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Environmental impacts of vapour compression and cryogenic transport refrigeration technologies for temperature controlled food distribution

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ABSTRACT

Cryogenic transport refrigeration systems using Liquid Carbon Dioxide or Liquid Nitrogen are proposed as good alternatives to current vapour compression transport refrigeration units powered by auxiliary diesel engines due to their potential for lower environmental impacts and rapid cooling capability. This paper analyses the greenhouse gas emissions of cryogenic and diesel driven vapour compression refrigeration systems for two different temperature controlled lorry sizes and a number of chilled and frozen food products. Both the production and operation emissions have been considered. The results showed that the production emissions of diesel and refrigerant in the vapour compression system can be up to 66% lower than the production emissions of cryogens. However, when taking total emissions into consideration, emissions from all three transport refrigeration technologies are fairly similar and within the margin of error of the assumptions made. The major disadvantage of cryogenic systems is their much higher mass intensity (20 to 60 kg/h), defined as the mass of liquid cryogen per mass of product transported per km, which is almost 10 times higher than that of diesel (2.0–4.0 l/h). This limits their food distribution range per cryogenic fluid tank and together with lack of refilling infrastructure present a barrier to the wider adoption of cryogenic systems for temperature controlled food distribution.

1. Introduction

The development of integrated food chains in developing countries is increasing the worldwide demand for temperature controlled food distribution. It is predicted that the number of refrigerated vehicles globally could increase from an estimated number of 3 million in 2013 to 15.5 million by 2015 [1]. The number of transport refrigeration units (TRUs) in the UK alone is predicted to reach 97,000 by 2025 compared to around 84,000 currently in use [2]. The vast majority of refrigerated vehicles employ vapour compression refrigeration systems driven through an auxiliary diesel engine and use refrigerants as the working fluid.

It is estimated that the commercial food transport, excluding food shopping, is responsible for annual emissions of 12 $MtCO_2e$ in the UK. Approximately a third of food transportation is temperature controlled with cooling invariably provided by vapour compression refrigeration systems driven through an auxiliary diesel engine [2,3]. These systems employ hydrofluorocarbon refrigerants with high Global Warming Potentials (GWP), such as R-404A and R134a (for chilled distribution only) with GWPs of 3922 and 1430 respectively [4]. Estimates of refrigerant leakage from vapour compression TRUs vary between 5% and 25% annual charge per year, with a recent study indicating a leakage rate in the UK of 8% per annum for refrigerant charge quantities between 3 and 8 kg [5]. Even though the direct environmental impacts from refrigerant leakage can be 65–86% lower than indirect emissions from energy consumption, they are still significant and need to be addressed [6].

Tassou et al. [7,8] estimated the average energy intensity and CO_2e emissions for temperature controlled distribution of different food products and different size lorries. The methodology employed is used in this study to compare the performance of vapour compression and cryogenic systems. Bagheri et al. [9] carried out field investigations into the real time performance of diesel driven vapour compression TR systems to identify opportunities for GHG emission reductions. The authors concluded that significant reductions of GHG emissions could be achieved by replacing the diesel engine-driven vapour compression systems with battery-powered systems [9]. Experimental work by Kayansayan et al. [10] investigated the thermal behaviour and COP of a diesel driven TR system in the laboratory. The authors concluded that the most important parameter influencing the performance of the refrigeration system is the air temperature difference outside to inside the refrigerated compartment.

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Nomenclature

C_p	specific heat capacity ($kJ\ kg^{-1}\ K^{-1}$)
D	total distance (km)
D_{hr}	total distance travelled per hour (km/h)
EF_{diesel}	emission factor of diesel ($kgCO_2e\ l^{-1}$)
EFP_{diesel}	production related emission factor of diesel ($kgCO_2e\ l^{-1}$)
EFP_{LCO2}	production related emission factor of LCO_2 ($kgCO_2e\ kg^{-1}$)
EFP_{LIN}	production related emission factor of LN_2 ($kgCO_2e\ kg^{-1}$)
$EFP_{refrigerant}$	production related emission factor of refrigerant ($kgCO_2e\ l^{-1}$)
F	total fuel consumption (l)
F_{fluid}	mass intensity of LCO_2/LN_2 [kg of fluid $kg^{-1}\ km^{-1}$]
F_{fuel}	fuel intensity of diesel (l of diesel $kg^{-1}\ km^{-1}$)
$GD_{operation}$	operation related GHG emission per kg of product per km ($kgCO_2e\ kg^{-1}\ km^{-1}$)
$GD_{production}$	production related GHG emission of diesel per kg of product per km ($kgCO_2e\ kg^{-1}\ km^{-1}$)
$GLCO2_{production}$	production related GHG emission of LCO_2 per kg of product per km ($kgCO_2e\ kg^{-1}\ km^{-1}$)
$GLN2_{production}$	production related GHG emission of LN_2 per kg of product per km ($kgCO_2e\ kg^{-1}\ km^{-1}$)
$GR_{production}$	production related GHG emission of refrigerant ($kgCO_2e\ kg^{-1}\ km^{-1}$)
L_v	latent heat of vapourisation ($kJ\ kg^{-1}$)
M_c	total mass of LCO_2/LN_2 consumed per hour ($kg\ h^{-1}$)
M_{pallet}	total mass of food products on a pallet (kg)
m_c	mass of cryogenic liquid expanded (kg)
Q_c	energy required for transformation (kJ)
$Rate_{leakage}$	annual leakage rate (%)
Ref_{charge}	refrigerant charge (kg)
T_s	desired temperature of cargo space (K)
T_v	temperature of vapourisation (K)
V_{pallet}	average volume load (number of pallets)

Concerns about the environmental impacts of TRUs, have increased the urgency to seek alternatives to vapour compression refrigeration systems for food transport applications [2,7,11]. Among the alternatives, cryogenic TR systems using liquid carbon dioxide (LCO_2) or liquid nitrogen (LN_2) as cryogenic fluids have emerged as prominent options which can reduce the dependency on both diesel and refrigerants to provide cooling [12,14].

