Emission Freight and Logistics Trial) to create a working knowledge of the technology costs, emissions and operational factors. Results should be used to inform supporting policy and potential grant structure.
- **Air quality impacts study (responsibility: Local or National government):** instigate a Portable Emission Testing (PEMs) testing program to develop an evidence base for air quality emissions from diesel TRUs (both alternator connected and diesel auxTRU).
- **Trailer recognition (responsibility: Local or National government):** the current inability to register and recognise insulated trailers and a register of installed TRU equipment would be a barrier to the implementation of schemes encouraging more efficient or cleaner technology trailers. An investigation into the solutions for this should be undertaken.
- **Curtains (responsibility: Local or National government):** curtains are heavy and have some impact on payload, and hence increase the number of additional vans required for supermarket fleets. The cost/benefit impact of curtains needs further research.

TCT Operational efficiency recommendations

It is recommended that the following items can be developed to form a series of measures that support increased operational efficiency of TCT:

- **Increased insulation (responsibility: National government):** implement ATP compliance for TCT. Review policy impacts and implementation options with TCT stakeholders.
- **TCT Stakeholder training (responsibility: Local or National government):** Develop toolkits and guidance documents to encourage best practice operations in TCT transport, these can include alt. technology information, case studies, advising industry on factors such as vehicle body colour, curtains, reduced door openings etc. The technology guidance would also need to include an initial research step to develop the required evidence for guidance. Compliance with best practice can be linked with the Freight Operator Recognition Scheme (FORS).

TCT Policy Recommendations

It is recommended that the following policy option are considered to encourage low emission TCT operation.

- **Preferential treatment (responsibility: Local government):** Implement preferential and out of hours access for low emission TCT, review policy options with TCT and local authority stakeholders for preferential treatment of zero-emission TRUs.
- **Introduction of tighter emission standards (responsibility: National government):** review policy options for implementing more stringent emissions standards for TCT. This would review best practice examples from around the world, including consideration of applying traction engine standards to auxTRU equipment. The use of red diesel for existing auxTRU units arguably gives an unfair advantage to an excessively polluting engine. Removing TRUs from the NRMM and incorporating them into the main traction engine emission compliance would significantly alter the distribution of diesel auxTRUs on the UK roads.
- **Consolidation centres (responsibility: Local government):** initiate a feasibility study into consolidation centres allowing zero emission TCT delivery in to London.
- **Infrastructure grants (responsibility: National or Local government):** emissions at depots and unloading bays can be reduced through running TRU units on electricity (cold-ironing), but infrastructure installation and depot electrical capacity is a major barrier. Business may require financial assistance to adopt the technology. A review of the impacts of grant mechanisms should be undertaken.

Further considerations for some of the policy options discussed above are provided in Appendix D.

10 Conclusions

TCT stakeholders consulted were willing to acknowledge the importance of TCT's impacts on AQ and were open to the possibility of changing their technology and/or working practices. A well evidenced and supported plan, brought forward by TfL, has excellent prospects of making long term reduction in emissions arising from the TCT sector.

Some low emission technologies are suitable for implementation in the short term, but will require support to implement quickly. Direct drive electrically powered TRUs are a mature technology already making inroads to this sector. Operational constraints limiting their adoption could be overcome with the installation of depot and point-of-delivery based charge points. Other technologies such as cryogenic based refrigeration are possible longer-term solutions. Real world trials are required to provide evidence of operational suitability and costs.

There are a broad range of policy options available. These range from the short-term solutions with immediate impacts (for example driver training courses) to long-term projects requiring additional feasibility studies, stakeholder engagement and significant resources (for example TCT and other freight consolidation centres, implementing stricter emission standards on auxTRUs).

One issue that has impacted this research was the quality of the data available. TCT is not well studied in the literature and there is relatively little published real-world data. The table below summarises the levels of confidence attached to the different data types used in this report.

