Liquid Air on the European Highway

The economic and environmental impact of zero-emission transport refrigeration



Dearman.

Defining our terms

Throughout this report, 'liquid air' is a shorthand that describes both liquid air, which is not yet produced in commercial quantities, and liquid nitrogen, which can be used in the same way, and is produced in bulk throughout the industrialised economies. In the longer term, liquid air would be cheaper to produce, but in the short to medium term it is likely that liquid nitrogen – for which there is substantial spare production capacity – will provide the 'fuel' for liquid air transport refrigeration units (TRUs). The phrase 'liquid air' should be taken to cover both liquid air and liquid nitrogen throughout. For more detail, see Spotlight on: Liquid air and liquid nitrogen and Appendix 1.

Throughout this report, the phrase 'liquid air transport refrigeration unit' or 'liquid air TRU' refers only to TRUs that extract both cooling and mechanical power from the phase-change expansion of liquid air or liquid nitrogen. The phrase excludes systems that extract cooling only – such as those from Cryofridge, Frostcruise, natureFridge and blueeze – which are described as 'evaporation only'. Since such systems fail to extract the mechanical power available from the expansion of liquid air, they are far less efficient and far less competitive against diesel. For more detail please see the Spotlight on: Zero-emission transport refrigeration and the case for fuel duty reform or Appendix 2.

Throughout this report the phrase 'transport refrigeration' refers only to the cooling of a refrigerated vehicle and not its propulsion.

Throughout this report we use European numbering conventions rather than Anglo-Saxon, so the decimal mark is represented by a comma, and thousands are separated by a space – eg €1,2 million not €1.2 million, and €540 000 not €540,000.

The modelling for this report was converted from sterling to euros at an exchange rate of £/€ 1,36.

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Liquid Air on the European Highway

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Zero-emission transport refrigeration and the case for fuel duty reform

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Foreword

The world relies heavily on cold. The food we eat, the buildings we inhabit, the data we consume and the medicines that keep us healthy all need cooling. Getting food from the farm to our plates depends on a seamless network of refrigerated processing, storage and transport to ensure it arrives in good condition and doesn't go to waste.

Transport is vital: it's no good producing food and then just leaving it in a cold store; it needs to move quickly and efficiently from producer to consumer, and that requires a large fleet of refrigerated vehicles.

The problem is that those vehicles cause serious damage to the environment and health. The vast majority of refrigerated trucks use diesel-powered refrigeration, and burning diesel leads to emissions of not only CO_2 but also toxic particulate matter and nitrogen oxides. Worse, in many refrigerated vehicles the cooling is powered by a secondary diesel engine that is generally inefficient and can emit many times more air pollution than the propulsion engine hauling it around. Yet more absurd, in some countries these secondary engines are even allowed to run on highly subsidised 'red' diesel, meaning taxpayers' money is being used to support the polluters, and prevent clean cold technologies from gaining a foothold.

The impacts of this kind of air pollution are felt right across Europe. In the EU, it causes more than 400 000 premature deaths each year, and chronic ill-health for many more. This imposes a heavy social cost on every European nation. Refrigerated vehicles also leak highly potent climate-warming HFC refrigerants, although our analysis shows that this problem is less significant than generally thought.

Although there are around 1 million refrigerated vehicles in the EU, until now these hidden polluters have gone all but unnoticed. Their cost to society has never been assessed – until now – nor addressed through effective regulation.

As the European Commission begins to formulate its Heating and Cooling Strategy, we have a precious opportunity to clean up transport refrigeration. The good news is that although refrigerated vehicles are grossly disproportionate polluters, transport refrigeration can be made lower carbon and zero-emission while simultaneously reducing costs.

Zero-emission transport refrigeration is a rare case of a genuine triple win – for the environment, our health and the economy. The time to act is now.

Professor Toby Peters
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Introduction

Transport refrigeration is vital to modern society

Transport refrigeration is a vital but little noticed pillar of modern society; without it the supply of food and medicine would simply break down. In advanced economies such as the EU, a seamless 'cold chain' of refrigerated warehousing and transport stretches all the way from the farm gate to the consumer's plate, and also ensures the efficacy and safety of many medicines and vaccines. Unfortunately, the transport refrigeration units (TRUs) that keep cargo cool in transit are overwhelmingly powered by diesel and highly polluting.

This report investigates the environmental and health damage caused by TRUs throughout the EU, and the potential benefits of converting to zero-emission units that extract both cold and power from liquid air or liquid nitrogen. We calculate that switching to this kind of zero-emission refrigeration would save €1,9 billion per year by 2025 in reduced damage to the environment and health. These reductions in social costs are in addition to any direct financial savings to the owners of the equipment.

The problem with current technology

TRUs emit CO_2 and grossly disproportionate amounts of toxic NO_x (nitrogen oxides) and PM (particulate matter) – pollutants that cause more than 400 000 premature deaths in the EU each year. They also leak highly potent climate-warming HFC refrigerants ('F-gases'), although our analysis shows that this problem is less significant than generally thought: F-gas leakage accounts for just 17% of lifecycle CO2e emissions of TRUs in the EU, and diesel consumption accounts for most of the rest.

This situation persists in part because EU policies – including the recently introduced F-gas regulations, and the proposed new Non-Road Mobile Machinery (NRMM) standards – have so far failed to tackle the problem decisively. Yet liquid air TRUs could provide an elegant and affordable solution, especially if TRU emissions were regulated under the Low Emission Zones springing up in Europe's cities – where the damage is greatest. Converting to liquid air would reduce TRU greenhouse gas emissions by 50% in 2025 – more if integrated with renewables – and eliminate their emissions of NO_x and PM altogether.

Liquid air as a fuel

Using liquid air as a 'fuel' for TRUs is a relatively new idea, yet Europe has ample infrastructure to support its uptake. In the near term, TRUs could be fuelled by liquid nitrogen, which works in the same way, causes no damage to the environment or health, and is already widely available. We estimate that the ten countries that operate 80% of the EU TRU fleet have enough spare liquid nitrogen production capacity to fuel 70 000 zero-emission TRUs. In other words, the early deployment of liquid air TRUs would require no immediate investment in nitrogen production capacity or distribution networks.

Cryogenic refrigeration systems based on the simple evaporation of liquid nitrogen are already available from companies such as Cryofridge, Frostcruise, natureFridge and blueeze, but these derive only cooling from the expansion process, and fail to capture the mechanical energy that is also available, and as a result are far less efficient. This report investigates the potential of 'liquid air' TRUs, which can run on either liquid air or liquid nitrogen, but which harvest both cooling and shaft power from the same tank of cryogen, and so are far more efficient.

The Dearman liquid air engine has many other potential applications, including zero-emission back-up electricity generators, and 'heat hybrid' engines for heavy duty vehicles that reduce diesel consumption by 25%. This report focuses exclusively on the first application to market, the liquid air TRU, and makes a compelling case for its economic, environmental and health benefits, and for its rapid adoption across Europe. Throughout this report the phrase 'transport refrigeration' refers only to the cooling of a refrigerated vehicle and not its propulsion.

Main findings, conclusions and recommendations

Cost to society

Pollution from transport refrigeration could cost European Union countries €22 billion over the next decade, as the EU refrigerated road vehicle fleet grows to almost 1,2 million by 2025. If nothing is done, the environmental and health impacts of emissions of CO_2, HFCs, NO_x and PM will impose an annual burden of around €1,9 billion in 2015, rising to more than €2,5 billion in 2025.

Environmental damage

The cost to society of transport refrigeration is due to the cost of dealing with its emissions of CO_2 and other greenhouse gases, and the environmental and health impacts of toxic NO_x and particulate matter (PM), which cause over 400 000 premature deaths per year in the EU.[1] In 2015 the cooling of refrigerated vehicles in the EU will emit around:

- 13 million tonnes of CO2e;
- 40 000 tonnes NO_x, equivalent to more than 26 million Euro 6 diesel cars;
- 5 000 tonnes of PM, equivalent to 56 million Euro 6 diesel cars.

Benefits of zero-emission cooling

Converting Europe's transport refrigeration to zero-emission units that extract both cold and power from liquid air or liquid nitrogen over the course of the next decade would eliminate its emissions of NO_x and PM altogether, with annual savings of 47 000 tonnes and 6 000 tonnes respectively by 2025. All our projections are based on the conservative assumption that the refrigerated vehicle fleet will grow by 1,5% per year, but other studies assume annual cold chain market growth of as much as 12%, so our forecasts could prove to be substantial underestimates.

Since diesel transport refrigeration units (TRUs) are effectively unregulated in Europe and emit much more local air pollution than a modern Euro VI truck propulsion engine, these savings are the NO_x equivalent of taking almost 2 million trucks off the road, more than the EU's entire fleet of articulated trucks, and the PM equivalent of removing 12 million such trucks from service – almost a third of the EU's entire fleet of rigid trucks.[2]

Converting transport refrigeration to liquid air TRUs over ten years would also reduce diesel consumption by 4,7 billion litres in 2025, and 21,7 billion in the decade 2016-25 – worth almost €30 billion at average EU prices in 2014.[3] Annual greenhouse gas emission reductions would reach around 8 million tonnes of CO_2 equivalent (8mtCO2e) or 50% in 2025, and emissions would keep falling as the grid electricity used to produce liquid air or nitrogen continues to decarbonise.

"Pollution from transport refrigeration could cost European Union countries €22 billion over the next decade, as the EU refrigerated road vehicle fleet grows to almost 1,2 million by 2025."

Existing infrastructure

Europe has ample liquid nitrogen infrastructure to begin such a transition. The 10 EU countries ('EU10' – see Table 1) that operate 80% of the EU refrigerated vehicle fleet have estimated spare liquid nitrogen production capacity of around 9 000 tonnes per day, enough to fuel some 70 000 liquid air transport refrigeration units (TRUs). Seven of the EU10 countries also have the potential to produce extremely cheap liquid air or nitrogen by recycling the waste cold given off at LNG import terminals (see Spotlight on: LNG waste cold). This resource could in principle provide over 27 000 tonnes of liquid air or nitrogen per day, enough to fuel refrigeration on almost 210 000 vehicles.



Conclusions and recommendations

The results of our study – the first detailed analysis of the impact of transport refrigeration across Europe – provide a compelling case to support the rapid development of liquid air transport refrigeration in the EU and lead us to conclude:

- The social costs of diesel powered transport refrigeration are high, grossly disproportionate and provide a compelling argument for policy support for zero-emission alternatives;
- Liquid air transport refrigeration would eliminate NO_x and PM emissions; deliver substantial and progressively larger reductions in greenhouse gas emissions; and could provide an efficient route to eliminating damaging F-gases entirely;
- The annual benefit to society of each zero-emission TRU in 2025 is €1 700, in addition to any direct savings made by owners of the equipment;
- Europe has ample liquid nitrogen infrastructure to support the shift to liquid air transport refrigeration;
- Policy around TRUs is currently focussed on F-gases, which – although important – account for only 17% of aggregate TRU lifecycle greenhouse gas emissions, whereas diesel is responsible for most of the rest, and all of the NO_x and PM;
- The NRMM regulations provide no incentive for the industry to make meaningful reductions in TRU emissions of NO_x and PM, even after the proposed new standards become law;
- Policy should be re-set to focus not only on F-gases but on the larger problem of reducing TRU diesel emissions. If it is too late to tighten the new standards proposed for NRMM Stage 5, other measures should be found;
- Since NO_x and PM emissions are especially damaging in cities, TRU emissions should be regulated under Low Emission Zones. These should demand a single move to zero-emission TRUs, rather than an extended trajectory of gradual emissions reductions;
- In a handful of countries, including Britain, France, Spain and Belgium, TRUs are still permitted to run on subsidised 'red' diesel, meaning that taxpayers' money is being used to support a mature, highly polluting technology, creating a high barrier against the adoption of zero-emission transport refrigeration technologies that would otherwise undercut diesel; it is time to close this loophole;
- Many major cities such as Paris and Milan lack the data needed to estimate the impact of TRU emissions, and we recommend that national governments and city authorities should act quickly to improve the quality and granularity of their transport and emissions data; you cannot manage what you cannot measure.