Only a limited number of investigations published in the open literature considered the environmental impacts of cryogenic TRUs and their comparison with the impacts of conventional vapour compression refrigeration TRUs. A report by UNEP on low GWP alternatives for commercial and transport refrigeration systems provided a small number of case studies on vapour compression and LCO_2 and LN_2 cryogenic food TR systems [13]. Bengherbi [15] and Tassou et al. [12] provided analyses of the potential economic and environmental benefits of using cryogenic TR systems in Europe. Pedolsky and LaBau [14] outlined the development of cryogenic refrigeration systems and detailed the economic and environmental benefits of these systems over the conventional vapour compression refrigeration TRUs.

A recent report published by the Californian Air Protection Agency assessed the Well-to-Wheel (WTW) GHG emissions of different TR alternatives, including cryogenic TR systems using data for the state of California [11]. The report includes estimates of the environmental impacts of LN_2 and makes an assumption that the environmental impacts of LCO_2 will be similar. The results showed the Well to Tank (WTT) emissions of cryogenic systems to be approximately double those of diesel due to the higher energy required to produce the cryogenic liquid compared to diesel. However, the overall Well-to-Wheel emissions for the cryogenic systems were estimated to be 50–60% lower than those of the diesel driven conventional TRUs due to the assumption of zero emissions from the use phase of the cryogenic fluids.

Apart from Ref. [11], previous comparative studies between vapour compression and cryogenic TRUs were based on the GHG emissions during the operation phase of the TRUs only and did not consider the emissions of the production phase of the fluids in the systems. To fill this gap, this paper investigates and compares the environmental impacts of diesel driven vapour compression refrigeration systems and LCO_2 and LN_2 cryogenic systems for temperature controlled distribution of a number of food products and delivery operations. The aim is to extend the research beyond previous studies and account for all the environmental impacts including those from the manufacture and use phase of the working fluids of both vapour compression and cryogenic systems.

2. Overview of vapour compression TRUs and cryogenic TR systems

The compressor drive method of vapour compression transport refrigeration system can vary depending on various factors such as, duty requirements, weight, noise, maintenance, environmental and fuel taxation [16]. The two most commonly used compressor drive methods, 90% of market, are auxiliary diesel engines with direct drive to run the compressor and fans, and auxiliary diesel engines which drive a generator that electrically powers the compressor and fans [17]. The fuel consumption of these engines can vary between 1 and 5 litres per hour depending on the size of the unit [7]. Besides auxiliary engines, there are TRU systems that are driven directly from the vehicle's main engine power using either an alternator unit or direct belt drive to run the compressor. However, the market share of these systems in long distance transport is still very limited [17]. Fig. 1 illustrates a simple schematic diagram of a vapour compression transport refrigeration unit run with a diesel engine.

The working principles of cryogenic transport refrigeration systems run using LCO_2 and LN_2 are very similar. A large vacuum-insulated tank, mounted underneath the chassis with storage capacity within the range of 420 and 700 kg, is used to store liquid cryogen at controlled pressure [18,19]. The storage pressure is a function of the thermophysical properties of the cryogen. LCO_2 is stored at 8.6 bar while LN_2 is stored at 3 bar [20,21]. The fluids in storage tanks at filling stations are at much higher pressure and lower temperature, LN_2 at 18 bar and −196 °C and LCO_2 at around 22 bar and −57 °C [20,22]. There are three variations of the system, direct type, indirect type and hybrid.

With direct systems, as illustrated in Fig. 2, the cryogenic fluid from the tank is directly injected into the cargo space using sprayers and is released to the atmosphere during door openings. The boiling temperature of LCO_2 at stored pressure is −44.074 °C and that of LN_2 is −185.24 °C. When the liquid fluid comes into contact with the higher temperature air inside the trailer, the fluid starts rapidly expanding to gaseous state. A cool down temperature

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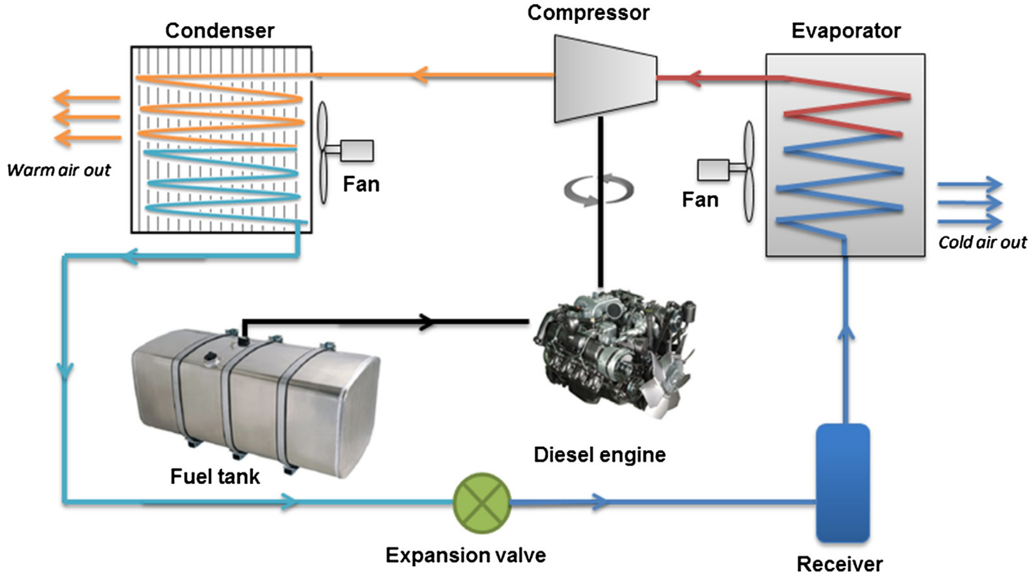

Fig. 1. Schematic diagram of vapour compression transport refrigeration unit driven by a diesel engine.