High Confidence
The following information were established from independent sources and verified through stakeholder consultation and/or trial data. • **CO_2 emissions from auxTRUs**: Brunel University's energy model was used to calculate fuel consumption from diesel auxTRU units and were verified against operational data. • **London TCT vehicle duty cycle:** Extensive surveys and interviews conducted by Cenex. • **Emissions from TCT traction engines:** Real world data and validated numeric models for other freight and logistics sectors, developed by Cenex, were applied to the TCT fleet duty cycles.
Medium Confidence
The following information were established from incomplete data sets and a clear consensus from stakeholders was not formed. • **Number of auxTRUs operating in London**: ANPR data gives a good indication of the no. of insulated rigid vehicles. However, there is some uncertainty due to the unregulated nature of aftermarket insulated vehicle conversions. Plus, a lack of information on the no. of insulated articulated trailers.
Low Confidence
The following information were gained from manufacturers and/or is unverified by independent real-world trials or data. • **Air quality emissions from auxTRUs**: No robust evidence of auxTRU emissions were identified. Majority of London auxTRUs fall outside of current emission test criteria. A partial AQ impact assessment was undertaken using closest relevant emission standard limit values. • **Emission savings from alternative technologies (incl. alternator connected systems)**: rigorous, real world, tests of the latest TCT refrigeration technologies have not been published. The Brunel University study relied on manufacturer data for alternative technologies. • **Cost assessments**: cost assessments in this report are based on manufacturer claims. • **London TCT fleet mileage**: The mileage declared in the is report is based on the total mileage of TCT vehicles which enter London. The actual mileage undertaken in London is unknown.

Table 18: Data quality assessment

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A. Appendix - Data tables

A1. London TCT fleet Euro compliance

The tables below show the Euro compliance of all the insulated vehicles operating in London, and the Euro compliance of the vehicles operating with a diesel auxTRU units.

Distribution of Euro Standards in the London TCT (insulated bodies only) Fleet						
Euro Standard	**<=3.5t**	**3.5t-12t**	**12t+**	**Artic.**	**Total**	**% Euro Std. penetration in total fleet**
Eu 0	5	3	2	0	10	0%
Eu I/1	18	19	9	53	99	1%
Eu II/2	28	9	34	71	142	1%
Eu III/3	180	122	86	427	815	5%
Eu IV/4	1,179	308	380	107	1,974	13%
Eu V/5	3,233	1,121	2,501	694	7,549	51%
Eu VI/6	3,020	485	545	213	4,263	29%
All	7,663	2,067	3,557	1,565	14,852	100%

Table 19: Euro compliance of the London insulated body vehicle fleet

Distribution of Euro Standards in London Diesel auxTRU Fleet						
Euro Standard	**<=3.5t**	**3.5t-12t**	**12t+**	**Artic.**	**Total**	**% Euro Std. penetration in total fleet**
Eu 0	0	1	1	0	2	0%
Eu I	0	5	5	36	46	1%
Eu II	0	2	17	53	72	2%
Eu III	0	31	43	320	394	12%
Eu IV	0	77	190	89	356	10%
Eu V	0	280	1,251	516	2,047	59%
Eu VI	0	121	273	160	554	16%
All	0	517	1,779	1,174	3,470	100%

Table 20: Euro compliance of the London fleet utilising diesel auxTRU engines

Appendix A2. TCT type by sector

The table below shows the percentage of the TCT vehicle fleet that services each main sector. The data is shown by vehicle temperature control type and sector type. The information combines the opinions of the project stakeholder group with questionnaire data to form an average opinion.

Estimates of London TCT fleet - combined results (survey and industry opinion)				
	<=3.5t	**3.5t-12t**	**12t+**	**Artic.**
London fleet of vehicles (Q3 all ANPR)	7,666	2,088	3,744	1,565
Estimated London fleet of diesel auxTRU	0	522	1,872	1,174
% MTJD General mixed, chilled foods & frozen	14%	14%	29%	14%
% MTJD Supermarket	40%	60%	60%	60%
% MTJD Pharmaceutical	4%	4%	4%	4%
Total MTJD	**58%**	**78%**	**93%**	**78%**
% TMVD Chilled only	20%	10%	-	5%
% TMVD Frozen only	15%	5%	-	10%
% TMVD Fish only	3%	3%	3%	3%
% TMVD Meat only	2%	2%	2%	2%
Total TMVD	**40%**	**20%**	**5%**	**20%**
% Other	2%	2%	2%	2%
Total (MTJD+TMVD+Other)	**100%**	**100%**	**100%**	**100%**

A3. London TCT fleet insulated compartment characteristics

Based on the data provided from surveys, workshops and interviews, Table 10 below presents further information on the usage profiles of TCT operating in London. This information, together with information on the TCT fleets operating mileages, is used to calculate energy and emissions from the London auxTRU fleet in section 6 of this report.

