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# Sustainable Refrigerated Road Transport – Investigating the Scale of Carbon Emissions from Direct-Drive Last Mile Refrigerated Vehicles

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**Ted Perry Student Research Prize Winner Paper**

### What you will learn

- The challenges to reducing the direct and indirect emissions of refrigeration road transport vehicles.
- The causes of leakage of refrigerant in refrigeration road transport. There is significant potential to reduce refrigerant leakage within the truck-drive compressor by replacing the type of components used
- How modelling can be used for the design and development of components for more sustainable refrigerated road transport systems.

## 1.0 Introduction

Decarbonisation of road transport vehicles is associated with some particular challenges, one of which is refrigerant leakage. The F-Gas regulations (EU) 517/2014, requires both manufacturers and fleet owners of refrigerated vehicles above 3.5 tonnes to record refrigerant leakage as well as ensure leak tight and efficient refrigeration systems. In addition, manufacturers and fleet owners have to balance the competing interests of maintaining temperature control while reducing the energy consumption of these refrigerated vehicles. Thus, reducing the overall environmental impact (i.e. contribution towards global warming and climate change) of refrigerated road transport (RRT) systems and developing sustainable designs are imperative for the cold chain industry.

The research outlined herein consists of two (2) main parts. **PART 1** focused on evaluating the scale of direct carbon emissions from RRT systems. The independent study investigates the annual refrigerant leakage for belt-driven RRT units typically fitted to light commercial vehicles (approximately 3.5 tonne). It identifies the extent of leakage from the individual refrigeration components in belt-driven RRT units and explores the likely root causes and possible solutions. **PART 2**, investigates the scale of indirect carbon emissions of RRT vehicles. The paper provides a brief overview of the mathematical modelling and experimental methods used to analyse the real-time performance of urban direct-drive refrigerated vehicles. Finally, conclusions are drawn from both parts, which can be incorporated, into best practice guidelines for the design and development of sustainable refrigerated road transport systems.

## 2.0 PART 1 – LEAKAGE ANALYSIS

### 2.1 Methodology

Part 1 of the research was aimed at developing a spreadsheet to analyse the rate of refrigerant leakage from belt-driven RRT units. It also determined the common faults and components prone to leakage associated with the units which should be considered for redesign.

#### 2.1.1 Data Profile

An analysis of 397 existing service maintenance records for typical belt-driven RRT units employed in small-sized 3.5 tonne refrigerated vehicles was conducted. The sample data was provided from two food retail companies (fleet operators) referred to as Company A and Company B. A total of five different last mile RRT home delivery vehicle models from three different manufacturers were identified in the sample. The model for each RRT manufacturer distinguishes the unique style and specifications of the unit comprising e.g. the refrigerating capacity and operating temperatures, the size and design of the heat exchangers and ancillary components (e.g. single fan or twin fan evaporator), refrigerant type, the recommended volume for the insulated box, design number (no.) of door openings per hour and type of defrost. Despite the unique characteristics of each make and model, these units generally had the same split system design, whereby the condensing unit was either located on the rooftop or above the vehicle cab with a single temperature compartment i.e. one evaporator.

The incident reports for Company A were recorded only for one year, while those for Company B were recorded over 2 ¼ consecutive years. Company A vehicles were from three different Manufacturers (denoted Make: X, Y and Z) and had four different models (denoted Model 1 through to 4). Company B had only one model (denoted as Model 5) from one Manufacturer (Make Z) in the sample size. The refrigerant charge size for the units ranged from 1.75 kg – 2.25 kg of R404A refrigerant. Throughout the period investigated a total of 456.19 kg of refrigerant was used to replace refrigerant that was lost in 327 vehicles; and a total of 639 individual faults were identified. The age of RRT unit assembly, which was identified by the vehicle registration, ranged from 1 to 8 years for Company A, while for Company B this ranged from 0 to 2 years.