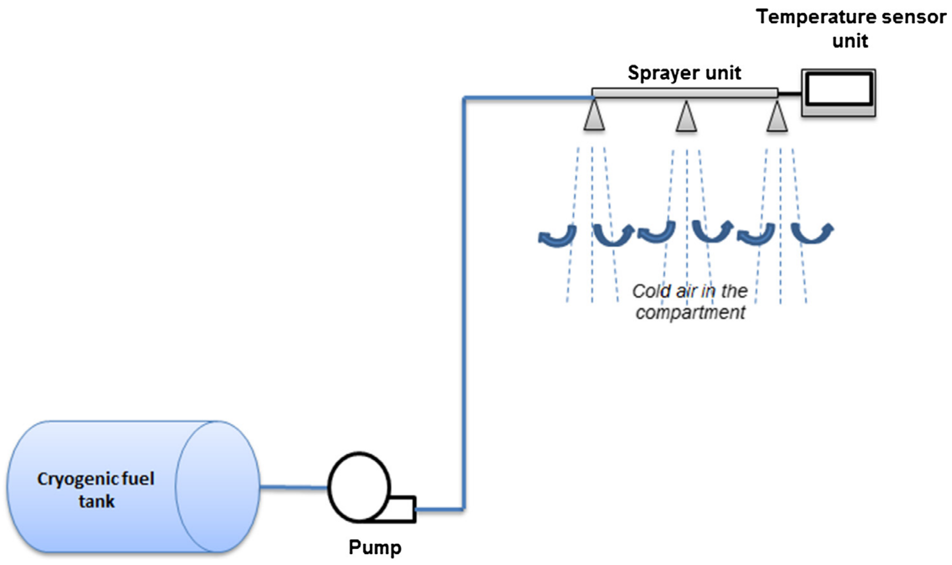

Fig. 2. Schematic diagram of direct cryogenic transport refrigeration system.

of −20 °C can be achieved at ambient temperature of 30 °C in time-frame of less than thirty minutes [13]. Since the gas is released to the atmosphere once it transfers all its thermal energy, the exit condition of the gas is equivalent to ambient. The system provides fast and efficient cooling but also imposes safety risks from reduction of oxygen concentration in the cargo space. In modern direct system designs, a number of overlapping controls are incorporated to monitor the oxygen level and prevent entry into the refrigerated space in situations where low oxygen level (below 19.5%) is detected using a safety gate [14].

Indirect systems, shown schematically in Fig. 3, overcome the safety issues of direct systems by expanding the cryogen in a heat exchanger in the cargo space before discharging it to the atmosphere. The boiling temperatures of the fluids of the indirect system are same as the ones for direct system. The cooling generated by the expansion of the cryogen is transferred to the cargo space by air circulated across the heat exchanger coil by a fan. A cooling capacity of approximately 0.101 kW h per kg of cryogenic fluid can be achieved using the system [15]. The temperature pulldown of indirect system is, however, not as rapid as direct system. The exit condition of the vented gas to the atmosphere is equivalent to the ambient conditions. The design of the system can vary from manufacturer to manufacturer depending on the cooling capacity, size of the cargo, and employment of additional cooling units.

3. Modelling method

The analysis in this paper was carried out using a spreadsheet model developed to determine the energy consumption and GHG emissions of both vapour compression and cryogenic food transport refrigeration systems. The energy consumption was estimated as fuel intensity or mass of cryogen required per kg of food item per km of the distance travelled. The GHG emissions were calculated as the mass of CO_2e per functional unit of the product. Only the fuel/mass intensity required to run the refrigeration system was taken into account and not the fuel consumption from the vehicle's main engine.

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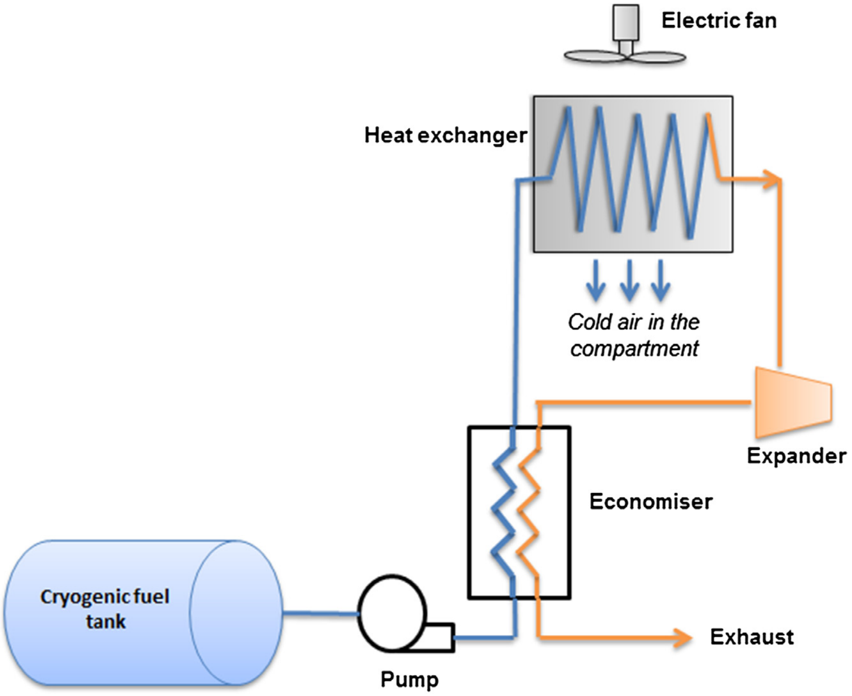

Fig. 3. Schematic diagram of indirect cryogenic transport refrigeration system.