Vehicle type/size	<=3.5t	3.5t-12t	>12t	Artic.
Typical configuration and temperature setting	TMVD 2°C	MTJD 50% = -25°C 50% = 2°C	MTJD 50% = -25°C 50% = 2°C	MTJD 50% = -25°C 50% = 2°C
Deliveries per day	38	26	10	6
Door openings per delivery	2	3	4	5
Average door opening time (mins:secs)	02:48	05:00	08:48	15:00
Refrigeration time required per day (hours)	12.0	10.0	14.0	24.0
Approx. insulation thickness (mm)	75	75	75	75
Air flow rate in refrigerated compartment (m^3/hr)	1550	2600	3667	5600
Refrigerated compartment dimensions (m)	3.7 x 1.9 x 1.9	5.0 x 2.3 x 2.3	6.5 x 2.3 x 2.3	11.8 x 2.3 x 2.6
Refrigerated compartment door opening (m)	1.9 x 1.85	2.2 x 2.2	2.2 x 2.2	2.2 x 2.7
Estimated Power of TRU (W) at 0°C	3,330	5,250	9,600	15,000

Table 21: London TCT fleet characteristics

B. Appendix - Refrigeration emissions modelling

There were several key stages to the emission modelling of the TCT refrigerated compartments and their associated power supplies. The first stage of the assessment was to define the ambient temperature and incident day light that the refrigerated compartment experiences. The second stage was to define the duty cycle. The energy required for a specific category of vehicle, considering the refrigerated compartment as if it were a static refrigeration unit, was then calculated using BUL's refrigeration modelling software. The key outputs from this were:

- **Transmission load**, an estimate of the cooling power required for the vehicle volume, based on its air flow rate, insulation, and heat transfer coefficients for radiative and conductive heat transfer.
- **Precooling load**, the additional energy input required to get the refrigerated compartment down to the desired temperature or temperatures is considered.
- **Product load**, the additional energy required from the loaded product and its thermal mass/heat generation during transport was calculated (e.g. fresh vegetables respire and add to the thermal load of the compartment, milk has a different thermal mass to frozen fish etc.).
- **Infiltration load**, the ingress of warm air and other room temperature products as the door to the compartment is opened for deliveries and the return of empty delivery crates and packaging were considered.

The thermal load in kWhs was then calculated as an average for each month. The model then considered more detailed duty cycle aspects such as the time of day of the deliveries. An example of the resultant total thermal load calculation for a modelled TCT scenario is shown in the table below.

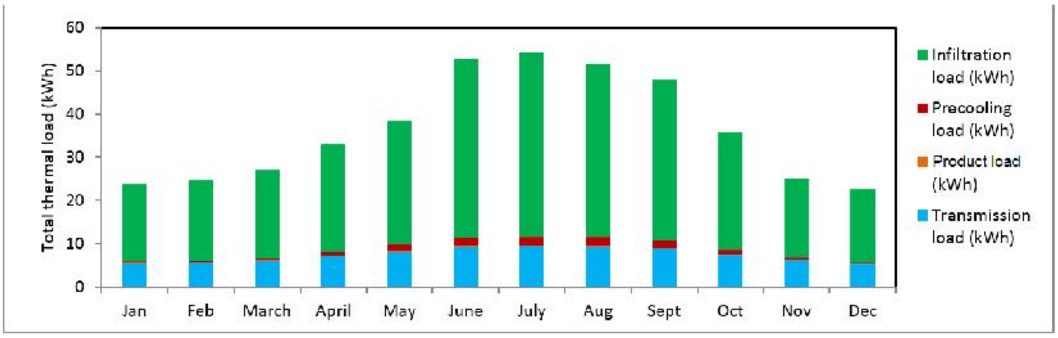

Figure 5: Example thermal load calculation

Model validation

Two different model validations were completed:

I. Fuel consumption of auxTRUs established in the TCT surveys were compared with the fuel consumption results obtained using the model for each vehicle category.

II. Fuel consumption results obtained from the model were compared with fuel consumption recordings provided by a driver in collaboration with Kuehne +Nagel Ltd.

Excluding outlier data points (which we suspect were due to errors in manually recorded refuelling quantities), the overall model predicted energy consumption were on average within 13% of the recorded fuel consumption values. This seems a reasonable margin of error for modelled vs real-world fuel consumption performance of auxTRU units.

C. Appendix - Infrastructure assessment

Electrical infrastructure

The key features of electric drive (PTO or alternator driven) TRUs are:

- Main traction engine powers the unit.
- During driving the main traction engine (indirectly) powers the TRU.
- During longer delivery times and storage between shifts, the engine must be switched off and cold ironing (drawing electricity from an external power source while the engine is switched off) takes place. This requires additional infrastructure on site (400 Volt / 50 Hz, 32 A, slow fuse charging points required for each vehicle) [8].