Liquid air and liquid nitrogen

The idea that the air that we breathe could turn into a liquid is counterintuitive to say the least, but scientists have known how to liquefy the constituents of air for well over a century, and the industrial gases industry now produces thousands of tonnes of liquid nitrogen and liquid oxygen every day. However, these gases need not be separated when liquefied, in which case the result is liquid air. A number of technologies are now being developed to exploit liquid air – or liquid nitrogen, its main constituent – as an energy 'vector'.

Air can be turned into a liquid by cooling it to around -196°C using standard industrial equipment powered by electricity. 700 litres of ambient air becomes about 1 litre of liquid air, which can then be stored in an unpressurised insulated vessel. When heat is reintroduced to liquid air it boils and turns back into a gas, expanding 700 times in volume. This expansion can be used to drive a piston engine or turbine to do useful work. In principle, a liquid air engine works just like a steam engine, only 300°C colder. The main potential applications are in the provision of cold and power, electricity storage, transport and the recovery of waste heat.

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, is produced throughout the industrialised world. The industrial gas companies have large amounts of spare nitrogen production capacity for the simple reason there is four times more nitrogen in the atmosphere than oxygen but proportionately less commercial demand. We estimate the ten countries that operate 80% of the EU TRU fleet have spare liquid nitrogen production capacity of around 9 000 tonnes per day, enough to fuel some 70 000 liquid air TRUs. This surplus could be used in place of liquid air to support early deployment. In future, liquid air would be cheaper to produce than liquid nitrogen, because there is no need to separate the nitrogen and oxygen, meaning liquefaction requires less equipment and around a fifth less energy. Both liquid air and liquid nitrogen can be produced extremely cheaply by incorporating the waste cold from LNG re-gasification (see Spotlight on: LNG waste cold).

As with batteries or hydrogen, the purpose of liquid air is to store 'wrong-time' low- or zero-carbon electricity, and use it to displace coal or gas in electricity generation and petrol or diesel in vehicles. Liquid air and nitrogen have some significant advantages over other forms of energy storage, however, particularly when cooling is required, and would frequently be far cheaper. Both liquid air and liquid nitrogen are zero-emission at the point of use.



Liquid Air on the European Highway

The economic and environmental impact of zero-emission transport refrigeration

Introduction

The business case for liquid air in commercial transport in Britain was conclusively demonstrated in Liquid Air on the Highway[4], a report published in June 2014. Liquid air has also been recognised by the European Road Transport Research Advisory Council (ERTRAC) as an energy carrier offering 'significant potential' to help achieve the EU's 2050 transport greenhouse gas emissions reductions target.[5]

Liquid Air on the Highway established that – unlike most low-carbon powertrains – liquid air-equipped vehicles, including transport refrigeration units (TRUs) and buses and trucks with 'heat hybrid' engines, would repay their investment quickly and without subsidy, while also producing large reductions in emissions of both CO_2 and toxic local air pollutants such as NO_x and PM. It did not assess the full range of pollutants, however, nor attribute any economic value to those it did.

First detailed study of transport refrigeration across the EU

Liquid Air on the European Highway focuses exclusively on TRUs – the other applications of liquid air will be the subject of future reports – but extends the analysis to encompass the entire EU, and all the major forms of TRU pollution. It estimates the economic cost to society of NO_x, PM, CO_2 and F-gas refrigerants on a business-as-usual scenario, and the value of the environmental benefits to be gained from a shift to a zero-emissions solution such as liquid air over the next ten years. It is the first detailed study of transport refrigeration across Europe, and is timely because:

- Many major European cities are choking on local air pollution, and the European Commission is taking action against Belgium, Bulgaria, Sweden, Poland and the UK – supported by rulings from the European Court of Justice and the British Supreme Court;
- While the EC is starting to 'get tough' on local air pollution among member states, proposed EU emissions standards for TRUs (NRMM Stage 5) look extremely weak, and urgently need to be strengthened, or reinforced with other policy measures such as regulating TRU emissions through Low Emission Zones;
- At the same time, new EU regulations that came into force in January 2015 effectively phase out the supply of high global warming potential (GWP) 'F-gas' refrigerants by 2030, giving another pressing reason to rethink our approach to transport refrigeration;
- Dearman's liquid nitrogen TRU has undertaken on-vehicle testing with HORIBA MIRA, with funding from Innovate UK (the British government's innovation agency), and project partners include Air Products and Loughborough University. Dearman plans to have the unit – integrated by Hubbard Products Ltd, part of Zanotti – in European fleet trials in 2016.

"Liquid air TRUs would eliminate NO_x and PM emissions, sharply reduce the volume and leakage of high global warming potential (GWP) F-gas refrigerants, and slash both CO_2 emissions and social costs"

A cleaner, greener solution

Liquid air TRUs would eliminate NO_x and PM emissions, sharply reduce the volume and leakage of high global warming potential (GWP) F-gas refrigerants, and slash both CO_2 emissions and social costs. Some operators have tested vehicle refrigeration based on the simple evaporation of liquid nitrogen, which also eliminates NO_x, PM and F-gases, but these technologies are more expensive than diesel and remain niche or showcase products. The Dearman TRU is a significant advance because it produces both cooling and shaft power from a single unit of cryogen, which makes it more efficient and competitive against diesel.

A strong business and environmental case

Liquid Air on the Highway[6] demonstrated a strong business case for several promising liquid air transport applications including TRUs, which it found would repay incremental investment costs in as little as three months without subsidy. The report also demonstrated major environmental benefits, since diesel TRU emissions are essentially unregulated, and conventional trailer TRUs emit six times as much NO_x and 29 times as much PM as a modern Euro VI truck propulsion engine.

As a result, a fleet of just 13 000 liquid air refrigerated trailers would reduce NO_x emissions by the same amount as taking 80 000 Euro VI trucks or 1,2 million Euro 6 diesel cars off the road. It would be the PM equivalent of removing 377 000 such trucks from service – more than three times the entire UK articulated truck fleet today – or 2,2 million Euro 6 diesel cars.

Yet these environmental benefits – and others, such as major CO_2 savings – were not factored into the business case. Liquid Air on the European Highway extends the analysis by:

- quantifying the environmental benefits across the whole range of pollutants – NO_x, PM, CO_2 and F-gas refrigerants – and ascribing an economic value;
- extending the analysis to ten EU economies and the EU as a whole;
- assessing the liquid nitrogen supply infrastructure, and its adequacy to fuel early deployment;
- analysing the current policy framework in Europe to see if this supports or inhibits the roll-out of liquid nitrogen for zero-emission transport refrigeration.

The results of our modelling suggest huge environmental, health and financial benefits to society of introducing liquid air transport refrigeration across Europe.

Transport refrigeration in Europe

The EU refrigerated road fleet numbers around 1 million vehicles, made up of vans, trucks and articulated trailers. Four fifths of these vehicles are registered in just ten member states ('EU10', see Table 1).

The industry is long-established and regarded as mature, meaning it is generally thought unlikely to grow faster than GDP, although the recent emergence of supermarket home delivery and 'click and collect' could lead to renewed growth in some segments (see Spotlight on: Grocery market). One recent report has forecast 12% annual growth in Europe's cold chain between 2015 and 2019, however, in which case the results of our modelling could prove substantial under-estimates. [7]

Even if the transport refrigeration market growth remains muted, its impacts on our environment and health will be heavy because TRUs are overwhelmingly powered by diesel, and rely on HFC refrigerants – or 'F-gases' – with a high global warming potential (GWP), which tend to leak. As a result, TRUs emit a cocktail of greenhouse gases and large amounts of NO_x and PM – the toxic pollutants responsible for much respiratory and heart disease and more than 400 000 premature deaths in the EU in 2011[8] (see Local air pollution and TRUs – the case for action in cities).

It is clearly vital that we develop sustainable transport refrigeration technologies to eliminate these emissions.

Country	*ATP fleet	National fleet	Vans	Trucks	Trailers & semi-trailers
Belgium	3 000	22 000	12 791	4 589	4 620
Czech Rep.	4 250	20 000	13 820	4 400	1 780
France	120 000	150 000	85 500	33 000	31 500
Germany	25 500	180 000	78 744	59 886	41 370
Italy	56 700	115 000	69 888	35 824	9 288
Netherlands	5 250	35 000	13 748	7 720	13 532
Poland	9 500	80 000	44 132	17 452	18 416
Portugal	4 150	22 000	11 215	4 578	6 207
Spain	112 500	120 000	73 815	31 964	14 221
UK	N / A	84 000	50 000	16 000	18 000
EU10	N / A	828 000	453 653	215 413	158 934
EU28	N / A	1 000 000	530 456	235 210	234 344

Table 1: Estimated refrigerated vehicle fleets. Sources: Cemafroid; UK industry.
* ATP: Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage

Grocery market

The transport refrigeration market in Europe is widely seen as mature, and unlikely to grow any faster than GDP, but the grocery sector is undergoing radical changes that could force that opinion to be revised. The growing popularity of online grocery shopping with home delivery or 'click and collect', the shift from out-of-town supermarkets towards local convenience stores, and the arrival of aggressive new competitors such as Amazon, could all lead to increased demand for transport refrigeration, and yet higher levels of urban TRU pollution. One recent report has forecast 12% annual growth in Europe's cold chain between 2015 and 2019, in which case the results of our modelling could prove substantial under-estimates.

The shift to online grocery shopping is most pronounced in the UK, causing rapid growth in the supermarket van fleet to 50 000, and where the market is forecast to grow from £8 billion in 2014 to £17 billion in 2019.[30] But other major European economies are now catching up. In several European countries the number of people buying groceries online doubled between 2008 and 2013, and the French market is forecast to jump from €5 billion in 2012 to €11 billion in 2016, while Germany is expected to more than double to €2,5 billion over the same period.[31] The German market is under-developed so far, but expected to grow faster now that its second largest retailer, REWE, has begun home delivery, and Amazon Fresh has announced its plans to start operating there.[32] AT Kearney expects the German market to triple to €5 billion by 2020.[33]

Home delivery is increasingly popular but, for supermarkets, making it pay is a challenge[34], so many have launched click and collect services where customers pick up their pre-packed shopping at the store or a remote collection point. Asda for example has opened six collection stations in London and plans 1 000 in the UK by 2018.[35] Click and collect will involve fewer additional vehicles than home delivery but more than the conventional supermarket model.

Another pronounced trend is away from supermarkets towards smaller local convenience stores. IDG forecasts the British convenience store market will grow 30% to £49 billion, almost a quarter of the grocery market, by 2019.[36] Since these shops often have very little storage space, they must be re-supplied more often, requiring yet more refrigerated vehicles to operate in urban areas already suffering from traffic congestion and high levels of air pollution.

If European economies continue to follow the trends pioneered in Britain, what was a mature market in transport refrigeration could be reinvigorated. Even relatively modest shifts could have a significant impact on vehicle demand and the associated pollution in a European grocery market worth more than €1 trillion.[37]

Greenhouse gases

The greenhouse gas emissions of TRUs comprise of CO_2 emissions from diesel fuel, and leaks of high global warming potential (GWP) HFC refrigerant gases or 'F-gases'. It is the F-gases that have captured the attention of policymakers, and it is easy to see why: the most commonly used F-gas, R404A, is 4 000 times more powerful than CO_2, meaning that a leak of one kilogramme of refrigerant has the same global warming impact as four tonnes of carbon dioxide. To tackle this, the EU introduced new F-gas regulations in 2015 which are designed effectively to phase out HFC refrigerants by 2030 and force the market to develop alternatives.

However, our modelling, based on fleet performance data from Cemafroid, the French vehicle testing and transport refrigeration consultancy, suggests that refrigerant leakage accounts for only 17% of the lifecycle greenhouse gas emissions of the TRU fleet, with around 90% of the remainder due to the burning of diesel fuel. So although it is clearly important to minimise and eventually eliminate F-gas leakage, it is even more important to eliminate the CO_2 emissions from TRU diesel consumption.

Our analysis suggests an average refrigerated van consumes almost 900 litres of diesel per year for cooling alone, the average truck around 6 000 litres, and the average trailer more than 9 000. Liquid air TRUs eliminate the need for diesel for cooling, and converting the European TRU fleet to liquid air over the next decade would produce progressively larger greenhouse gas reductions as fleet penetration increases and electricity grids decarbonise. By 2025 the annual greenhouse gas savings would reach 8mtCO2e – a reduction of 50%.