The spreadsheet model comprised of three main calculations:

- Thermal load of each trailer based on the average cooling demand for each month of the year.
- Energy intensity and environmental impact during temperature-controlled food distribution using vapour compression transport refrigeration system
- Energy intensity and environmental impact during temperature controlled food distribution using cryogenic transport refrigeration system

The model calculates the GHG emission parameters using the equations detailed in EN16258 Standard [4].

3.1. Food distribution parameters

The following temperature controlled food distribution parameters and assumptions were considered in the investigations:

- Three different TR systems, (i) diesel powered vapour compression TR system with R452A refrigerant, (ii) indirect LCO_2 cryogenic TR system, and (iii) indirect LN_2 cryogenic TR system.
- Two vehicle sizes, an 18 tonne medium rigid vehicle and a 38 tonne articulated vehicle.
- A refrigerant leakage rate of 10% per year for the vapour compression system [5,23].
- A stamped Euro pallet with dimension of 1.2 m × 0.8 m for the transportation of food products. Products are normally stacked to a height of 1.6 m on the pallet.
- A capacity of 6 pallets for the medium rigid vehicle and 17 pallets for the articulated vehicle.
- A selected range of food products, as listed in Table 1. All food products were assumed to have been pre-chilled or frozen at the required temperature before loading in the vehicle.
- A delivery journey of 10 h with door opening taking place every other hour.
- For each round trip, the trailer was assumed to be fully loaded and the refrigeration system switched on for the delivery journey. On the return journey, the vehicle was assumed to be empty and the refrigeration system switched off, hence, the return journey did not account for any fuel/mass intensity for refrigeration.
- The driving distance was estimated using the combined drive cycle specified by Common Artemis Driving Cycles (CADC) for HGVs heavier than 12 tonnes as illustrated in Fig. 4.

Table 1
Selected range of refrigerated food products.

Food Product	Euro pallet equivalence	Total weight in Euro pallet (kg)
Milk in roll container	726 l	750
Cheese in cardboard box	36 boxes	1036.8
Ready meals	1500 packs	750
Fresh meat	500 packs	500
Frozen chips in cardboard box	64 boxes	640
Frozen peas in cardboard boxes	72 boxes	576

3.2. Thermal load calculations

The transport refrigeration system maintains the temperature of the cargo space at the required level by removing heat from the interior of the trailer. The amount of heat that needs to be removed is the thermal load encountered by the trailer. Once the thermal load is determined, the consumption rate of the fluid required to provide the required cooling can be worked out using the cooling demand. The overall thermal load takes into account the main sources of heat flow in the cargo space; transmission load, infiltration load, precooling load, and product load. The model determines the average thermal load for each month using the specification of each trailer: size, internal and external dimensions, thermal characteristics, and the temperature difference of the cargo space with ambient. The average monthly ambient temperature is illustrated in Fig. 5. Each thermal load was calculated using the methodology specified by ASHRAE [25].

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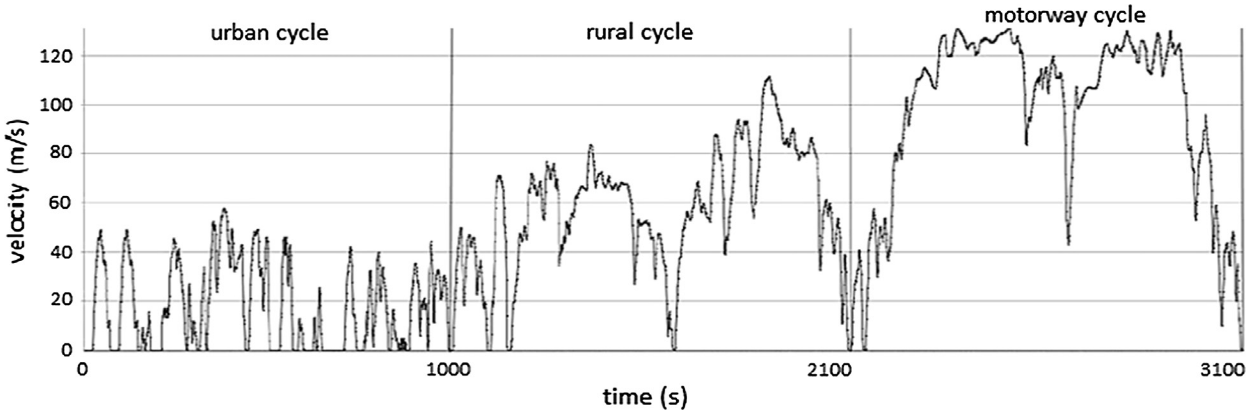

Fig. 4. Common Artemis Driving Cycle (CADC) for urban, rural and motorway with total duration of 3100 s and driving distance of 50,878 m [24].

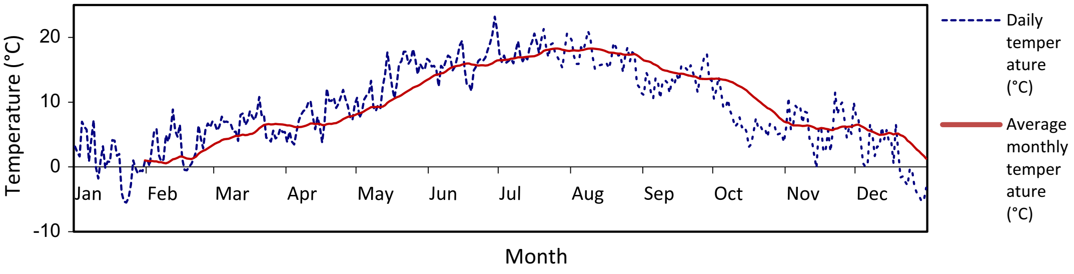

Fig. 5. Average ambient temperature for each month of the year (°C).