The economic model considers the following:

- In terms of deliveries, the mean delivery time suggests that for most vehicles under the 12t weight class, there would be little need for cold-ironing during delivery. With 12t+ vehicles indicating door opening delivery times greater than 8 minutes, the options for cold-ironing should be available at many delivery locations.
- Utilising a mean figure of £375 per charge point installation, and the vehicle numbers reported, there is approximately £7.2M of costs to business for charge point installation alone.
- It was estimated that the implementation of alternator-driven TRUs would mean an additional peak load of 9MW (mostly at night as the vehicles are stored/loaded between delivery shifts). In terms of power delivery, it was estimated that 30.2 MVA (mega volt-amperes) of additional substation facilities will be required across London. This equates to 10% of the planned upgrades to substation facilities already under way and, based on the reported costs [26] of those facilities it is estimated the cost for additional substations would be £8.6M.
- Therefore, the total infrastructure cost of electrification of the existing diesel auxTRU fleet is estimated at £15.8M. A detailed feasibility study is recommended before proceeding to verify this initial estimate. If the stated manufacturing capabilities of Frigoblock and Carrier Transicold are correct, this transition could be made in 12 to 18 months.

Please note that this is a very high-level estimate and a detailed feasibility study would be required to estimate the figures with any degree of accuracy.

It would be problematic for logistics companies to negotiate cold-ironing deals with every customer across the greater London region. There is an obvious case to be made for local government to intervene and assist in the installation and upgrade cost of cold-ironing at delivery sites.

Cryogenic infrastructure

Cryogenic solutions require the manufacture, storage and supply of an additional ‘fuel’ in terms of the cryogenic fluid used to provide temperature control to TCT vehicles. This limits the uptake to return to base fleets, or requires additional infrastructure for fuelling cryogens away from the depot. Air Liquide are actively engaged in developing forecourt based LiN alongside other gases such as hydrogen and biomethane.

This economic scenario covers the following assumptions

- **Land**: The area required for the refuelling station requires a tank for LiN and, based on information received from Air Liquide, a dedicated pumping station with a footprint of approximately 11m^2 for the tank and 1.5m^2 for the filling pump station (the two need not be next to each other, but installation costs increase the further apart the two units are). Footprint estimates assume one tank, with two refuelling pumps, each of which can service two HGVs (i.e. up to four vehicles refuelling at the same time). This estimate assumes additional land is available at the mean London rental price of £136 (from 28 sites reviewed – which ranged from £11 to £366) per meter square per year.
- **Construction**: Construction costs should be completed on a case by case basis. The estimates provided here are indicative only. Two sets of construction costs are presented. The lower case assumes a £930/m^2 for a basic HGV ‘garage’ build [26]. The upper cost case assumes £2,060/m^2 for a refuelling station cost [26].
- **Number of stations:** The Q3 ANPR data indicates there is a resident London fleet of 18t and larger vehicles of approximately 3,050 vehicles (excluding artics). Assuming up to 40 vehicles per day could utilise a single LiN refuelling station, up to 76 stations would be required if all vehicles utilised LiN and refuelled daily.

Refuelling equipment: The costs below do not include the LiN refuelling equipment. Costs for the LiN dispenser were included in the TCO modelling. The cost submitted by both Dearman and Air Liquide for the TCO model each assumed depot based refuelling.

LiN construction estimates	HGV Garage Estimate	Refuelling Station Estimate
Building cost per m^2 [26]	£930	£2,060
One LiN tank (11m^2)	£10,230	£22,660
Two fuellers (each at 1.5m^2)	£2,790	£6,180
Space for up four HGV vehicles (each at 200m^2)	£744,000	£1,648,000
Construction costs total	**£757,020**	**£1,676,840**
Annual mean London land rental (814m^2)	**£110,748**	**£110,748**
Capital cost total (76 stations across London)	**£57,500,000**	**£127,000,000**

Table 22: LiN depot and forecourt fuelling costs estimates

It is likely that, if cryogenic cooling were adopted across the rigid 18t + London TCT fleet, many vehicles would operate a return to base and depot based fuelling system as far as possible. Therefore in Table 22 the HGV garage estimate assumes 100% adoption of back to base, depot refuelling of vehicles with minimal additional construction cost. Air Liquide are actively engaged in developing

cenex

forecourt based solutions. Whether depot based or forecourt based, LiN providers have extensive experience of delivering large amounts of gas or liquid to commercial premises to locations through London already. There would be some additional traffic for LiN deliveries to bunker fuel sites, but these would be largely offset by the reduction in diesel deliveries that currently provide energy to the existing TRU technologies.