Liquid air TRUs do also reduce the amount of F-gas required by about half (see Liquid air transport refrigeration), and may provide a route to eliminate them entirely in future (see Spotlight on: F-gases), but this issue remains far less significant than the elimination of diesel.

These results suggest the policy focus should be widened to tackle not just F-gases but also the more significant issue of CO_2 emissions from TRU diesel consumption – especially since diesel powered TRUs emit grossly disproportionate amounts of NO_x and PM.

F-gases

New EU F-gas regulations mean that from January 2015 refrigerated transport operators must record and report leakage rates. The same regulations will also reduce the volume of F-gases available in the EU to scarcely a fifth of current levels by 2030, so the market will be forced to find alternatives.

Although F-gases are extremely potent greenhouse gases, our modelling suggests refrigerant leakage accounts for only 17% of the lifecycle greenhouse gas emissions of Europe's TRU fleet, with around 90% of the remainder due to the burning of diesel fuel. So although it is clearly important to minimise and eventually eliminate F-gas leakage, it is even more important to eliminate the CO_2 emissions from TRU diesel consumption – for example, through the use of liquid air or nitrogen.

Nevertheless, liquid air TRUs do address the problem of F-gas emissions in two ways. In the short term, since most of the cooling is provided by the evaporation of liquid nitrogen, the secondary, vapour compression cycle has far less cooling work to do, and needs only around half the F-gas 'charge' of an equivalent diesel unit. As a result, the volume of leaks should be proportionately smaller.

In the longer term, liquid air TRUs could be designed to work with natural refrigerant gases such as CO_2, which are climate neutral. The problem with these has been that they tend to become far less efficient when ambient temperatures exceed 20-23°C, but liquid air TRUs could provide a solution. Since they run on cryogenic liquids, these TRUs are able to 'subcool' their compressors to maintain their efficiency even at higher ambient temperatures. Subcooling already doubles the efficiency of an F-gas vapour compression cycle on a liquid air TRU compared to a diesel unit, and may make the difference between CO_2 being a practical possibility in transport refrigeration or not.

NO_x and PM

It may be hard to believe, but the TRU cooling an articulated trailer emits many times more NO_x and PM over the course of a year than the (Euro VI) main propulsion engine hauling it around. This situation has developed because the 'Euro' regulations covering truck propulsion engines have become far more stringent over the past 20 years, whereas TRU emissions remain effectively unregulated.

Current legislation

TRUs are covered by the EU Non-Road Mobile Machinery (NRMM) regulations, but at present these impose no emissions limits whatsoever on engines rated at less than 19kW – which includes all TRUs. Brussels is soon expected to approve legislation revising the regulations to match existing standards in the US, but these are hardly stringent.

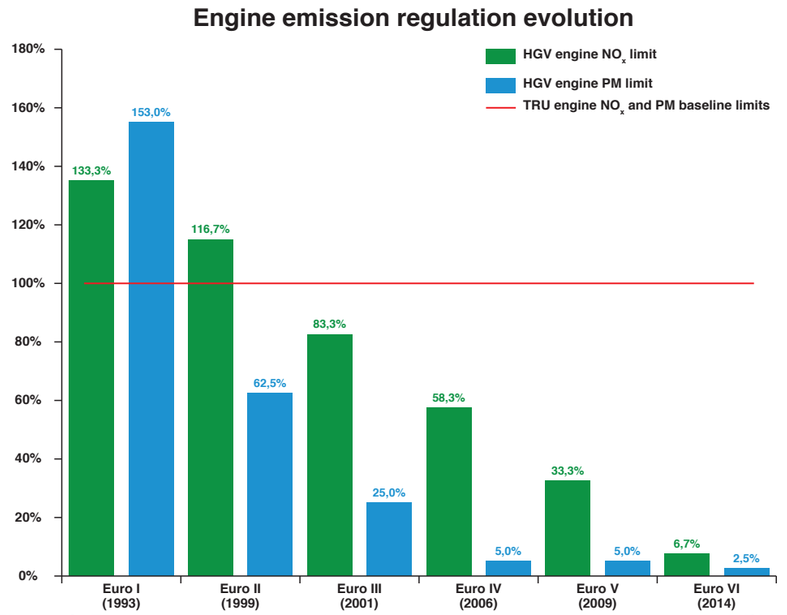


Figure 1: Euro truck engine emission standards compared to the proposed NRMM Stage 5 TRU standard. Source: European Commission; DieselNet.[9]

Figure 1 compares the amount of NO_x and PM that successive generations of European truck propulsion engines have been allowed to emit against a baseline of what TRUs will be allowed to emit under the new standards. This shows that for each kWh produced, the latest Euro VI propulsion engine is allowed to emit only 7% of the NO_x allowed for a TRU, and just 2,5% of the PM. In other words, under the new European standards, a trailer TRU will still be allowed to emit 15 times more NO_x and 40 times more PM per unit of energy consumed than the tractor unit pulling it around.

	NO_x	PM
Euro VI, g/kWh emissions limit	0,40	0,01
NRMM Stage 5, (<19kW), g/kWh emissions limit[11]	7,5	0,4
NRMM g/kWh / Euro VI g/kWh	16x	14x
Annual emissions, TRU / Euro VI	6x	29x
Annual emissions, TRU / Euro 6 diesel car	93x	165x

Table 2: TRU emissions compared to Euro VI trucks and Euro 6 diesel cars. Sources: European Commission; DieselNet.[12]

Disproportionate NO_x & PM emissions

A TRU consumes less energy than a propulsion engine, however, so the annual emissions comparison is not quite as extreme, but shocking nonetheless. Based on standard duty cycle assumptions[10], we calculate that over the course of a year a diesel TRU currently emits up to six times as much NO_x and 29 times as much PM as the Euro VI truck pulling it around (Table 2). Compared to a Euro 6 diesel car, a diesel TRU is likely to emit 93 times as much NO_x and 165 times as much PM.

Smaller TRUs – those used in vans and a minority of trucks – are driven by the vehicle's propulsion engine through a belt drive or an alternator.

NO_x and PM emissions from this source may decline over time, as the fleet is progressively replaced with cleaner Euro VI propulsion engines – although against that, these engines may still need to idle continuously when the van is stationary to keep the cargo cool. But larger TRUs, used in the majority of trucks and virtually all articulated trailers, are powered by a separate diesel engine, and the emissions from these engines will be scarcely constrained even after the new NRMM Stage 5 standards have been introduced.

If nothing more is done, the significance of truck and trailer TRU emissions will only grow as propulsion engines are progressively replaced with cleaner Euro VI models over the next decade.

Our modelling suggests each truck TRU currently emits 67kg of NO_x and 9kg of PM per year, and each trailer TRU almost 100kg and 14kg. A liquid air TRU would eliminate NO_x and PM emissions altogether – as well as reducing the F-gas charge and leakage by around half, and progressively reducing lifecycle greenhouse gas emissions.

Calculating the social cost of transport refrigeration

We have calculated the social cost of transport refrigeration by combining the 'damage costs' of NO_x and PM emissions to health, crops and infrastructure, and the 'abatement cost' of its emissions of greenhouse gases including carbon dioxide and HFC refrigerants. Together these costs represent the burden to society of continuing to base our cold chains on diesel-powered TRUs.

First we modelled the fuel consumption and emissions of TRUs, based on detailed TRU fleet and duty cycle data provided by Cemafroid and other industry sources, and our own analysis of TRU NO_x and PM emissions, and made the conservative assumption that fleets would grow at just 1,5% per year for the next decade. These results were then combined with damage and abatement cost factors calculated by Ricardo-AEA for the European Commission[13] to produce the social costs of a business-as-usual approach in each country and the EU as a whole. Finally we calculated the progressively larger reductions in emissions and social cost that could be achieved by converting to liquid air transport refrigeration over the next 10 years.

The 'damage costs' of NO_x and PM are estimates of the costs imposed by those pollutants in terms of hospital treatment, premature death, lost life and productivity, and damage to buildings and crops, and they vary according to the wealth of each country. The 'abatement costs' of CO_2 and HFCs are an estimate of the cost of avoiding a given amount of emissions by the cheapest means possible. The figure calculated by Ricardo-AEA for the entire EU, and consistent with keeping global warming within 2°C, is €90 per tonne. For a full explanation of damage costs, abatement costs and our methodology, please see Appendix 3.

Modelling results

These results demonstrate the benefits to be gained from a progressive conversion over the next decade to liquid air TRUs – those which extract both cooling and mechanical power from the same tank of liquid air or liquid nitrogen. These benefits could not be achieved by evaporation only systems – such as those from Cryofridge, Frostcruise, natureFridge and blueeze – which are far less efficient and deeply uncompetitive against diesel (for more detail please see Spotlight on: Zero-emission transport refrigeration and the case for fuel duty reform or Appendix 2).

NO_x and PM savings

The results are broadly consistent across all 28 EU member states, but with some variation due to national factors such as grid carbon intensity and exact proportion of vans, trucks and trailers in each national TRU fleet.

In 2025 the fleet-weighted average[14] TRU in the EU28 would save:

- almost 4 000 litres of diesel per vehicle per year;
- reduce greenhouse gas emissions by 7tCO2e, including 1,6tCO2e from F-gas leakage;
- reduce NO_x emissions by 40kg and PM by 5kg.

In aggregate, the EU28 economies would save 4,7 billion litres of diesel per year by 2025, and almost 21,7 billion litres in the decade 2016-2025 – worth almost €30 billion at average EU prices in 2014.[15] Greenhouse gas emissions would fall by 36mtCO2e over ten years – including almost 7mtCO2e from refrigerant leakage – and by 8mtCO2e in 2025 alone. NO_x emissions would decline by 224 000 tonnes and 47 000 tonnes; PM by over 30 000 tonnes and almost 6 000 tonnes respectively. Since diesel TRUs are effectively unregulated and emit much more local air pollution than a modern Euro VI propulsion engine, the annual savings are the NO_x equivalent of retiring:

- 2 million trucks, more than the EU's entire fleet of articulated trailers[16], or
- 30 million Euro 6 diesel cars.

They are the PM equivalent of scrapping:

- 12 million Euro VI trucks from service – almost a third of the EU's entire fleet of rigid trucks,[17] or
- 65 million diesel cars.

Economic value of the social benefit

In 2025, the annual economic value of the social benefits – ie including environment and health and excluding fuel – would total €1,9 billion. The cumulative social benefits for 2016-25, assuming a progressive conversion to liquid air TRUs over the next decade, would be worth €8,7 billion (Table 3).

In 2025, the average TRU would generate social benefits – quite apart from any cost savings to its owners – worth more than €1 700 per vehicle. The cumulative social benefit divided among all the TRUs sold over a decade amounts to €7 500 per vehicle.



2025 Annual Saving		UK	DE	SP	IT	FR	NE	EU28
Fleet size in 2025		97 485	208 897	139 265	133 462	174 081	40 619	1 160 541
Diesel consumption per year	kg	283 785 076	767 910 938	422 738 722	376 706 403	548 842 498	166 854 808	3 898 411 115
Annual NO_x emissions	kg	3 350 844	9 500 730	4 808 027	4 216 074	6 539 886	2 145 406	47 228 165
Annual PM emissions	kg	440 633	1 254 424	629 893	551 662	860 559	284 147	6 223 690
Annual CO_2 emissions	tCO2e	661 305	1 328 331	928 645	1 042 705	1 947 667	262 107	8 018 720
Annual damage cost due to NO_x emissions	€	29 757 823	218 622 560	32 230 538	61 629 038	115 273 836	33 534 235	742 312 421
Annual damage cost due to PM emissions	€	24 928 244	109 347 007	19 079 992	28 564 908	46 789 605	27 486 313	367 487 595
Annual CO_2 eq climate cost	€	68 620 568	138 132 204	99 610 756	103 847 930	178 162 755	26 915 308	835 567 017
Total social cost	€	123 306 635	466 101 771	150 921 286	194 041 876	340 226 196	87 935 855	1 945 367 033
Cumulative saving 2016-2015								
Diesel consumption	kg	1 294 492 669	3 637 923 473	1 991 995 323	1 808 964 988	2 528 446 927	763 111 278	18 025 355 828
NO_x emissions	kg	15 747 553	45 761 773	23 566 999	21 132 098	30 976 099	9 919 896	223 599 730
PM emissions	kg	2 076 231	6 050 681	3 098 548	2 776 003	4 085 910	1 315 022	29 525 796
CO_2 emissions	tCO2e	2 393 483	5 036 136	4 081 702	4 837 100	8 545 980	1 044 339	36 408 050
Damage cost due to NO_x emissions	€	134 319 577	1 010 253 232	151 436 818	295 807 671	524 213 239	149 044 683	3 371 180 971
Damage cost due to PM emissions	€	112 806 020	505 984 574	89 958 785	137 629 712	213 277 191	122 271 624	1 676 208 587
CO_2 eq climate cost	€	254 777 886	526 553 695	424 797 173	470 493 936	779 404 961	106 195 499	3 655 707 994
Total social cost	€	501 903 483	2 042 791 502	666 192 775	903 931 319	1 516 895 391	377 511 807	8 703 097 552

Table 3: The economic value of the environmental and social benefits of a complete conversion to liquid air transport refrigeration by 2025. NB. these figures exclude any direct financial savings made by the owners of liquid air TRUs.