The average thermal load calculated by the model for each month is illustrated in Fig. 6. Fig. 7 illustrates the contribution of each load type to the overall thermal load. It can be seen that the transmission load is the highest, followed by the infiltration load, the precooling load and product load.

3.3. Energy intensity and environmental impact of vapour compression transport refrigeration system

Once the thermal load of the vehicle for a delivery round is determined, the energy consumption by the vapour compression system can be calculated based on the cooling capacity of the TRU. The energy density of diesel is approximately 42.612 MJ/kg which translates to 11.83 kW h/kg diesel [26]. For the available energy density of the fuel, only 20–25% is converted into work due to the low efficiency of the small diesel engines employed in conventional vapour compression TRUs [27]. From the useful energy produced by the diesel engine, a third is used to run the ancillary systems and only two-thirds is available to drive the compressor of the vapour compression system, providing cooling of approximately 1.58 kW h/kg diesel. This is not very dissimilar to the value of 2.17 kW h/kg of diesel indicated by [2].

The fuel, F, required by the TRU to satisfy the thermal load can be calculated from:

$$F_{diesel} = \frac{F}{D \times V_{pallet} \times M_{pallet}} \tag{1}$$

Using the most recent GHG emission conversion factor for UK, an emission factor of 2.676 $kgCO_2e$ per litre for diesel and 0.462 $kgCO_2e$ per kW h for electricity were used in the model [28]. The production related emission factor was estimated to be around 0.926 $kgCO_2e$ per litre of diesel [29].

In the absence of data specifically for the production related emissions of R452A, it was assumed that the production of R452A will have similar emissions to other HFCs. Data for R404A, R410A and R407F published by Casini et al. [30] confirm this to be the case with very little differences between the three refrigerants. Based on this assumption, the production emission of R452A was estimated to be 0.214 $kgCO_2e$ per kg of refrigerant.

The operation related GHG emissions are the sum of emissions due to fuel combustion (indirect emissions) and refrigerant leakage (direct emission). The overall GHG emission per kg of food product per km during the operation was determined using;

$$GD_{operation} = Indirect\ emissions + Direct\ emissions \tag{2}$$

$$Indirect\ emissions = F_{diesel} \times EF_{diesel} \tag{3}$$

$$Direct\ emissions = \frac{Ref_{charge} \times GWP\ factor \times Rate_{leakage}}{V_{pallet} \times M_{pallet} \times 100} \tag{4}$$

The production related GHG emissions of diesel fuel per unit mass of food product per km of delivery can be calculated from:

$$GD_{production} = F_{diesel} \times EFP_{diesel} \tag{5}$$

And the production emissions of the refrigerant from:

$$GR_{production} = Amount\ of\ leakage \times EFP_{refrigerant} \tag{6}$$

3.4. Energy intensity and environmental impact of cryogenic transport refrigeration systems

In order to determine the fluid mass consumption, the thermophysical properties of the two fluids at tank's storage pressure, as presented in Table 2, were determined using the REFPROP software [31].

Liquid cryogens when expanded to atmospheric pressure become gaseous. The overall mass (m_c) required to overcome the thermal load was determined using the energy transformation equation below:

$$Q_c = m_c(L_v + C_p(T_s - T_v)) \tag{7}$$

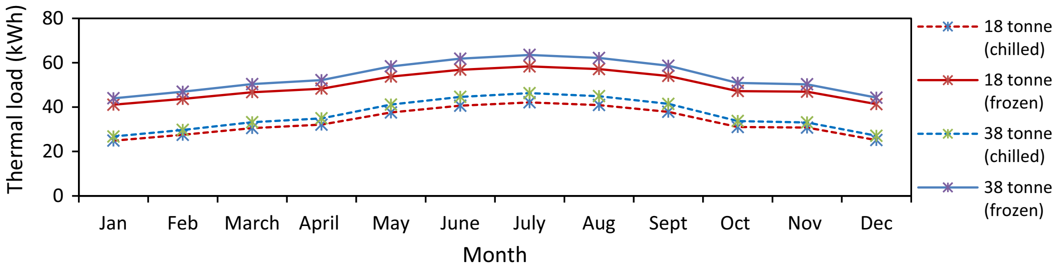

Fig. 6. Average thermal load for each month of the year (kW h).

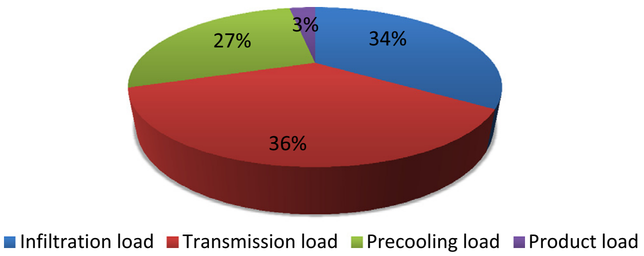

Fig. 7. Contribution of each type of load to the thermal load.

Table 2
Thermophysical properties of selected fluids.

Properties	LCO_2	LN_2
Vehicle's tank pressure (bar)	8.6	3
Boiling point (°C)	−44.074	−185.24
Latent heat of vapourisation (kJ/kg)	329.65	183.96
Specific heat capacity at constant pressure (kJ/kg K)	0.9954	0.8841
Liquid density (kg/m^3)	1132.2	755.7

The fluid consumption per kg of food product per km was determined from:

$$F_{fluid} = \frac{M_c}{D_{hr} \times V_{pallet} \times M_{pallet}} \tag{8}$$

Tajima et al. [34] estimated the energy required during separation of CO_2 using clathrate hydrate formation as 0.853 kW h/kg. ASCO, a CO_2 manufacturer, provided energy consumption values for separation of CO_2 as a function of the plant's capacity: 0.414 kW h/kg for capacity of 70 kg/h, 0.325 kW h/kg for 160 kg/h, 0.295 kW h/kg for 285 kg/h, 0.266 kW h/kg for 500 kg/h and 0.241 kW h/kg for 1000 kg/h [32]. Data from Latif et al. [33] and emission factor of 0.462 $kgCO_2e$ per kW h of electricity results in an emission factor of 0.305 $kgCO_2e/kgLCO_2$ for the production of LCO_2, which falls between the values that can be derived from [34,32]. The value of 0.305 was selected for this paper.