### 2.1.2 Strategy

A refrigerant leakage evaluation spreadsheet similar to that described in [1] was developed to analyse 397 historical service maintenance records for RRT systems. Microsoft Excel software was used to create a list of predefined questions and a range of possible answers. The structured approach used enabled the capture of critical information about the leak/fault from the maintenance incident-record (e.g. the extracted data would include information on the incident date, vehicle registration number, RRT unit model and make) as well as more basic information about the nature of the faults and the net refrigerant added.

The locations of the faults were categorised using a simplified schematic of a typical RRT unit found on a small-sized 3.5 tonne refrigerated vehicle as shown in Figure 1. The truck drive compressor (also called the road compressor) is located towards the front at the vehicle engine. The suction and discharge pipes from the road compressor are typically connected to the evaporator and condenser respectively by a flexible metallic hose which runs along the vehicle chassis for an average length of 8 metres. The remaining connecting pipes between the vapour compression (VC) refrigeration circuit components are generally made of rigid copper pipe.

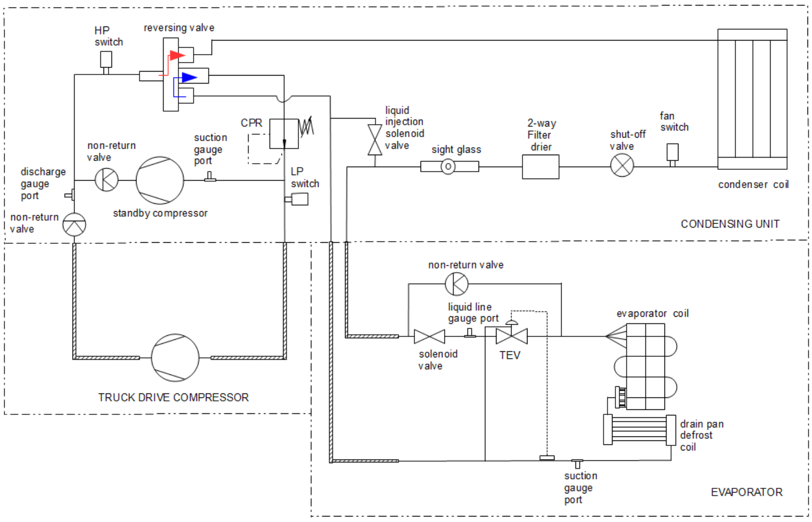

**Figure 1: Belt-driven RRT system schematic partitioned to show potential leakage points**

System boundaries were used to define distinct regions of the refrigeration circuit and consisted of three main regions referred to as system level fault locations, and were: Truck Drive Compressor; Condensing Unit and Evaporator. The Excel spreadsheet was then used to appropriately itemise and map each fault or refrigerant leakage incident reported according to the type of fault; into one of three categories as well as to the individual components within each of the distinct categories of the RRT system. As reported in [1], each region or “system level-fault location” was selected from a drop-down list menu in the Excel spreadsheet analysis. The selected “system level-fault location” then enabled a variety of corresponding sub-components to be selected via the “component level-fault location” drop-down list menu. Subsequently, each fault category could also be selected from a drop-down list menu. This process facilitated comparison between the fault types and locations.

A minimum data set was required from the list of predefined questions and answers, which facilitated data consolidation and comparison from different sources. The minimum data input fields were: Refrigerant Type; Fault Category; Fault Location- system level AND/OR –component level; Net Refrigerant Added. Consequently, the method of analysis ensured standardisation which enabled the data to be easily sorted to determine where leaks or faults were commonly found. A number of general assumptions were made for the analysis of the service records [1].

## 2.2 Establishing the Annual Leakage Rate of Belt-Driven RRT Units

Analysis of the sample data implied that the overall leakage per refrigerated vehicle was approximately 1.40 kg. However, based on the number of records and the corresponding number of vehicles/units, it also implied that some units were inspected and refilled more than once during the period. Ideally belt-driven RRT units are serviced annually or every 20,000 km whichever comes first. It is also necessary that the compressor belt-drive pulley systems be changed every 40,000 – 48,000 km to prevent breakdown. However, prior to the revised F-gas regulations, in practice refrigerant refills may have only occurred once every two years on inspection e.g. during the replacement of the belt-drive mechanism or during breakdown maintenance. Therefore, to establish the actual annual leakage rate from this type of refrigerated vehicle, the data was first sorted according to the number of services or inspections within the year to determine the average refrigerant leakage per unit inspection (see Table 1).Thereafter, the data was sorted to determine the annual leakage rate per unit make as shown in Table 2.