Germany

As shown in Table 3, the German TRU fleet grows to 209 000 vehicles by 2025, remaining the largest in Europe, and if it converted entirely to liquid air over that period, Germany would save 923 million litres of diesel per year in 2025 and 4,4 billion over the decade. Within ten years its greenhouse gas emissions reductions would reach 1,3mtCO2e per year and a cumulative 5mtCO2e. Annual NO_x emissions would fall by 9 500 tonnes, and PM by 1 200 tonnes. The social cost of transport refrigeration to Germany would fall by €466 million per year and €2 billion over the decade.

France

In France, the TRU fleet grows to 174 000 by 2025, which if fully converted to liquid air would save 3 billion litres of diesel over a decade and almost 660 million litres in the final year. Greenhouse gas emissions would fall by 8,5mtCO2e over ten years and 1,9mtCO2e in 2025 alone. NO_x emissions would shrink by 6 500 tonnes in 2025 and almost 31 000 tonnes over the decade. For PM the savings are 860 tonnes and 4 000 tonnes respectively. The social savings – ie excluding fuel – would be worth €340 million in 2025, and €1,5 billion between now and then.

Spain

Spain's fleet remains the third largest in Europe and grows to 139 000 TRUs in 2025. By then the progressive conversion to liquid air would have saved a cumulative 2,4 billion litres of diesel, with savings of over 500 million litres in the final year alone. Greenhouse gas emissions reductions would reach 4mtCO2e over the decade and more than 930 000 tonnes in 2025. Emissions of NO_x would fall by 23 500 tonnes and those of PM by 3 000 tonnes over ten years, and by 4 800 tonnes and 630 tonnes respectively in the final year. The social costs of transport refrigeration in Spain would fall by €151 million per year in 2025 and €666 million over the decade.

Italy

The Italian TRU fleet grows to 133 000 by 2025, by when the country would have saved €903 million in social costs; the annual savings would grow to €194 million by 2025. In addition there would be fuel savings of 452 million litres of diesel in 2025, and 2,1 billion litres over the decade. This in turn would reduce NO_x emissions by 4 200 tonnes in 2025 and 21 000 tonnes over ten years. PM emissions would fall by 552 tonnes and 2 800 tonnes respectively. Greenhouse gas emissions would drop by 1mtCO2e in 2025, and 4,8mtCO2e over the decade.

Britain

In Britain the TRU fleet grows to more than 97 000 by 2025, when it would save the country 340 million litres of diesel, the final instalment of a ten-year saving of 1,5 billion litres. Greenhouse gas emissions would fall by 661 000tCO2e in 2025 and 2,4mtCO2e during 2016-2025. NO_x emissions decline by almost 15 700 tonnes over the decade and 3 400 tonnes in 2025; PM would fall by almost 2 000 tonnes and 440 tonnes respectively. The social cost of transport refrigeration in the UK would fall by €123 million in 2025 and €502 million over the preceding decade.

Netherlands

Netherlands' TRU fleet grows to almost 41 000 in 2025, and if fully converted to liquid air would deliver annual emissions savings of 262 000tCO2e, 2 100tNO_x and 284tPM. Over the course of ten years, the cumulative savings would reach of 1mtCO2e, 9,900tNO_x and 1 300tPM. As a result the social cost of transport refrigeration to Netherlands would fall by €88 million in 2025 and €378 million during 2016–2025. The country would also save over 917 million litres of diesel over the decade and 201 million litres in the final year.

LNG waste cold

Natural gas is refrigerated to -162°C to become Liquefied Natural Gas (LNG) to be transported by supertanker from producing to consuming nations. Each tonne of LNG contains the cold energy equivalent of 240kWh, quite apart from the chemical energy contained in its methane molecules. At the import terminal the LNG is warmed to re-gasify before entering the pipeline network, when most of the cold is usually discarded. This spectacular waste of energy will become even more significant in future since the IEA forecasts European LNG imports will double to 120bcm/year by 2040. One good way to recycle LNG waste cold would be through the production of liquid air or nitrogen.

When LNG is re-gasified from its liquid state at -162°C to enter the gas grid, the cold it gives off can be recycled through a co-located air liquefaction plant to help produce liquid air at -194°C or nitrogen at -196°C. This reduces the electricity required to produce the cryogen and its carbon intensity by about two thirds, and the cost by about half. This approach has been demonstrated for some years at an LNG terminal at Osaka in Japan. If it were adopted more widely the impact could be huge. Our modelling suggests that the waste cold given off by LNG imports into the EU10 during 2014 could have been used to produce over 27 000 tonnes of extremely cheap liquid air or nitrogen per day, enough to fuel refrigeration on almost 210 000 vehicles – equal to the entire projected German refrigerated fleet in 2025.

Barcelona LNG terminal

Liquid air infrastructure in Europe

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, has long been produced for industrial purposes in all the major economies (see Spotlight on: Liquid air and liquid nitrogen). Our analysis shows that Europe also has ample liquid nitrogen infrastructure to begin the transition to liquid air. The ten EU countries ('EU10') that operate 80% of the EU refrigerated vehicle fleet have estimated spare liquid nitrogen production capacity of around 9 000 tonnes per day, enough to fuel some 70 000 liquid air TRUs (Table 4).

"The ten EU countries ('EU10') that operate 80% of the EU refrigerated vehicle fleet have estimated spare liquid nitrogen production capacity of around 9 000 tonnes per day, enough to fuel some 70 000 liquid air TRUs"

Seven of the EU10 countries also have the potential to produce extremely cheap liquid air or nitrogen by recycling the waste cold given off at their LNG import terminals (see Spotlight on: LNG waste cold). This resource could in principle provide over 27 000 tonnes of liquid air or nitrogen per day, enough to fuel refrigeration on almost 210 000 vehicles – equal to the entire projected German refrigerated fleet in 2025.

"converting to liquid air TRUs would require no immediate investment in nitrogen production capacity or distribution networks"

A third source of low cost and low carbon liquid nitrogen would be from pre-combustion carbon capture and storage ('Oxy-CCS') power stations, which need ASUs to provide copious oxygen, but have no need of the nitrogen by-product. The White Rose Oxy-CCS plant planned at the Drax power station in Yorkshire, in Britain, for example, will employ two ASUs to produce 6 000 tonnes per day of oxygen, meaning 20 000 tonnes of nitrogen will be vented to the atmosphere daily – enough in principle to fuel 157 000 TRUs, almost double the current UK fleet.

Liquid nitrogen is routinely delivered from the Air Separation Units (ASUs) where it is produced to industrial customers by road tanker. In Britain, all but two (Plymouth and Aberdeen) of the 33 largest cities are within typical commercial delivery distances of up to around 160 km. Among the EU10 countries, there are 78 cities with a population greater than 300 000, and of these 55, or 70%, are within typical commercial delivery distances (Figure 2). Of the 15 cities in the EU with a population greater than 1 million, only Warsaw is much beyond current delivery distances. In other words, converting to liquid air TRUs would require no immediate investment in nitrogen production capacity or distribution networks.

	LiN capacity tonnes per day	Estimated spare LiN capacity tonnes per day	Potential liquid air from LNG imports tonnes per day	TRU fleet supported by spare LiN units	TRU fleet supported by LNG LiN units
Belgium	500	150	980	1 181	7 716
Czech Republic	600	180	0	1 417	0
France	3 400	1 020	4 600	8 031	36 220
Germany	7 000	2 100	0	16 535	0
Italy	3 200	960	3 300	7 559	25 984
Netherlands	250	75	420	591	3 307
Poland	5 000	1 500	0	11 811	0
Portugal	250	75	980	590	7 716
Spain	1 900	570	8 000	4 488	62 992
UK	6 100	2 200	8 500	17 322	66 929
Total	28 200	8 830	26 780	69 527	210 866

Table 4: Liquid nitrogen (LiN) resources in EU10 countries. NB fleet estimates are based on the fleet weighted average fuel consumption of various different vehicle types. Sources: gasworld, Spiritus, GIIGNL 2015.

Countries	Liquid Nitrogen Capacity (tonnes per day)	Potential Liquid Air from LNG imports (tonnes per day)
Belgium	500	980
Czech Republic	600	0
France	3 400	4 600
Germany	7 000	0
Italy	3 200	3 300
Netherlands	250	420
Poland	5 000	0
Portugal	250	980
Spain	1 900	8 000
UK	6 200	8 500
Sources:	gasworld	Derived from GIIGNL (2015)

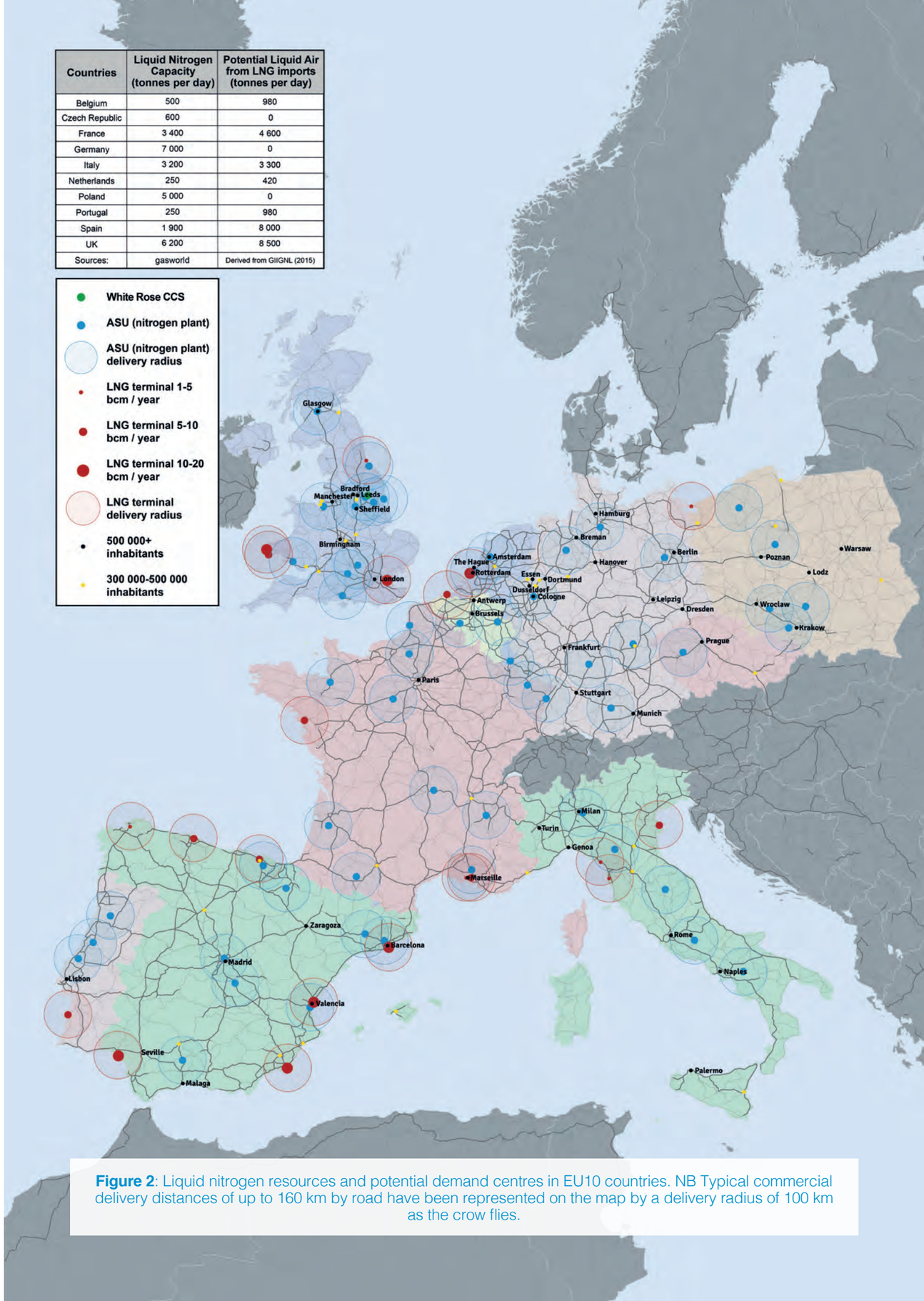


Figure 2: Liquid nitrogen resources and potential demand centres in EU10 countries. NB Typical commercial delivery distances of up to 160 km by road have been represented on the map by a delivery radius of 100 km as the crow flies.