The guide capital cost of converting to cryogenics (for the 18t+ section – excluding artics) of the existing diesel auxTRU fleet is estimated at between £0.7M and £1.7M per station, resulting in a total cost of £58M to £127M for 76 stations estimated to be required to support 100% fleet conversion. A detailed feasibility study is recommended before proceeding to verify this initial estimate.

Phase change materials

No economic information was provided by suppliers or manufacturers of eutectic or other phase change materials for TCT operation. This makes even a preliminary assessment of the costs for transition to this technology extremely difficult. Some high-level issues can be considered:

- It is not essential to provide direct power consumption for these items by the vehicle during operation.
- Phase change materials can (and often are) used in conjunction with other technologies, assisting PTO and alternator driven TRUs in making deliveries to locations without charge points for TRUs. This makes zero tailpipe emission and silent operation during the delivery possible in many cases.
- To achieve overall energy savings, it is strongly recommended that the eutectic materials be cooled in large, non-mobile refrigeration units. These are considered the most efficient refrigeration units available today, and as such total energy required to cool the eutectic products is reduced.
- Phase change assisted cooling benefits from centralised delivery depots, where renewable power and large scale, high efficiency, static chiller units can be combined to minimise emission and energy costs.
- Most of the London TCT fleet could not make exclusive use of phase change materials. However, the combination of insulated boxes and phase change materials can be a flexible alternative to MTJD vehicles. The use of solid CO_2, which sublimes to gas and is expelled from the vehicle during deliveries, can circumvent some of the additional weight issues that have limited the uptake of eutectic plates in many cases.

D. Appendix - Policy considerations

The table below presents a variety of possible policy suggestions and some considerations. It should be noted that a full feasibility study on policy implementation was not in scope of this report, therefore the considerations below require further investigation and development. The barriers presented are not an exhaustive list. Policy options are presented in order of ease of implementation.

Driver and Fleet / depot manager training in TCT operation and monitoring for reduced emissions
Responsible body: Various. Could be managed through FORS or LoCITY training schemes. **Implementation suggestion:** Voluntary adoption through existing best practice schemes (e.g. FORS – Gold). Procurement policy to only award contracts to trained FORS gold TCT fleets. Cost savings to companies through fuel savings should be shared with drivers to incentivise best practice. **Barriers to implementation:** Need to quantify best practice benefits to foster best practice adoption. Insufficient data exist for many practices (for example curtains). Experienced TCT personal will have to be recruited to deliver the training. Training course content must be developed by competent organisation. **Monitoring and enforcement:** FORS Driver License Checking Service. FORS registration cross reference for ULEZ ANPR systems. **Economic impact:** FORS cost profiles increase for audits and memberships? Auditor training. Driver /operator training classes. **Estimated emission saving per year for the London TCT fleet:** 15% (refrigeration), 24,000 t/year of CO_2e.
Body colour: White and silver refrigerated compartment bodies only
Responsible body: TfL **Implementation suggestion:** Included in training packages and best practise guides (as mentioned above). **Barriers to implementation:** **Monitoring and enforcement:** Traffic enforcement officer training. Appeals process. **Economic impact:** Cost saving for fleets (reduced cost for vehicle designs vinyl wraps). Reduced marketing impact for companies that brand delivery vehicles. **Estimated emission saving per year for the London TCT fleet:** 1.3% (refrigeration). 2,000 kt/year of CO_2e
Increased insulation
Responsible body: Cambridge Refrigeration Technology Ltd, DVSA **Implementation suggestion:** Compulsory ATP registration in the UK. Apply ATP standards to all TCT transport, not just perishable foods. **Barriers to implementation:** Replacement of existing, non-ATP compliant TCT fleet will require time (7-year operational lifetimes are typical for TCT vehicles). Re-certification of older TCT vehicles after six years would require dedicated test facilities. These would need to be funded and constructed in all regions of the UK. ATP training budgets will need to be allocated for organisations tasked with enforcing the new ATP standard. **Monitoring and enforcement:** Clearly displayed ATP compliance and expiry date – enforcement officer training. ATP database, and traffic enforcement training. ATP registration cross-referenced for ULEZ ANPR systems. **Economic impact:** Type approval typically costs £2.5k per vehicle, and applies for approximately 200 vehicles before re-certification inspections are required. Operators who do not currently run ATP approved vehicles will need to replace existing stock – flooding of refrigerated vehicles market place likely and residual values could be reduced. Additional testing required after 6 years. Additional regional test facilities will be required, along with the trained staff. Typically, frozen approved ATP vehicles are downgraded to chilled approved at the 6-year test, and are certified suitable for chilled work for 3 more years. Vehicles are not ATP compliant after 9 years and no longer suitable for TCT. New refrigerated 3.5t vehicles likely to need additional £3k to meet standard. ATP certification and compliance at start of life required. **Estimated emission saving per year for the London TCT fleet:** 1.6% (refrigeration), 2,500 t/y of CO_2e**.**