The European Industrial Gases Association (EIGA) specifies a benchmark for the production of LN_2 to be 0.549 kW h/$kgLN_2$, which, assuming an emission factor of electricity as 0.462 $kgCO_2e$/kW h results in an emission factor of 0.254 $kgCO_2e/kgLN_2$ [35]. The collected data were used in the model to calculate the GHG emissions of the fluids during the production stage. Assuming that both LCO_2 and LN_2 were recovered and then released to the atmosphere after use, their operation related emissions can be neglected. The production related GHG emission of LCO_2 and LN_2 can be calculated from:

$$GLCO_{2_{production}} = F_{fluid}\ of\ LCO_2 \times EFP_{LCO2} \tag{9}$$

$$GLN_{2_{production}} = F_{fluid}\ of\ LIN \times EFP_{LN2} \tag{10}$$

4. Results and discussion

The paper assesses the environmental impacts of the cryogenic transport refrigeration systems and provides a comparison of the new systems with conventional diesel powered vapour compression systems. The results indicate that when both the production and operation related greenhouse gas emissions are considered, all three transport refrigeration technologies result in similar environmental impact. The production of cryogen fluids accounts for the highest emission in comparison to diesel and refrigerant combined, indicating a significant need for further improvement in the area.

4.1. Fuel/mass intensity of diesel, LCO_2 and LN_2

Table 3 illustrates the total amount of diesel, LCO_2 and LN_2 required for a 10 h temperature-controlled distribution journey

Table 3
Total amount of diesel, LCO_2 and LN_2 required for a 10 h distribution journey.

Month	Diesel intensity of 18 tonne vehicle (l)		Diesel intensity of 38 tonne vehicle (l)		LCO_2 mass consumption of 18 tonne vehicle (kg)		LCO_2 mass consumption of 38 tonne vehicle (kg)		LN_2 mass consumption of 18 tonne vehicle (kg)		LN_2 mass consumption of 38 tonne vehicle (kg)	
	Chilled	Frozen	Chilled	Frozen	Chilled	Frozen	Chilled	Frozen	Chilled	Frozen	Chilled	Frozen
Jan	18.92	31.21	20.35	33.41	239.9	415.8	258.0	445.0	257.7	445.6	277.1	476.9
Feb	20.91	33.20	22.59	35.67	265.1	442.3	286.5	475.1	284.8	474.0	307.8	509.2
March	23.21	35.51	25.21	38.27	294.3	473.0	319.7	509.8	316.2	506.9	343.4	546.4
April	24.40	36.70	26.56	39.63	309.5	488.9	336.8	527.9	332.4	523.9	361.8	565.8
May	28.55	40.85	31.27	44.34	362.1	544.1	396.6	590.6	389.0	583.2	426.0	633.0
June	30.88	43.18	33.91	46.98	391.6	575.2	430.0	625.7	420.6	616.5	461.9	670.6
July	32.02	44.32	35.20	48.26	406.0	590.3	446.3	642.8	436.2	632.6	479.4	688.9
Aug	31.10	43.40	34.15	47.22	394.4	578.1	433.1	629.0	423.6	619.5	465.3	674.1
Sept	28.77	41.06	31.51	44.57	364.8	547.0	399.6	593.7	391.9	586.2	429.2	636.3
Oct	23.58	35.88	25.63	38.70	299.1	477.9	325.1	515.5	321.2	512.2	349.2	552.4
Nov	23.38	35.67	25.14	38.21	296.5	475.2	318.8	508.9	318.5	509.3	342.5	545.4
Dec	19.11	31.40	20.58	33.65	242.3	418.3	261.0	448.2	260.3	448.3	280.4	480.3

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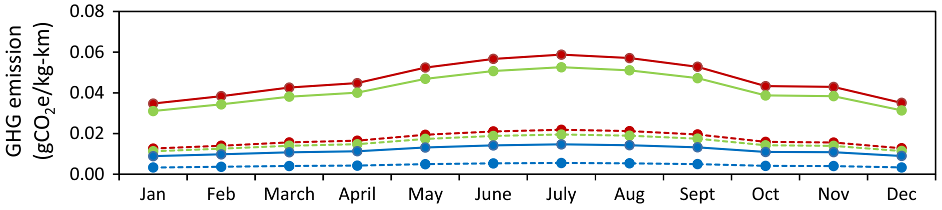
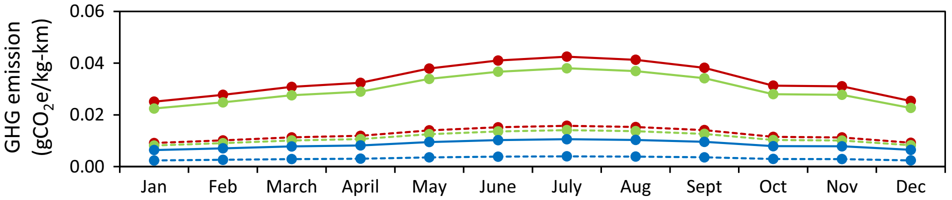
for the average ambient temperature of each month in the London area.