**Table 1: RRT unit inspections or maintenance checks and refrigerant leakage**

| | Company A | | Company B | |
|---|---|---|---|---|
| | **Year 3 (Jan – Dec)** | **Year 1 (Jan – Dec)** | **Year 2 (Jan – Dec)** | **Year 3* (Jan – Mar)** |
| Total no. of vehicles/units | 145 | 85 | 97 | 31 |
| Total no. of service inspection or maintenance checks | 151 | 99 | 115 | 32 |
| No. of total vehicles undergoing more than one service inspection or maintenance check | 5 | 13 | 14 | 1 |
| Percentage (%) of total vehicles undergoing more than one service inspection or maintenance check | 3.45% | 15.29% | 14.43% | 3.23% |
| Net refrigerant added (kg) | 189.39 | 104.6 | 127.8 | 34.4 |
| Refrigerant leakage per unit (kg) for one service inspection only | 1.23 | 1.02 | 1.06 | 1.05 |
| Refrigerant leakage per unit (kg) with >1 service inspections | 3.41 | 2.42 | 2.84 | 3.00 |
| Average refrigerant leakage per unit (kg) | 1.31 | 1.23 | 1.32 | 1.11 |

* Data presented for only three months (Jan-Mar) in Year 3

**Table 2: Estimated annual leakage rate based on RRT unit make and model**

| **RRT Unit Make** | **RRT Unit Type** | **No. of vehicles** | **Refrigerant leakage per vehicle/unit (kg)** | **Percent (%) of original charge leaked over an estimated 2 years** | **Estimated annual rate of leakage** |
|---|---|---|---|---|---|
| X | Model 1 | 65 | 1.21 | 69% | 35% |
| Y | Model 2 | 65 | 1.38 | 62% | 31% |
| Z | Model 3 | 10 | 1.44 | 64% | 32% |
| | Model 4 | 5 | | | |
| | Model 5 | 182 | | | |

Table 1 highlights that the percentage of vehicles where there was more than one inspection or maintenance check (which includes refrigerant refills) within a given year ranged from 3% to 15%. This may suggest that not all of the leak(s) were found and repaired, or possibly that physical damage or an accident occurred. The minimum and maximum net refrigerant added to units that were checked more than once within a year was 2.42 kg and 3.41 kg respectively. In contrast, the net refrigerant added for units that only had one inspection within a given year ranged between 1.02 kg – 1.23 kg. The overall average refrigerant leakage per unit inspection in a given year was 1.15 kg ± 0.58 kg.

To estimate the annual leakage rate based on the unit make, the refrigerant quantity leaked per vehicle was compared to the original refrigerant charge estimated over a two year period. Table 2 indicates that the annual leakage rate for each of the unit makes investigated (i.e. X, Y and Z) varied slightly averaging about 32.4% for units using R404A. This value is significantly higher than the estimated 10% of charge per year for units using similar refrigerants [2] which includes leaks, total charge losses due to ruptures, service losses and end of life losses. This estimate for belt-driven RRT units also exceeds the 25% leakage rate estimated by other authors [3]. In comparison with the annual leakage rate estimated for the manufacturers investigated in this study (i.e. X, Y and Z) shown in Table 2, this suggests that some unit makes may leak more than others. In fact, that the selected pipe fittings commonly used by each manufacturer and installation company may heavily influence the quantity of refrigerant leaked. In addition, the lower leakage value reported [3] may be also due to an array of other reasons including the refrigerant type, operating temperatures and climatic conditions, as well as the use of preventative maintenance and service contracts and the technician workmanship.

Considering the 25% leakage rate reported by others [3], in relation to the annual leakage rate of the various manufacturers analysed in the present study (Table 2), it can be established that the annual leakage rate of belt-driven units as a percentage of the full refrigerant charge amounts to 30% for systems using hydrofluorocarbons (HFCs).