Liquid air transport refrigeration

Liquid air is a novel form of energy storage that could eliminate the NO_x and PM emissions from transport refrigeration and progressively shrink its carbon footprint. It has been recognised by the European Road Transport Research Advisory Council (ERTRAC) as an energy carrier with 'significant potential' to help achieve the EU's 2050 transport greenhouse gas emissions reductions target.[18]

"The only exhaust is clean cold air"

'Free' cold from liquid air

Air turns to liquid when refrigerated to around -196°C at ambient pressure, and can be conveniently stored in insulated but unpressurised vessels. Exposure to heat – even at ambient temperatures – causes it to boil and expand 700-fold in volume, and this expansion can be used to drive a turbine or piston engine. The only exhaust is clean cold air. As liquid air expands into a gas it also gives off large amounts of valuable cold, which can be used to provide 'free' refrigeration or air conditioning, and this makes it an ideal energy carrier for transport refrigeration – far more efficient and economic than other zero-emission technologies.

Transport refrigeration systems that work simply by evaporating liquid nitrogen through a heat exchanger in the refrigerated goods compartment have existed for some time. These evaporation-only systems, including those from Cryofridge, Frostcruise, natureFridge and blueeze, have no means of recovering the mechanical energy available from the evaporation, and so are less efficient and deeply uncompetitive against diesel.

The Dearman liquid air TRU, by contrast, extracts both cooling and mechanical power, meaning it produces around 80% more cooling from the same tank of cryogen. Nor are evaporation-only systems strictly zero-emission, since the power to run the refrigeration system's pumps and fans must be provided by the vehicle's main engine, whereas in the Dearman TRU this energy (and more) is produced by the expansion of liquid air. The Dearman system has the lowest lifecycle costs of all zero-emission, low-carbon alternatives to the diesel TRU – for more detail see Spotlight on: Zero-emission transport refrigeration and the case for fuel duty reform or Appendix 2.

The invention of the Dearman engine

The Dearman engine was invented by Peter Dearman, a classic British 'garden shed' inventor, and runs on liquid air or nitrogen. It is now being developed by Dearman (the company) to perform a variety of roles. The engine is being tested as a TRU on a vehicle at present, and is due to start fleet trials in 2016.

In the Dearman TRU, liquid nitrogen is stored at -196°C at ~3bar in a cryogenic vessel until needed. Then it is pumped to ~40bar and transferred to a vaporising heat exchanger in the goods compartment, where it absorbs heat from the goods and provides around two thirds of the cooling.

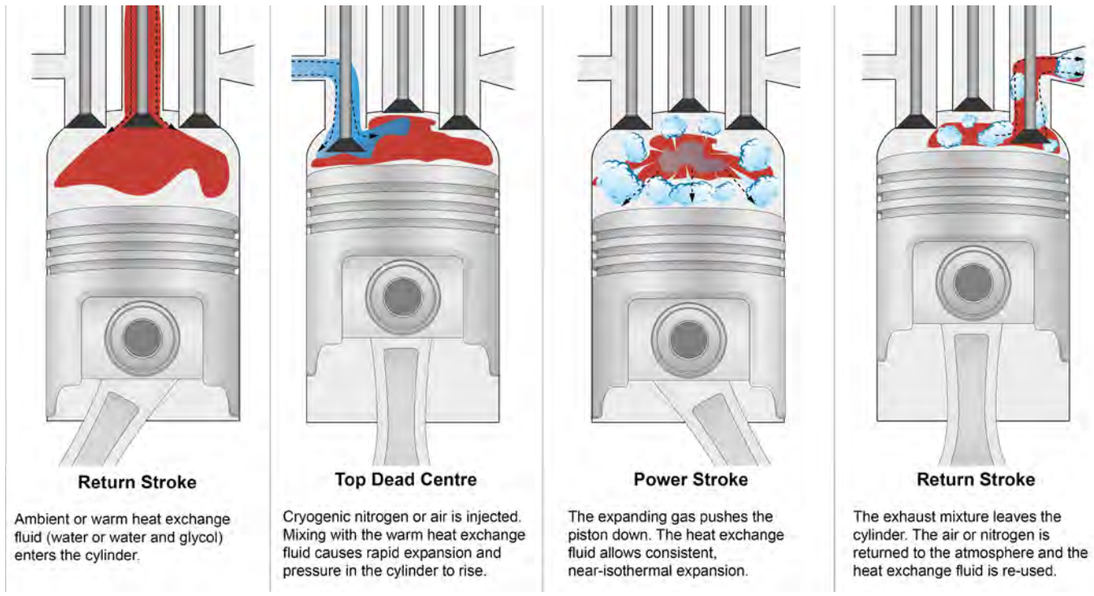


Figure 3: The Dearman engine power cycle.

The absorbed heat causes the liquid nitrogen to turn into a cold gas, which is then injected into the cylinder of the Dearman engine along with some water that has been warmed to room temperature. The nitrogen now absorbs heat from the water and expands, driving the piston down to generate shaft power. This shaft power is used to drive secondary systems such as pumps and fans, and also a secondary, conventional vapour compression cooling system, which provides around one third of the cooling.

The heat removed from the goods compartment by the secondary system is then used to re-warm the water in the engine – a clever synergy that further raises the efficiency of the TRU. Because the secondary cooling system need only provide one third of the cooling, its F-gas charge is around half the mass required for a conventional, diesel powered TRU, meaning the volumes that leak are smaller and less damaging. For more detail see Appendix 1.



Figure 4: The COOL-E project in on-vehicle testing at HORIBA MIRA.

Cold and power research – The University of Birmingham

"The cold and power laboratory in the school of mechanical engineering is addressing cold and power process challenges with the development of high efficiency heat and cold exchange devices. Our work supports that undertaken by Dearman, which is developing a piston engine that runs on liquid air, delivering both power and cold, which can serve as an efficient and zero-emission transport refrigeration unit (TRU). The research group comprises academics, researchers, students and a technician. The group is a key partner in a project to deliver a bench prototype of an Auxiliary Power Unit in 2016. The project is funded by Innovate UK and in partnership with Dearman, Hubbard Products Ltd and Air Products. The facilities contain bespoke engine testing chambers for modified cryogenic Stirling engines and a Dearman engine as well as a tribological suite to examine physics of 'cold' contact."

Dr Karl D Dearn
Lecturer in Mechanical Engineering, School of Mechanical Engineering
The University of Birmingham

Zero-emission transport refrigeration and the case for fuel duty reform

This report is largely about the social case for zero-emission transport refrigeration; we have clearly shown how this would reduce the F-gas leakage and lifecycle CO_2 emissions of a TRU, and eliminate its NO_x and PM.

A separate analysis of the business case reveals liquid air TRUs would be the most economical of all the zero-emission, lower-carbon alternatives. This modelling, based on UK input prices and grid carbon intensity, highlights a fuel duty anomaly that persists in a handful of EU member states, and which raises a substantial barrier to zero-emission transport refrigeration.

For most large trucks and almost all trailers, the TRU is powered by an auxiliary diesel engine. As we explain elsewhere, these are essentially unregulated in Europe and emit grossly disproportionate amounts of NO_x and PM. They are cheap, however, partly because they lack any emission control technology, and partly because some countries – including Britain, France, Spain and Belgium – allow them to run on subsidised diesel originally introduced to support agriculture. In Britain this 'red' diesel costs about half the normal pump price, and skews the business case against zero-emission transport refrigeration.

As shown in Table 5 below, to buy and operate an auxiliary TRU in Britain for five years would cost around €80 000 running on subsidised red diesel, or €130 000 if the unit were forced to run on full price fuel – an effective subsidy of €10 000 per unit per year. As a result, the Dearman TRU, with the lowest total costs of all the zero-emission alternatives, would cost just 9% more than a conventional auxiliary TRU running on subsidised red diesel, and 32% less than one running on full-price fuel. In fact, were it not for the subsidy, all the zero-emission alternatives bar hydrogen would undercut the auxiliary diesel TRU.

In short, taxpayers' money is being used to support a highly polluting mature technology whose emissions cause huge damage to the environment and health, so raising a high barrier to the adoption of a range of clean cold technologies that would mitigate or eliminate those problems and save society huge sums of money. There is a compelling argument to abolish red diesel for TRUs in the countries where it is still allowed; it is time to close this loophole.

Auxiliary diesel TRU

Used on most trucks and almost all trailers. Secondary diesel engine powers the refrigeration system. Effectively unregulated in Europe, emit grossly disproportionate NO_x and PM. Can run on subsidised red diesel where permitted – reducing its owner's costs by €50 000 over five years in the UK.

Alternator TRU

An alternator on the vehicle's propulsion engine produces electricity to run the refrigeration system. More efficient than an auxiliary unit, and the main engine is likely to emit far less NO_x and PM. Against that the main engine may have to idle continuously to keep the cargo cool when the vehicle is stationary. Must run on full-price diesel, so currently more expensive than an auxiliary unit in the UK, but cheaper if the red diesel subsidy is abolished.

Battery TRU

The battery is charged at base overnight with grid electricity, which is typically cheaper and lower carbon than diesel. Lowest CO_2 emissions, but the cost of batteries required to run the TRU for a full day on a single charge is high. More expensive than auxiliary unit running on red diesel, but far cheaper if red diesel subsidy abolished.

	Auxiliary Diesel TRU (red diesel)	Auxiliary Diesel TRU (road diesel)	Alternator driven from vehicle diesel engine	All-eletcric TRU	Hydrogen fuel cell TRU	Liquid nitrogen TRU (evaporation only)	Dearman TRU
Energy efficiency	2,17kWh cooling / kg diesel	2,17kWh cooling / kg diesel	2,76kWh cooling / kg diesel	0,501kWh cooling / kWh grid electricity	9,25kWh cooling / kg hydrogen	0,101kWh cooling / kq liquid nitrogen	0,182kWh cooling / kq liquid nitrogen
Cost of a unit of cooling (1kWh)	€ 0,429	€ 0,836	€ 0,663	€ 0,244	€ 1,074	€ 0,805	€ 0,449
Annual operating cost	€ 10 554,74	€ 20 553,98	€ 16 307,05	€ 6 014,01	€ 26 414,54	€ 19 808,17	€ 11 045,23
Capital cost	€ 20 400,00	€ 20 400,00	€ 23 800,00	€ 68 000,00	€ 31 375,20	€ 25 500,00	€ 23 800,00
Annual maintenance cost	€ 1 632,00	€ 1 632,00	€ 816,00	€ 408,00	€ 1 632,00	€ 544,00	€ 1 632,00
Additional infrastructure cost per vehicle over the life of the TRU	-	-	-	€ 5 440,00	€ 5 440,00	€ 1 360,00	€ 1 360,00
5-year total cost of ownership (TCO)	€ 81 333,72	€ 131 329,88	€ 109 415,27	€ 105 550,05	€ 177 047,88	€ 128 620,85	€ 88 546,15
5-year lifecycle CO_2 emissions (TCO2e)	195	195	170	106	174	344	151

Table 5: TRU technologies compared. For notes to this table, please see Appendix 2. NB the lifecycle CO_2 emissions for this business case were calculated on the basis of current UK grid average carbon intensity, meaning the emissions of the Dearman TRU and other technologies whose fuel is derived from electricity will continue to improve as the grid decarbonises. The CO_2 emissions for the social case presented in the rest of this report were based on the current grid average carbon intensity of each of the EU28 countries, and will also improve with the falling emissions from power generation.