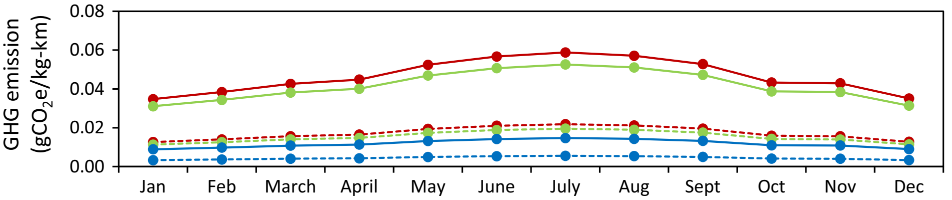
Comparing the fuel intensity of diesel with the mass intensity of the cryogens it can be seen that diesel has much lower mass intensity, meaning that a much smaller capacity tank will be required for diesel for the same distribution rounds. Alternatively, for the same size tank, diesel has much greater range of distribution before refuelling would be required compared to cryogenic fluids.



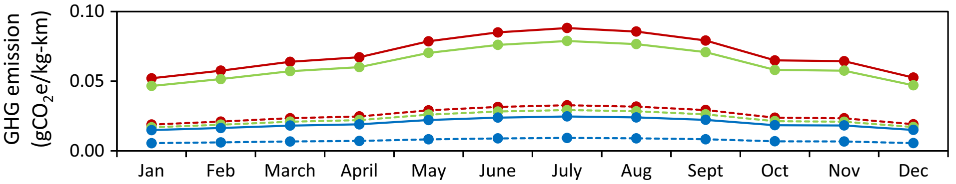
a. Production related GHG emissionsduring distribution of milk.



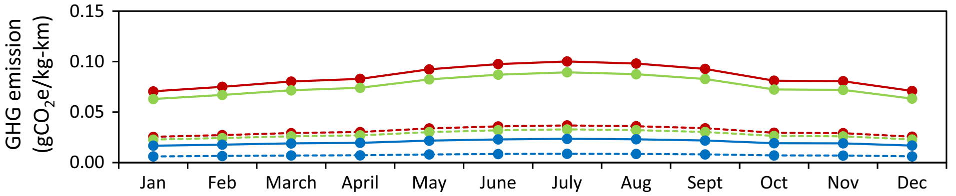
b. Production related GHG emissionsduring distribution of cheese.



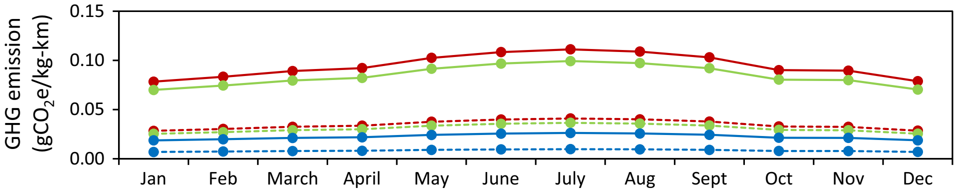
c. Production related GHG emission during distribution of ready meals.



d. Production related GHG emissionsduring distribution of fresh meat.



e. Production related GHG emissionsduring distribution of frozen chips.



f. Production related GHG emissionsduring distribution of frozen peas.

Fig. 8. Production related GHG emissions of different transport refrigeration technologies for different food products (a) milk (b) cheese (c) ready meals (d) fresh meat (e) frozen chips (f) frozen peas.

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The mass consumption of LCO_2 is between 5% and 10% lower than that of LN_2 due to the higher latent heat of LCO_2 at the stored pressure in the tank. The frozen food distribution operation accounts for higher fuel (mass) intensity than chilled operation due to the higher temperature difference between the refrigerated compartment and the ambient air, making it a more energy intensive process. The fuel intensity of the vapour compression system varies between 2 l/h for chilled distribution with a medium rigid vehicle to 6 l/h for frozen distribution with a large articulated vehicle. The mass intensity of LCO_2 varies between 20 kg/h and 60 kg/h and that of LN_2 between 25 kg/h and 65 kg/h for chilled and frozen food distribution for the two vehicle sizes respectively.

4.2. Environmental impacts

Using the mass consumption for the journey, the environmental impacts of each food product per unit mass of food per km of distance travelled were determined. Both production and operation related environmental impacts were calculated separately and then combined to estimate the overall impact value.

4.2.1. Production related GHG emissions

Fig. 8 illustrates the production related GHG emissions of the three different transport refrigeration technologies for different food products using an 18 tonne and a 38 tonne vehicle.

It can be seen that for all cases, LCO_2 has the highest production related GHG emissions followed by LN_2 and then diesel and refrigerant combined. The production emissions of diesel and refrigerant together for the vapour compression system are up to 66% lower than the production emissions of cryogenics fluids. This is mainly due to the energy intensive process of the manufacture of the cryogens and the larger quantities of fluid required for the same distribution trip compared to diesel fuel. Though the mass consumption of LCO_2 is lower than LN_2, the emissions from the LCO_2 are higher due to the higher production related emission factor of LCO_2. The production environmental impacts per unit mass of food transported with the 38 tonne vehicle is approximately 50% lower than that for the 18 tonne vehicle demonstrating the advantage of distribution with larger vehicles provided they are fully loaded.

4.2.2. Total GHG emissions (production and operation)

Tables 4 and 5 illustrate the total GHG emissions of different transport refrigeration technologies for different food products using an 18 tonne and a 38 tonne vehicle. The total GHG emissions are the sum of the production and operation related emissions.

During the operation phase, the vapour compression TRU is responsible for emissions from diesel fuel combustion and refrigerant leakage. For the cryogens, the emissions from the operation of the systems will be negligible as discussed earlier in the paper. From Tables 4 and 5, it can be seen that the emissions per kg food per km from the refrigeration systems of the large 38 tonne vehicle will be less than half the emissions from the 18 tonne vehicle for both chilled and frozen distribution of all food products investigated. This is due to the larger volume of product that can be distributed by the articulated vehicle during a distribution journey. Compared to the vapour compression and LCO_2 technologies, the LN_2 technology exhibits slightly lower emissions for all products and ambient temperatures. The difference is more distinct for the 18 tonne vehicle TRUs and chilled food distribution. Diesel emissions are slightly higher than the emissions from the cryogenic TRUs for frozen food distribution with the 18 tonne vehicle.