Also it is interesting to note that the nature of many of the faults recorded related to the electrical/electronic hardware and ancillary components; would not be expected to require refrigerant additions. However, the leakage data analysis indicated otherwise. The analysis suggested the existence of leaks within the unit which were not recorded accurately in the service record, since the leak was not observed or identified. Therefore, the average leak rate of RRT units was 80 g $yr^{-1}$ (i.e. 0.16 kg per incident over a two year period) for non-identifiable faults. In these cases where the unit requires refrigerant and the faults are not observed or detected by conventional soapy water or leak detection spray leak tests, the use of calibrated electronic leak detectors on site can assist in accurately pin-pointing leaks along with more frequent servicing of the unit.

## 2.3 Comparison of Refrigerant Recharged and Unit Age

In addition to establishing the annual leakage rate of belt-driven units, it was expected that the age of the unit would influence the leakage rate, whereby a higher leakage would be associated with an older RRT unit. In order to test this hypothesis, the quantity of refrigerant mass recharged indicated by the service record was analysed according to the unit age at the time of inspection or service, in order to observe any possible trends or correlations. Figure 2 shows a graph of the total sample data comparing the refrigerant recharged against the age of the RRT unit for each unit make.

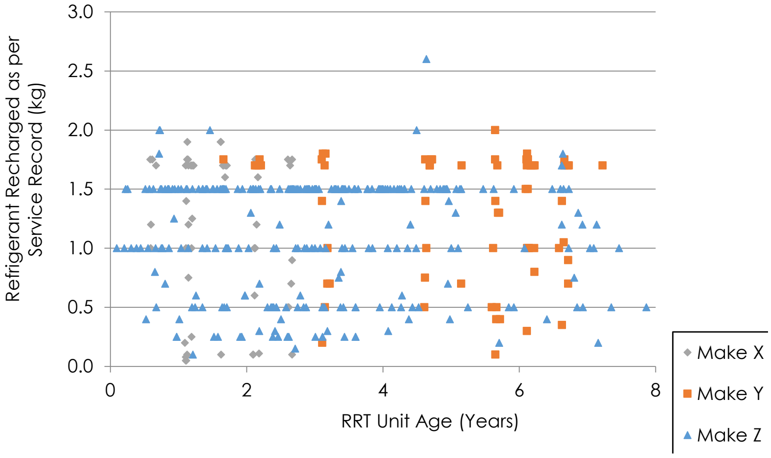

**Figure 2: Comparison of the refrigerant leakage and the RRT unit age analysed from the total sample of the service record data**

It should be noted that the sample data analysed indicates the age of the vehicle/RRT unit that underwent a service inspection. Therefore the units analysed for Make Y captured in the sample data were between ages of 2 – 7 years. This does not necessarily mean that Make Y vehicles under the age of 2 did not leak. Similarly for data provided for Make X age range between 1 – 3 years, this does not mean vehicles above age 3 did not leak. A quick observation for each unit make shows that the quantity leaked does not correlate to unit age. A regression analysis of the total sample data indicates that there is a weak linear relationship. In fact, the age of the unit is not statistically significant and does not predict or influence the quantity of refrigerant leaked (or recharged). Further regression analyses of each unit make output similar results, thereby confirming that RRT units are routinely leaking and leakage is not dependent on the age.

In fact, contrary to the expectations, the leakage rate for new units (age < 2 years) is relatively high (Figure 2). Typically, RRT units are purchased to order, manufactured and assembled in batches. Additionally, the installation, testing and commissioning of each unit may not be standardised as different service companies may be hired to install the unit which may be independent of the manufacturer (or make). Another factor to explain the observed randomness may be due to catastrophic failure due to physical damage, however the refrigerant leakage via this fault category was fairly small, only accounting for 5% of the total faults and 6% of the total refrigerant leaked from both companies, for the period investigated.

The findings herein indicate that the age of the unit does not have a direct impact on the quantity of refrigerant leaked. Hence the leakage rate is not a function of the wear and tear on the unit but rather a function of design.