Fuel cell TRU

A tank of hydrogen and fuel cell generate electricity to run the TRU. The fuel cell itself is efficient, but hydrogen is carbon intensive to produce – so CO_2 reductions are modest – and expensive, making this the only zero-emission alternative with total five-year costs higher than unsubsidised diesel.

Nitrogen evaporation TRU

Liquid nitrogen is evaporated through a heat exchanger in the goods compartment, but no mechanical power is extracted from the expansion. This means large amounts of nitrogen are required and carbon emissions are higher than diesel. It is however lower emission and cheaper than unsubsidised diesel over five years.

Liquid air TRU

Liquid air or liquid nitrogen are used to provide both cooling and mechanical power by means of a Dearman engine. Much lower capital costs than a battery system, and far more efficient than an evaporation-only nitrogen system, it has the lowest total cost over five years of any zero-emission TRU in the UK: just 9% more expensive than an auxiliary unit running on red diesel, 32% less than one running on full price fuel, and 19% less than the alternator unit.

Local air pollution and TRUs – the case for action in cities

The negative effect of air pollution on health

Local air pollution is rising rapidly up the political agenda, and with good reason; according to the European Environment Agency it causes more than 400 000 premature deaths through respiratory and heart disease in the EU each year.[19] In fact, this may be a gross underestimate since estimates are based on the known impacts of particulate matter (PM), but exclude those of nitrogen oxides (NO_x). Since the two pollutants typically occur together it has been difficult to disentangle their impact, but recent work suggests NO_x causes significant additional damage[20], and one study concluded there is evidence that the impact of nitrogen dioxide (NO_2) on long-term mortality is "as great as that of $PM_{2,5}$".[21]

In Britain, the government recently updated its guidance and concluded that NO_x and PM cause 44,750 - 52,500 premature deaths and cost society £25.3bn - £29.7 billion each year.[22]

Emissions of both PM and NO_x have fallen substantially over the last decade, but a study of 400 cities by the European Environment Agency has found that almost all city dwellers are still exposed to levels of pollution considered unsafe by the World Health Organisation[23], and most countries are still in breach of EU pollution laws introduced in 2010. Independent campaigners and the European Commission have won judgements against the UK in the European Court of Justice and Britain's Supreme Court, forcing the government to deliver a new air pollution reduction strategy to Brussels by the end of 2015. The Commission has recently referred Belgium and Bulgaria to the Court of Justice, and issued warnings to Sweden and Poland.[24] In total, 24 countries of the EU28 have zones in breach of legal limits for NO_x or PM or both (see Appendix 3). Stricter policies on air pollution are, it seems, inevitable across the EU.

Diesel emissions from road transport

Road transport is the biggest single source of NO_x in the EU, responsible for over 40% of total emissions[25], and an even higher proportion in cities, where the health impacts are greatest: 48% in London and Barcelona[26]; 56% in Paris – of which 94% comes from diesel vehicles.[27] Diesel emissions make commercial transport a disproportionate culprit, but the most disproportionate is the diesel-powered TRU.

Poor emissions data for cities

Beyond these headline figures, however, we have found that transport and emissions data for individual cities is often extremely poor. To estimate the impact of transport refrigeration in a city requires data for vehicle emissions, and kilometres driven, to be segmented between vans, trucks and trailers.

For two of our intended case studies, Paris and Milan, this information is simply not available. In Paris, for example, kilometres driven is given only for 'commercial vehicles', a category that lumps together not only vans, trucks and trailers, but also buses and coaches. Emissions data for Paris is broken down only as far as 'road transport', which includes not only commercial vehicles but also cars. In Milan, data is similarly problematic, and available only for the entire Lombardy region.

This lack of segmented city-level data would render any attempt to analyse the true impact of transport refrigeration highly speculative, and we recommend that national governments and city authorities should act quickly to improve the quality and granularity of their transport and emissions data. You cannot manage what you cannot measure.

"Road transport is the biggest single source of NO_x in the EU, responsible for over 40% of total emissions"

London is recognised as an exception, and does have segmented data for both vehicle emissions and kilometres driven. Combining this with figures for TRU penetration of commercial vehicle segments in the national fleet, we estimate that refrigerated vans, trucks and trailers travel 84,6 million km in London each year, where they emit more than 49 000 tonnes of CO_2, 163 tonnes of NO_x and 22 tonnes of PM. That is the CO_2 equivalent of driving a family car[28] 447 million km – almost 2,4 million laps around London's M25 orbital motorway or 11 200 times around the world. Replacing those TRUs with zero-emission units would be the PM equivalent of taking 327 000 Euro 6 diesel cars or almost 30 000 Euro VI diesel trucks off Britain's roads.

HGV transport refrigeration emissions

Even more striking, however, is the disproportionate impact of transport refrigeration in the context of HGV exhaust emissions in London. Of the total 84,6 million km travelled by refrigerated vehicles, trucks and trailers with TRUs travel 62,6 million km, which equals 7% of the total distance travelled in London by all HGVs. In stark contrast, the NO_x emissions from truck and trailer TRUs in Central London equate to 41,3% of those from HGV exhausts in the same area; while PM emissions from truck and trailer TRUs in Greater London equate to 76,7% of those from HGV exhausts. Far more NO_x and PM is produced from HGV brakes and tyres, but the tailpipe-only comparison is a powerful illustration of the extent of TRU pollution, and the 'easy win' that could be achieved by tackling it.

New Ultra Low Emission Zones

Major cities such as Paris and London are planning to introduce strict ultra-low emission zone policies in 2020 which either ban diesel vehicles or charge them for entering the zone. It also seems likely that the British government's new air pollution strategy will have to include some kind of national network of low emission zones to meet EU standards. Since emissions from diesel TRUs are so disproportionate, and since economically competitive zero-emission transport refrigeration will be available, there is now a strong argument to include TRUs in such schemes. Some preparatory steps towards this are already being taken: in London, officials are considering how to include emissions from TRUs in the next edition of the London Atmospheric Emissions Inventory, due to be published in 2017.[29]



Conclusions

The analysis conducted for this report demonstrates a compelling case to support the development of liquid air transport refrigeration across the EU:

- The social costs of diesel powered transport refrigeration are high, grossly disproportionate and provide a strong argument for policy support for zero-emission alternatives;
- Liquid air transport refrigeration would eliminate NO_x and PM emissions; deliver substantial and progressively larger reductions in greenhouse gas emissions; and could provide an efficient route to eliminating damaging F-gases entirely;
- The average annual benefit to society of each zero-emission TRU in 2025 is €1 700, in addition to any direct savings made by owners of the equipment;
- Europe has ample liquid nitrogen infrastructure to support the shift to liquid air transport refrigeration;
- Policy around TRUs is currently focussed on F-gases, which – although important – account for only 17% of aggregate TRU lifecycle greenhouse gas emissions, whereas diesel is responsible for most of the rest, and all of the NO_x and PM;
- The NRMM regulations provide no incentive for the industry to make meaningful reductions in TRU emissions of NO_x and PM, even after the proposed new standards become law;
- Policy should be re-set to focus not only on F-gases but on the larger problem of reducing TRU diesel emissions. If it is too late to tighten the new standards proposed for NRMM Stage 5, other measures should be found;
- Since NO_x and PM emissions are especially damaging in cities, TRU emissions should be regulated under Low Emission Zones;
- In a handful of countries, including Britain, France, Spain and Belgium, TRUs are still permitted to run on subsidised 'red' diesel, meaning that taxpayer's money is being used to support a mature, highly polluting technology, creating a high barrier against the adoption of zero-emission transport refrigeration technologies that would otherwise undercut diesel; it is time to close this loophole;
- Many major cities such as Paris and Milan lack the data needed to estimate the impact of TRU emissions, and we recommend that national governments and city authorities should act quickly to improve the quality and granularity of their transport and emissions data; you cannot manage what you cannot measure.

"The policy should be re-set to focus not only on F-gases but on the larger problem of reducing TRU diesel emissions"

"The average annual benefit to society of each zero-emission TRU in 2025 is €1 700"



Appendix 1: The Dearman technology

1.1. The Dearman engine

The Dearman engine is a novel piston engine driven by the vaporisation and expansion of liquid air or liquid nitrogen (LiN) to produce clean cold and power. Cryogenic expansion engines are not new, previous embodiments have worked on an open Rankine cycle akin to a traditional steam engine but operating across a different temperature range, expanding the gaseous LiN over several stages. The Dearman engine process innovation involves the use of a heat exchange fluid (HEF) inside the cylinder of the engine as a source of heat for the expanding LiN enabling a more efficient, nearly isothermal expansion. Ambient or low grade waste heat is used as an energy source with the LiN providing both the working fluid and heat sink. An example power cycle is shown in Figure 3. A further advantage of this approach is that the engine remains at nearly constant near-ambient temperature offering greater flexibility with materials choices.

Some key qualities of the Dearman engine are:

- Ability to use a low grade or ambient source of heat – e.g. heat rejected from a refrigerator condenser at around 50% thermal efficiency;
- Presence of low temperature working fluids, which can be used to assist refrigeration;
- A relatively high consumption of liquid air (~10x mass of 'fuel' per unit of energy delivered as mechanical power, compared to an ICE);
- Low capital cost and embedded CO_2 (few 'exotic' materials in the engine or cryogenic tank);
- Zero-emissions except for air or nitrogen;
- Use of a non-flammable 'fuel';
- Fast refuelling.

The Dearman engine exploits the expansion between liquid and gaseous phases of a cryogenic working fluid so it can operate using liquid air or nitrogen, with only slightly differing performance characteristics.

1.2. What is liquid air?

Liquid air is an intermediate step in the production of industrial gas products like liquid nitrogen, oxygen and argon. It is made by compressing ambient air and rejecting heat in a series of stages until the air's temperature is reduced to -196°C where it becomes a liquid. Typically, the air is then allowed to boil in a distillation column where it is separated into its fractions; nitrogen, oxygen and argon. Liquid nitrogen and air are zero-emission fuels at their point of use, offering the same potential for dramatic local air quality improvement as electricity or hydrogen. However, greenhouse gases from the liquefaction process require consideration as the liquefaction plant is usually electrically powered. The capability to operate intermittently combined with very low cost of bulk storage means that liquefaction plants are very suitable for pairing with intermittent renewables, offering significant opportunities for further carbon reduction. It also allows industrial gas producers to adapt the plant's utilisation profile to market conditions – in territories where there is a peak/off-peak price differential for electricity, plants tend to be used at lower capacity during peak times and higher capacity during off-peak times. In terms of infrastructure, we estimate that the 1 countries that operate 80% of the EU TRU fleet have over 28 000 tonnes per day of spare liquid nitrogen production capacity, enough to fuel almost 70 000 liquid air TRUs (see Summary, Table 4).



The Dearman engine

1.3. How does the Dearman TRU work?

In the Dearman system, refrigeration is provided by two means (Figure 3). First, latent heat of vaporisation of the LiN is extracted from the refrigerated compartment. The heated vapour thus produced drives the engine, which in turn performs two functions: firstly, to operate a generator so that the refrigeration system powers its own electrical systems, and secondly, to power a down-sized conventional vapour refrigeration cycle. This cycle must reject heat through a condenser, and this heat is used to warm the HEF for the engine, a synergy that raises the efficiency of engine and vapour cycles simultaneously. The system therefore has potential to be an efficient, self-contained, zero-emission refrigeration device, with low capital cost thanks to the relative simplicity of the engine, and the downsizing of refrigeration components to sizes used in automotive air conditioning. The first prototype (Figure 4) has undertaken testing at HORIBA MIRA[38] and the next generation transport refrigeration unit will be released to a UK customer in late 2015 for extended field trials.