It should be noted that this study has not considered particulate matter (PM) and Nitrogen Oxide (NOx) emissions from diesel engine driven TRUs. Currently, emissions from these engines are not regulated and there are concerns about their impact on air quality. This area is beyond the scope of the current paper that focuses on GHG emissions and will be addressed in future research.

4.3. Economic considerations

The price of diesel in the UK is approximately £1.2 per litre, while the price of the cryogenic fluids is approximately £0.12 per kg of LCO_2 and £0.08 per kg of LN_2 [36,37]. Using the fuel and mass intensities presented in Section 4.1 for the different transport refrigeration technologies, it can be estimated that the running cost of the cryogenic TRUs will be very similar compared to the running costs of diesel driven TRUs. In terms of capital cost, cryogenic systems at present have higher installation costs at around £22,000 compared to diesel driven TRUs, £18,000–£21,000 [11]. Moreover, unlike the petroleum fuel infrastructure already in place, additional investments would be required to achieve the

Table 4
Total GHG emissions (production and operation) of different transport refrigeration technologies for an 18 tonne vehicle.

Food products	Fluid type	Total GHG emissions (gCO_2e/kg-km) for 18 tonne vehicle (production and operation)											
		Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Milk	LCO_2	0.03	0.04	0.04	0.04	0.05	0.06	0.06	0.06	0.05	0.04	0.04	0.04
	LN_2	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.03
	Diesel + Refrigerant	0.03	0.04	0.04	0.04	0.05	0.06	0.06	0.06	0.05	0.04	0.04	0.04
Cheese	LCO_2	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03
	LN_2	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.02
	Diesel + Refrigerant	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03
Ready meals	LCO_2	0.03	0.04	0.04	0.04	0.05	0.06	0.06	0.06	0.05	0.04	0.04	0.04
	LN_2	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.03
	Diesel + Refrigerant	0.03	0.04	0.04	0.04	0.05	0.06	0.06	0.06	0.05	0.04	0.04	0.04
Fresh meat	LCO_2	0.05	0.06	0.06	0.07	0.08	0.09	0.09	0.09	0.08	0.06	0.06	0.06
	LN_2	0.05	0.05	0.06	0.06	0.07	0.08	0.08	0.08	0.07	0.06	0.06	0.05
	Diesel + Refrigerant	0.05	0.06	0.06	0.07	0.08	0.08	0.09	0.08	0.08	0.06	0.06	0.05
Frozen chips	LCO_2	0.07	0.08	0.08	0.08	0.09	0.10	0.10	0.10	0.09	0.08	0.08	0.07
	LN_2	0.06	0.07	0.07	0.07	0.08	0.09	0.09	0.09	0.08	0.07	0.07	0.06
	Diesel + Refrigerant	0.07	0.07	0.07	0.08	0.08	0.09	0.10	0.09	0.09	0.07	0.07	0.07
Frozen peas	LCO_2	0.08	0.08	0.09	0.09	0.10	0.11	0.11	0.11	0.10	0.09	0.09	0.08
	LN_2	0.07	0.07	0.08	0.08	0.09	0.10	0.10	0.10	0.10	0.09	0.07	0.07
	Diesel + Refrigerant	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.10	0.09	0.08	0.08	0.07

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Table 5
Total GHG emissions (production and operation) of different transport refrigeration technologies for a 38 tonne vehicle.

Food products	Fluid type	Total GHG emissions (gCO_2e/kg-km) for 38 tonne vehicle (production and operation)											
		Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Milk	LCO_2	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
	LN_2	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
	Diesel + Refrigerant	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
Cheese	LCO_2	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01
	LN_2	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Diesel + Refrigerant	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01
Ready meals	LCO_2	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
	LN_2	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
	Diesel + Refrigerant	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
Fresh meat	LCO_2	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
	LN_2	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
	Diesel + Refrigerant	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Frozen chips	LCO_2	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03
	LN_2	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	Diesel + Refrigerant	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Frozen peas	LCO_2	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03
	LN_2	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03
	Diesel + Refrigerant	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03

same level of refilling facilities for cryogenic systems, further increasing infrastructure cost.

5. Conclusions

The main conclusions from the study are as follows:

- The fuel intensity of diesel powered vapour compression TRUs (2.0–4.0 l/h) is much lower than the mass intensity of the LCO_2 and LN_2 cryogenic TRUs (20–60 kg/h) for all ambient temperatures, products and distribution journeys investigated enabling diesel driven systems to have much greater range of temperature controlled food distribution without tank refilling compared to cryogenic systems.
- Production emissions of the diesel fuel and refrigerant in diesel driven vapour compression systems are up to 66% lower that the production emissions of cryogenic fluids as larger quantities of cryogens are required to overcome the same cooling demand compared to diesel in diesel driven vapour compression refrigeration systems.
- When the total emissions (production and operation) are considered, the emissions from diesel driven vapour compression and cryogenic systems were found to be similar for the food products and distribution journeys considered. Even though the LN_2 system exhibited slightly lower emissions than the other two systems the differences are too small, and within the context of assumptions made, it is difficult to draw definitive conclusions.
- Emissions from TRUs in the distribution of temperature controlled food products with larger articulated vehicles are more than 50% lower than emissions from TRUs on smaller rigid vehicles due to the larger carrying capacity of articulated vehicles.
- The running costs of cryogenic transport refrigeration systems were found to be at a par with those of conventional driven TRUs but the installed and infrastructure costs are higher reducing their economic attractiveness under current conditions. This may change if future legislation places restrictions in the use of diesel driven TRUs due to particulate and NOx emissions from diesel engines.
- Further improvement in relation to energy consumption during the production of the fluids can significantly help reduce the overall environmental impact of cryogenic transport refrigeration system. The data generated in this paper can be very useful to studies concerned with the evaluation of Life Cycle Environmental impacts of temperature controlled food transportation.

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