## 2.4 Fault Locations in Belt-Driven RRT Units

### 2.4.1 Fault Locations at System Level

The faults within each distinct region classified as "system level fault locations" and the corresponding sub-components denoted as "component level-fault locations" of the RRT unit were analysed. Figure 3 categorises the fault locations at the system levels and indicates that an average of 10% of the combined total refrigerant leaked (i.e. 456.19 kg) for Makes X, Y and Z, were not clearly identified in the service maintenance records. The highest percentage of the refrigerant mass recharged was as a result of faults located in the condensing unit for all three makes (an average of 50% for the combined data). This was then followed by the compressor and evaporator for Make X and Z. Make Y had roughly the same percentage of refrigerant recharged due to faults located at the compressor and evaporator.

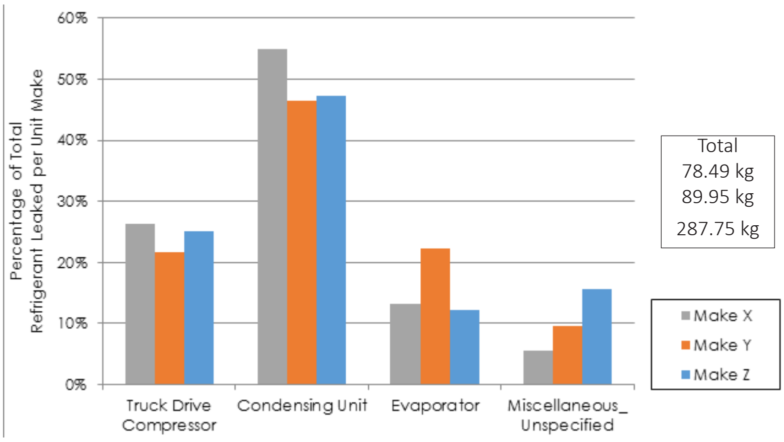

Figure 3: Comparison of the percentage total refrigerant leaked per unit make (by "system level fault locations")

The faults within each "system level fault location" were investigated to identify the leakiest components for each region in order to determine the target areas for leakage control. As such, the research focused on a leak prone “component level-fault locations” which were defined in this research as component(s) that had a fault frequency of greater than 5% and had leakage per incident of more than 0.5 kg (before the leak was found and rectified). This decision-making technique was implemented to identify and select the key causes that needed to be addressed to resolve the majority of problems. This approach was similar to the Pareto Analysis (also known as the 80/20 rule) statistical technique used for failure mode analysis, quality improvement and reliability engineering, which considers the concept that fixing a few key causes (20%) can resolve the majority of problems (80%). This technique is also called the vital few and the trivial many [4]. A bubble chart indicating the relative frequency, refrigerant leaked per incident and the equivalent tonnes of direct carbon emitted for the faulty components found within the Truck Drive Compressor and Condensing Unit Regions are presented in Figure 4.