1.4. Dearman transport refrigeration unit development status

To validate the Dearman engine system within a simulated real-world environment, a collaborative project (COOL-E) was launched in September 2013 between MIRA Ltd, Air Products Inc.[39], Dearman and Loughborough University with the financial support of Innovate UK[40]. In this project, one of the objectives was to develop, install and test a Dearman-powered transport refrigeration unit (TRU) as a retrofit to a heavy-duty vehicle (see Figure 4).

This demonstrator has been undergoing tests since March 2015 in a controlled environment – HORIBA MIRA's environmental test chambers and tracks. The aim is to establish performance figures for different duty-cycles, validate the anticipated benefits of the integrated Dearman transport refrigeration system and allow comparison to the standard diesel powered refrigeration system previously installed on the same vehicle.

The latest test results show that:

- the system is capable of delivering 12kW of cooling at -20°C;
- the system can pull the refrigerated compartment temperature from ambient temperature; down to -20°C in 25% less time than the baseline diesel unit;
- the system is exceeding its efficiency targets at this prototype stage – up to 25% more efficient than anticipated;
- the thermal balances at the heart of the technology are all performing as expected.

Controlled environment testing will continue until the end of the project in September 2015 – meanwhile an upgraded TRU system (generation 2) is being commissioned and will be released to a UK based refrigerated vehicle operator for several months of real-world commercial testing later this year.

The commercial status of the Dearman TRU technology can be summarised as follows:

- Dearman has a commercial collaboration relationship with two main partners:
  - Zanotti – a global refrigeration equipment manufacturer who acts as an integrator, manufacturing and technology development partner. Zanotti has offices and customers on the East Coast of the United States;
  - Air Products – an American industrial gas supplier with 20 000 employees and operations in more than 50 countries.
- Dearman has agreed trials with one of the UK's largest vehicle leasing businesses, those trials will take place in 2015.

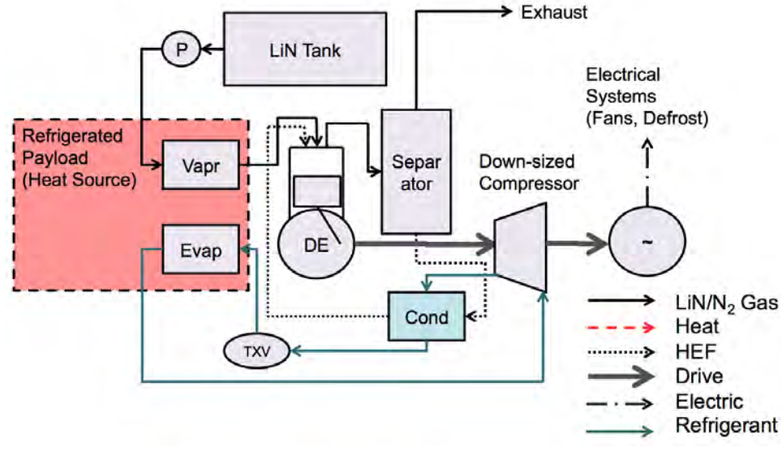


Figure 5: Dearman transport refrigeration system

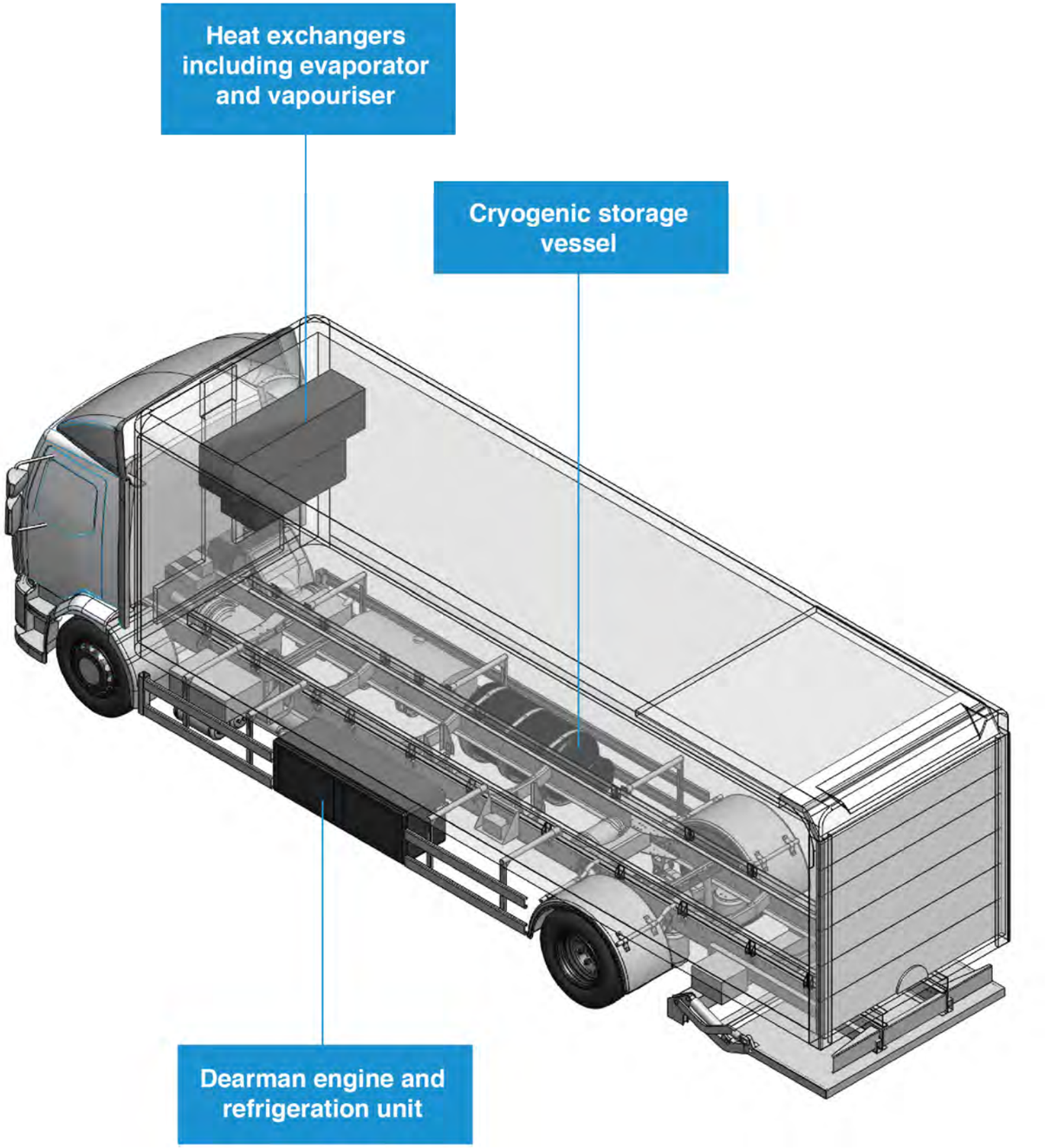


Figure 6: The Dearman transport refrigeration system

Appendix 2: TRU technologies comparison

The summary table below compares conventional diesel powered TRUs, all-electric TRUs, liquid nitrogen TRUs and Dearman TRUs in terms of the system's energy efficiency in producing cooling. It further considers the system's capital, operating and maintenance costs as well as lifecycle CO_2 emissions and criteria pollutant emissions. Because of the different nature of these systems, details on how the comparison has been put together as well as assumptions are given in the following sections.

	Auxiliary Diesel TRU (red diesel)	Auxiliary Diesel TRU (road diesel)	Alternator driven from vehicle diesel engine	All-eletcric TRU	Hydrogen fuel cell TRU	Liquid nitrogen TRU (evaporation only)	Dearman TRU
Energy efficiency	2,17kWh cooling / kg diesel	2,17kWh cooling / kg diesel	2,76kWh cooling / kg diesel	0,501kWh cooling / kWh grid electricity	9,25kWh cooling / kg hydrogen	0,101kWh cooling / kq liquid nitrogen	0,182kWh cooling / kq liquid nitrogen
Cost of a unit of cooling (1kWh)	€ 0,429	€ 0,836	€ 0,663	€ 0,244	€ 1,074	€ 0,805	€ 0,449
Annual operating cost	€ 10 554,74	€ 20 553,98	€ 16 307,05	€ 6 014,01	€ 26 414,54	€ 19 808,17	€ 11 045,23
Capital cost	€ 20 400,00	€ 20 400,00	€ 23 800,00	€ 68 000,00	€ 31 375,20	€ 25 500,00	€ 23 800,00
Annual maintenance cost	€ 1 632,00	€ 1 632,00	€ 816,00	€ 408,00	€ 1 632,00	€ 544,00	€ 1 632,00
Additional infrastructure cost per vehicle over the life of the TRU	-	-	-	€ 5 440,00	€ 5 440,00	€ 1 360,00	€ 1 360,00
5-year total cost of ownership (TCO)	€ 81 333,72	€ 131 329,88	€ 109 415,27	€ 105 550,05	€ 177 047,88	€ 128 620,85	€ 88 546,15
5-year lifecycle CO_2 emissions (TCO2e)	195	195	170	106	174	344	151

Table 5: Energy efficiency, 5 year total cost of ownership and environmental impact comparison

2.1 Auxiliary diesel engine powered refrigeration system

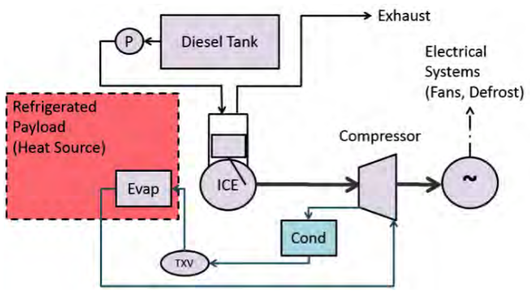


Figure 7: Auxiliary diesel engine powered TRU diagram

The energy density[41] for diesel fuel is 42,91MJ/kg, which translates[42] to 11,91kWh/kg. Of this available energy in diesel fuel, only 25%-30% is in practice converted to useful work through a conventional non-road diesel engine[43] – meaning that ~3,26kWh/kg of useful energy can be recovered from 1 kg of diesel fuel through a diesel engine. Of this useful energy, some will be used to drive ancillary systems like the alternator to charge the batteries (and power the engine radiator fan, fans to circulate air through the compartment, condenser fans, etc.) while the rest will be used to drive a vapour compression cycle (refrigeration machine) which effectively provides cooling. It is estimated that a third of the useful work produced by the engine is consumed by ancillaries[44] while the remaining two thirds of the useful work are used to drive the vapour compression cycle. Therefore of the 3,26kWh/kg of useful energy produced by the engine, only 2,17kWh/kg is used to drive the refrigeration system. Assuming that a conventional R404A refrigeration unit has on average a coefficient of performance[45] (COP) of 1, this means in turn that 2,17kWh of cooling energy per kg of diesel fuel can be generated using a transport refrigeration unit.

Assuming that a fleet operator in the UK would currently pay ~€ 0,7752L for red diesel, the unit operating cost of a diesel TRU therefore is € 0,429 per kWh of cooling.

2.2 Alternator driven transport refrigeration system

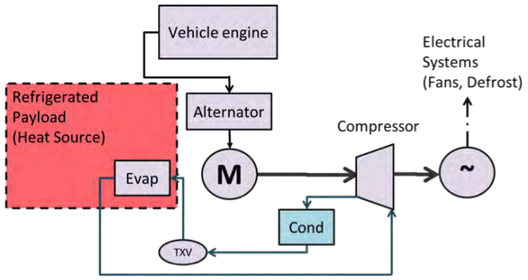


Figure 8: Alternator driven from vehicle engine powered TRU diagram

The energy density[46] for diesel fuel is 42,91MJ/kg, which translates[47] to 11,91kWh/kg. Of this available energy in diesel fuel, between 35% and 45% is in practice converted to useful work through modern on-road diesel engines[48] – meaning that 4,53kWh/kg of useful energy can be recovered from 1kg of diesel fuel through a diesel engine. Of this useful energy, similarly to other TRUs, around a third of the useful work produced by the engine is consumed by ancillaries[49] while the remaining two thirds of the useful work are used to drive the alternator. Therefore of the 4,53kWh/kg of useful energy produced by the engine, only 3,03 kWh/kg is used to drive the alternator. High efficiency alternators can be assumed to be on average 90% efficient, as well as electric motors – of the 3,03kWh/kg of useful energy produced by the engine, 2,51kWh/kg is available to drive the refrigeration system. Assuming that a conventional R410A refrigeration unit has on average a coefficient of performance (COP) of 1,1[50], this means in turn that 2,76kWh of cooling energy per kg of diesel fuel can be generated using an alternator driven transport refrigeration unit.