Electrification infrastructure support – conversion to powertrain driven TRUs
Responsible body: Distribution Network Operators (UK Power Networks for London). Planning permission from local authorities may be required in some installations. **Implementation suggestion:** Qualified site survey staff to assess suitability and cost of upgrades for cold ironing of electrified TRUs. **Barriers to implementation:** Significant infrastructure investment and additional renewable power generation. Time scale to upgrade thousands of depots, stockyards, and commercial premises. Need to ensure Euro-VI engines continue to operate in start-stop mode when using direct drive electrified TRUs **Monitoring and enforcement:** Normal services and operations apply, possibly some additional training for higher power levels required for small businesses. Potential to set an idling limit (as proposed in California case study) to encourage uptake of cold ironing. **Economic impact:** Grid reinforcement and infrastructure purchase required. Renewables needed to maximise emissions mitigation. Manufacturers claim a 50% reduction in TRU fuel use. Does not include life cycle impacts of additional infrastructure. **Estimated emission saving per year for the London TCT fleet:** 4.7% (total) or 50% (auxTRU), 42,000 t/year CO_2e
Euro VI/6 and stage V NRMM mandatory in ULEZ
Responsible body: TfL, DVLA, DVSA **Implementation suggestion:** Vehicle registration and owner/driver declaration. **Barriers to implementation:** Replacement of existing, non-EU VI/6 and NRMM Stage V TCT fleet will require time (7-year operational lifetimes are typical for TCT vehicles). **Monitoring and enforcement:** ANPR in ULEZ. **Economic impact:** Reduced residual value of older fleet vehicles. **Estimated emission saving per year for the London TCT fleet:** up to 60 times less PM and 4.5 times less NOx compared to Euro VI.
Remove auxTRUs from NRMM and classify it as a road engine
Responsible body: DVSA, DVLA **Implementation suggestion:** All TRUs become subject to standard road vehicle conditions (white diesel, MOT emission standards etc.) **Barriers to implementation:** Requires significant policy change at the national level. **Monitoring and enforcement:** As per existing road going vehicles. Trailers more problematic. Currently no register of trailers is publicly available. 3.5t and higher trailers must pass annual MOT; diesel auxTRUs on trailer can be incorporated into MOT emission testing. **Economic impact:** For rigid body vehicles MOT test procedures would require T-pipe joint emission monitoring, low additional cost even for a small MOT emission testing facility. Increased compliance costs. **Estimated emission saving per year for the London TCT fleet:** dependent on classification.
TCT (and other freight) consolidation centres
Responsible body: **Implementation suggestion:** Permitted transports only beyond the 'ring' formed by designated consolidation centres. Professional partnership body required to administer and maintain consolidation centre. **Barriers to implementation:** **Monitoring and enforcement:** Reduced cost per delivered kg of product (increased utilisation of HGVs, reduced refrigeration costs) [24,25]. Increased governmental cost for day to day operation – potential to create self-sustaining as a commercial service to logistics delivery in the CAZ/ULEZ area is limited. Extensive Capex costs for land purchase, planning and construction and commissioning of dedicated newly built structures, and vehicle replacements. Extensive legal fees for government/ commercial logistics agreements. **Economic impact:** **Estimated emission saving per year for the London TCT fleet:** Up to 60% (traction). Up to 433,600 t/year CO_2e.

Table 23: Policy comparison table

Independent, not-for-profit, low carbon vehicle technology experts

Research

Programme Development

Consultancy

Low Carbon Vehicle Event

Cenex
Advanced Technology Innovation Centre
Oakwood Drive
Loughborough
Leicestershire
LE11 3QF

Tel: 01509 635 750
Fax: 01509 635 751
Email: info@cenex.co.uk
Website: www.cenex.co.uk
Twitter: @CenexLCFC