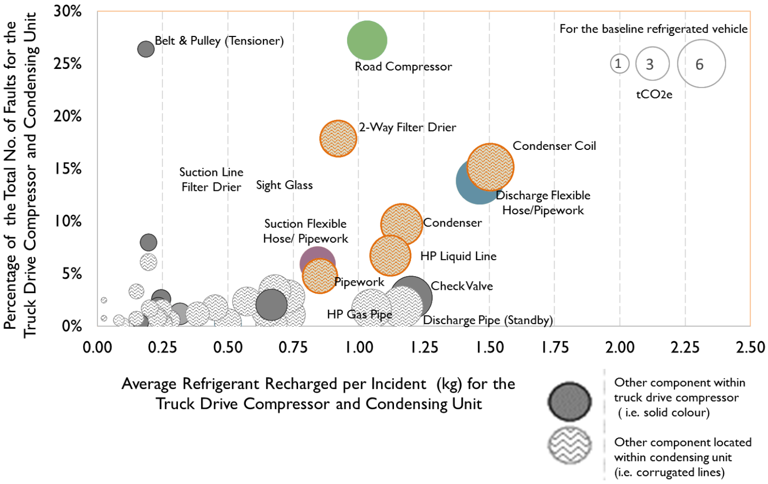

**Figure 4: Faulty components within the Truck Drive Compressor and Condensing Unit**

### 2.4.2 Impact of Leak Control

The leak prone components identified within the truck drive compressor were the open-type road compressor and flexible hoses/pipework, which when combined were responsible for directly emitting 18.2% of the total direct carbon emissions based on the sample data. Approximately 1.00 kg ± 0.17 kg of R404A had been leaked per incident before any issue with the refrigeration system was observed, and the leak subsequently repaired. Potential leak risks within the truck drive compressor which had an occurrence of 19%, can be reduced by replacing the belt-drive system with an alternator electric drive system which would use a semi-hermetic sealed compressor instead of the open-type currently used. In turn this would reduce the length of flexible piping by 6 metres, which would also reduce the volume of refrigerant charge required.

The leak prone components identified within the condensing unit were the condenser coil/unit, hp (high pressure) liquid line and 2-way filter drier. Measures that can be taken to reduce the refrigerant leakage include: driver training to avoid physical damage e.g. accidents affecting the condensing unit; and protection of the typical leak prone components along the hp liquid line. For example the use of vibration isolators as well as making the individual components more resilient to leakage. For this study, it was observed that the faults at the 2-way filter drier for all three manufacturers’ RRT unit were common, leaking on average 0.92 kg ± 0.15 kg of R404A per incident before repair. This individual “component level-fault location” was responsible for directly emitting 10.6% of the total direct carbon emissions based on the sample data. Recommendations for modifying the conventional mechanical connections of the two-way filter-drier were adopted by the sponsoring manufacturer, in order to minimise the risk of leakage by reducing the number of joints and fittings. Assuming a leakage reduction goal of 50% (similar to that achieved in the Society of Automotive Engineers (SAE) I_MAC Research Program), it was estimated that the potential leak risks could be reduced by up to 9% within the condensing unit.

## 3.0 PART 2 – REAL-TIME PERFORMANCE ANALYSIS

### 3.1 Methodology – Investigating the scale of indirect carbon emissions

PART 2 of the research, used a combination of mathematical modelling and experimental methods to describe and characterise the dynamic behaviour of urban direct drive (belt-driven) refrigerated vehicles. By analysing the real-time performance of the refrigerated vehicle, the relative scale of indirect carbon emissions contributed by the RRT system and the transport vehicle (motive work) could be determined.

### 3.1.1 Laboratory and Field Tests

Two sets of experimental data were used to validate the transient model of the RRT system.

For the first data set, the manufacturer’s performance data for a direct drive RRT unit operating under steady state conditions was collected using the general ATP (Agreement for Transport of Perishables) standard test procedure [5]. This involved measuring the effective cooling capacity for the RRT unit used in the study. From the ATP standard test it was determined that the unit had an effective refrigeration capacity of 1.55/2.7 kW for the transport of frozen/chilled produce respectively which were established by testing in a test environment of 30°C. The measured steady state performance data of the unit was used to verify: the evaporating temperature; the condensing temperature using the range of condenser inlet and outlet temperatures; the cooling capacity; and the power consumption (i.e. work done by the compressor), which were predicted by a mathematical model of the refrigeration unit.

The second data set was acquired by means of a year-long field study for the collection and analysis of real-time performance data for similar RRT systems used for the first data set, using sensors and data loggers fitted to three home delivery vehicles and compared while operating under normal conditions in London. The RRT unit was directly driven from the vehicle’s engine crankshaft. The refrigerated truck was based on a 3.5 tonne Mercedes-Benz Sprinter 313 CDi chassis cab.

Field performance data was obtained using telematics equipment and software. A Fleetboard telematics system installed on each vehicle was used to monitor a number of key parameters for each journey undertaken by the home delivery vehicle. This included information on the start and end times for the journey; the distance travelled; average driving speed; journey time; engine speed history; and the total fuel consumption and corresponding indirect carbon emissions (for both the refrigeration system and motive work). A Euroscan temperature monitoring system was used to record temperature measurements for the RRT system. Additionally, the Euroscan system used sensors to monitor and register a range of real-time events including: door openings; fridge unit on/off cycles; defrost on/off cycles; geographical position and average vehicle speed. An analysis of the rate of change of temperature within the refrigerated compartments was conducted in order to estimate the rate at which the heat was extracted from the fitted RRT unit.

Although the Fleetboard data provided information on the total fuel consumption and corresponding indirect carbon emissions for the refrigerated vehicle for a given journey, the software did not distinguish the contribution due to the RRT system of the vehicle. As such, a mathematical model was developed to assess the real energy/fuel consumption of the refrigeration system of the vehicle.

### 3.1.2 Dynamic Model of RRT System

A mathematical model of a RRT system was developed to simulate the dynamic performance of a VC refrigeration circuit as it extracts the heat load from the vehicle temperature controlled storage compartment. The dynamic model of the RRT system employed in this current study used convergent loops at each time increment to calculate steady state heat flows, temperatures and energy consumption at each time step. This was achieved by combining and modifying the subroutine codes of two existing models: CoolVan – a refrigerated delivery vehicle model [6] and ColdRoom – a model of a single stage VC cold room refrigeration system [7], similar to the approach described in [8]. The combined model was adapted to additionally include actual specifications for the RRT system previously used for the experimental tests. In particular, a model of the specified variable speed compressor fitted to the RRT unit was incorporated using the volumetric and isentropic efficiency maps. The compressor performance maps were generated using a simplified steady state model [9], which enabled prediction of the power (i.e. energy) and fuel consumption of the VC refrigeration circuit.

The combined transient model was made up of three different interfaces for the input data which include specifications for (i) the truck body; (ii) the vehicle journey and delivery schedule (including environmental weather conditions), (iii) the VC RRT unit. The simulation results for the refrigerated vehicle journey were recorded to two output files: one for the refrigerated compartment and the other for the VC RRT unit. The key output data for the combined transient model included the heat extracted from the refrigerated compartment and the energy consumed by the compressor. The results of the measured field data were used to validate the transient compartment air temperatures predicted by the RRT system model. A sample of the various real-time events captured in the field study were used to compare and validate the predictions of the air temperature variations inside the refrigerated compartment. These included: (i) with the vehicle stopped and door closed; (ii) with the vehicle stopped and door opened and (iii) with the fridge on and the vehicle moving. Subsequently, the total energy consumption over the journey period was used to estimate the total carbon emissions produced by the RRT system. To determine the annual compressor fuel consumption, the thermal load for the refrigerated vehicle was estimated based on the mean monthly external ambient temperature. It was assumed that 30% of the fuel used for the RRT system was used to operate the ancillary systems [10]. Thereafter, the field data was also incorporated, and used to estimate the annual relative proportion of the total fuel used for vehicle motive work.

### 3.1.3 Results and Discussion

The field tests for the urban home delivery refrigerated vehicle while operating in London indicated that the total journey time was an average of 7 hours per day based on a typical shift work and the vehicle travelled an average total distance of 89 km during this period. The total fuel consumption and corresponding indirect carbon emissions for the RRT system and motive work (i.e. combined) was 11 litres of diesel and 29.3 kg $CO_2$ respectively.

The manufacturer's steady state performance data for the RRT unit operating under ATP conditions was first used to validate the output results generated from the sub module for VC RRT unit. The output results predicted by the VC RRT unit transient model for the cooling capacity and power consumption showed good agreement with the manufacturer's performance test data to within 2%.

The key output results from the dynamic model were the rate of heat extraction and the power consumption of the refrigeration system of the home delivery vehicle. To further validate the model, the simulation results predicted for the rate of change of air temperature inside the refrigerated compartment(s) were compared with a sample of various events monitored under the real-time performance tests. It was considered that the results generated by the model of the RRT system were useful in verifying the performance and events of the refrigerated vehicle and had a relative difference of less than 4%.

The annual fuel consumption for the motive work for a small urban refrigerated vehicle estimated from the field data ranged between 2,517 litres to 3,061 litres depending on factors such as the driving style or the traffic encountered. Model predictions for the annual fuel consumption for the small multi-temperature VC RRT system conducting multi-drop distribution was estimated to be 395 litres i.e. 13% – 16% of the total fuel consumption. Thus the annual indirect carbon emissions due to the RRT system and vehicle motive work ranged between 7,770 to 9,221 kg $CO_2$. It was also estimated that the annual direct emissions due to refrigerant leakage of a system containing R404A could range from 314 kg $CO_2$e (for non-identifiable leak faults) to as high as 2,353 kg $CO_2$e (for an undetected 30% leak rate). Figure 5 summarizes the scale carbon emissions for the direct-drive last mile refrigerated vehicles used in the study.

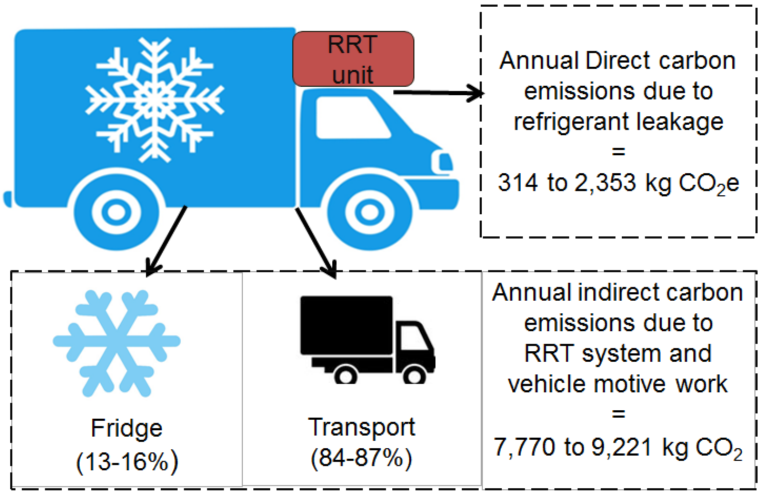

**Figure 5: Scale of carbon emissions for 3.5 tonne urban refrigerated vehicle**

The research study showed that the major carbon contributor is the drive to the wheels (motive work), thus the driving style or traffic encountered during deliveries may have a larger impact than turning on the fridge.

## 4.0 Conclusions

This paper has outlined the mathematical modelling and experimental methods used to analyse the real-time performance of direct-drive last mile refrigerated vehicles operating in London. The refrigerant leakage data analysis revealed that the relative direct carbon emissions due to leakage for a system using R404A refrigerant ranged from 3% (for non-identifiable leak faults) to as high as 30% of the annual indirect carbon emissions for the refrigerated vehicle. The sample data showed that the leakage rate was independent of the unit age for all three RRT unit manufacturers. This highlights the importance of redesigning the system components for improved reliability and/or improved workmanship and installation procedures to reduce refrigerant leakage. It can also be inferred from the real-time performance analysis that smaller lighter more efficient vans would be a far greater benefit to the environment than more efficient RRT units.

The integrated approach undertaken can further be used to model sustainable designs and develop best practice guidelines for RRT systems/vehicles. Additionally, this combined method can be extended to other types of refrigerated vehicles, as well as, exploring the performance of refrigerated vehicles in other climatic and geographical regions. The fuel consumption of the direct-drive RRT system influenced the vehicle motive work, however, current fleet management systems focus on either the RRT system or the transport vehicle as opposed to analysing them as a single unit. Therefore, based on this research, the authors recommend the future development of an integrated refrigerated vehicle management system (RVMS) to enable monitoring of both the fuel consumption and performance of the refrigerated vehicle fleet.

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## About the Author

Dr Christina Francis of London South Bank University, received the IOR's Ted Perry Award for student research in 2018. She carried out research on this topic as part of her studies at London South Bank University. The findings from this research provided new insights into the causes of direct emissions, by identifying the most common sites for refrigerant leakage in transport refrigeration systems. This has led to the redesign of key components and adoption within wider industry.

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