Assuming that a fleet operator in the UK would currently pay ~€ 1,5232/L[51] for diesel, the unit operating cost of a diesel TRU therefore is € 0,663 per kWh of cooling.

2.3 Dearman engine powered refrigeration system

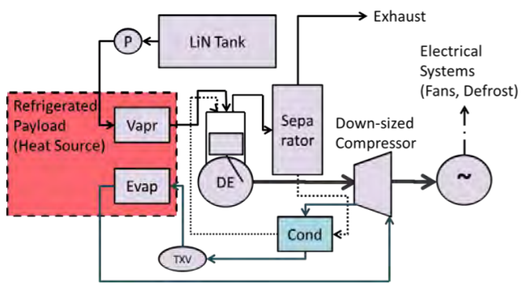


Figure 9: Dearman engine powered TRU

By comparison with diesel, it takes ~0,101 kWh of energy to warm 1 kg of liquid nitrogen (LiN) from -196°C up to -25°C – if the refrigerated vehicle is used to transport frozen goods at -20°C, the LiN would be warmed to around -25°C. This translates to 0,101 kWh of heat absorbed from the refrigerated vehicle per kg of LiN. In the Dearman refrigeration unit, the warmed nitrogen is then fed to the Dearman engine where it is expanded isothermally to produce mechanical work. For every 0,101 kWh of heat absorbed by the nitrogen before entering the engine, 0,060 kWh of work can be produced by expansion of the nitrogen in the Dearman engine[52]. Part of this work is used to drive ancillaries in the refrigeration system (alternator, fans, pumps etc) and the rest is used to drive a vapour compression cycle to provide additional cooling on top of the cooling provided by the LiN.

In the Dearman refrigeration unit, the vapour compression cycle air-cooled condenser is replaced by a water cooled condenser, allowing to more than double the efficiency of the vapour compression system. In fact the COP for this improved vapour compression cycle is 2[53].

Bringing all the numbers together for the Dearman refrigeration unit:

- Cooling from nitrogen warming before engine: 0,101 kWh/kg
- Work produced from nitrogen expansion in the Dearman engine: 0,060 kWh/kg
- Useful work available to drive vapour compression system: 0,040 kWh/kg
- Cooling from vapour compression system driven by the Dearman engine (COP = 2): 0,040 x 2 = 0,08 kWh/kg
- Total cooling energy from Dearman refrigeration system: 0,101 + 0,08 = 0,182 kWh/kg

In a Dearman powered refrigeration system, 0,182 kWh of cooling energy can be recovered per kg of liquid nitrogen.

Assuming that a fleet operator in the UK would currently pay ~€ 0,0816/kg of liquid nitrogen, the operating cost of Dearman units therefore is € 0,449 per kWh of cooling.

Note: Other cryogenic TRUs (liquid nitrogen, liquid CO_2) are not equipped with a means to recover mechanical energy from the cryogenic fluid (like the Dearman engine) – therefore they can only recover up to 0,101 kWh per kg of liquid nitrogen (resp. 0,103 per kg of liquid CO_2). In addition, these systems will require energy to drive the ancillary systems – typically this energy is taken from the main vehicle engine which will add to the system's operating cost and also means that the system is not emissions free at point of use.

2.4 Battery electric transport refrigeration system

2.4.1 System efficiency and operating costs

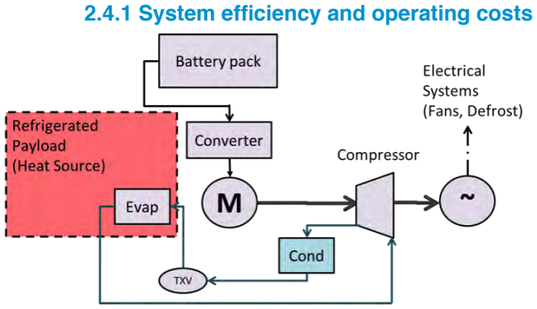


Figure 10: All-electric TRU

This analysis considers all-electric TRUs where the system comprises a battery large enough to provide energy to the refrigeration unit for a typical day's worth of operation (>6 hours). Electric TRUs where power is sourced from the vehicle main engine are not considered in this analysis – primarily because a) electricity produced from the main vehicle engine tends to be significantly more expensive than grid electricity b) despite the main vehicle engine being more efficient and less polluting than small auxiliary diesel engines, these systems use fossil-fuel as their energy source.

All-electric TRUs are charged before leaving their base using grid electricity, and during daily operation the refrigeration unit then draws its energy from the batteries. The batteries' electricity is used to run an electric motor which in turns powers the refrigeration machine – a vapour compression cycle as on diesel-powered TRUs. To quantify the system performance and operating costs, the following assumptions are made:

- advanced batteries (Li-ion) have a charge/discharge efficiency of 90%[54]
- the electric motor has a 92%[55] efficiency
- the refrigeration unit has on average a coefficient of performance[56] (COP) of 1
- similarly to diesel engine powered TRUs, the system needs to power electrical ancillaries such as fans. It is therefore assumed that 33% of the TRU's energy consumption is for ancillaries while the remaining 67% is available for cooling.

Under these assumptions, every kWh of grid electricity fed to the TRU's batteries will result in 0,50 kWh of cooling.

Assuming that a fleet operator in UK would currently pay ~€0,1224 kWh of grid electricity, the operating cost of all-electric TRUs therefore is €0,244 per kWh of cooling. emissions free at point of use.

2.4.2 Capital costs

Capital costs of all-electric transport refrigeration units will vary depending on customer requirements – the size of the battery required will be the main cost driver as advanced batteries are priced at ~€544/kWh[57]. Charging times are still too long to recharge the battery during daily operation, therefore a fleet manager would have to purchase batteries large enough to cope with the daily operation on a single charge. It is also worth noting that even if energy requirements will vary during the year, batteries must be sized for the worst case scenario (i.e. largest daily energy requirement) to make sure the vehicle does not run out of cooling during operation which would result in produce damage. Finally, batteries typically have a recommended 80% depth of discharge – meaning that of the total battery capacity only 80% is useable. Accounting for all these facts, a trailer in hot conditions can be expected to require a battery with a capacity of at least 100 kWh[58] (to provide 80 kWh effective energy) – therefore costing €54 400. As this is the battery cost only, the rest of the system (electric motor, electrical systems and refrigeration machine) will cost around €13 600 bringing the total system cost to €68 000.

Annual maintenance costs are estimated at ~€408.[59]

2.5 Fuel cell powered transport refrigeration units

2.5.1 System efficiency and operating costs

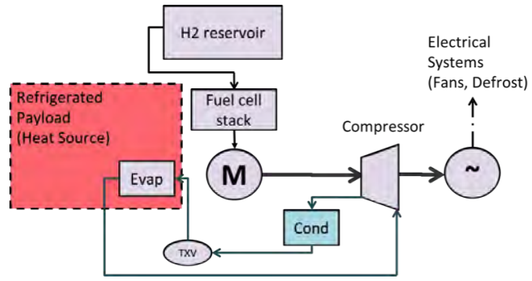


Figure 11: Hydrogen fuel cell TRU

In fuel cell powered TRUs, hydrogen is stored in a tank and when power and/or cooling is required hydrogen is supplied to the fuel cell stack which drives an electric motor, which in turns drives the refrigeration cycle (similar to diesel/battery electric TRUs). To quantify the system performance and operating costs, the following assumptions are made:

- fuel cell stacks have an energy efficiency of ~15 kWh/kg-hydrogen[60]
- the electric motor has a 92%[61] efficiency
- the refrigeration unit has on average a coefficient of performance[62] (COP) of 1
- similarly to diesel engine powered TRUs, the system needs to power electrical ancillaries such as fans. It is therefore assumed that 33% of the TRU's energy consumption is for ancillaries while the remaining 67% are used for cooling.

Under these assumptions, 9,25 kWh of cooling will be recovered in a fuel cell TRU per kg of hydrogen.

Assuming that a fleet operator in the UK would currently pay ~€9,928/kg of hydrogen[63], the operating cost of hydrogen fuel cell TRUs therefore is €1,074 per kWh of cooling.

2.5.2 Capital costs

A hydrogen fuel cell system is similar in its architecture to an all-electric system – instead of having a large battery the hydrogen TRU has a hydrogen reservoir with a fuel cell stack (and balance of plant components) driving an electric motor which in turns drives the refrigeration machine (see Figure 9). Currently the costs for fuel cell stacks and balance of plants components are around €680/kW – a 15 kW fuel cell would be required to drive the refrigeration equipment along with a hydrogen tank which in the current market retails at ~€7 480. As for the all-electric TRU, the rest of the system (electric motor, electrical systems and refrigeration machine) will cost around €13 600 – bringing the total system cost to more than €31 375.

Appendix 3: Calculating the social cost of transport refrigeration

We have calculated the social cost of transport refrigeration by combining the costs of the damage caused by its emissions of NO_x and PM to health, crops and infrastructure, and the abatement cost of its emissions of greenhouse gases including carbon dioxide and HFC refrigerants. Together these costs represent the burden to society of continuing to base our cold chains on diesel-powered TRUs.

First we modelled the fuel consumption and emissions of TRUs, based on detailed TRU fleet and duty cycle data provided by Cemafroid and other industry sources, and our own analysis of TRU NO_x and PM emissions, and made the conservative assumption that fleets would grow at just 1,5% per year for the next decade. These results were then combined with damage and abatement cost factors calculated by Ricardo-AEA for the European Commission[64] to produce the social costs of a business-as-usual approach in each country and the EU as a whole. Finally we calculated the progressively larger reductions in emissions and social cost that could be achieved by converting to liquid air transport refrigeration over the next 10 years.

€ / tonne (2010)	NO_x all areas	NO_x all areas	NO_x all areas
Belgium	10 927	67 278	90
Czech Republic	15 788	48 279	90
France	13 052	40 260	90
Germany	17 039	64 546	90
Italy	10 824	38 341	90
Netherlands	11 574	71 628	90
Poland	13 434	52 375	90
Portugal	1 957	26 457	90
Spain	4 964	22 429	90
United Kingdom	6 576	41 891	90
EU 28	**10 640**	39 604	90

Table 6: Emission cost factors for selected EU countries. Source: Ricardo-AEA[71]

The damage caused by local air pollution in Europe is enormous. The European Environment Agency estimates it causes over 400 000 premature deaths in the EU each year, ten times more than die in road accidents, making it the biggest environmental cause of death. Local air pollution kills through respiratory and cardiovascular disease, and this illness imposes health costs across the EU estimated at between €330 and €940 billion in 2010, or 3%-9% of GDP.[65] Local air pollution also damages buildings and crops. In the EU, more than 40% of NO_x emissions come from road transport.[66] The EU introduced new air pollution limits in 2010, and 24 out of 28 countries have zones that are in breach of the legal limits for NO_x or PM or both (see Figure 12).

The British Government recently updated its guidance and concluded that NO_x and PM together cause 44,750 - 52,500 premature deaths and cost society £25.3bn – £29.7 billion each year.[69]

The damage caused by each tonne of NO_x and PM, the two main toxic pollutants, was calculated by Ricardo-AEA on the basis of factors including health costs; the value of the years of lost life and output; and damage to crops and buildings. These 'damage costs' vary according to country, on the basis of wealth, population density, exposure and other factors (Table 6). A tonne of NO_x in Germany, for example, causes damage worth €17 039, whereas a tonne emitted in Portugal does damage worth €1 957. The average values for the EU28 as a whole are €10 640 per tonne of NO_x and €39 604 per tonne of PM.[70]

The damage cost of 1 tonne of emissions is typically higher in cities than in the countryside, and around 90% of European city dwellers are exposed to harmful levels of local air pollution.[72] The impact of transport emissions is also greater in cities than elsewhere. For example transport accounts for about 18% of PM and about a third of NO_x emissions in Britain as a whole[73], but about 50% of each in central London.[74]

Government figures show that around 90% of Britain's 600-plus Air Quality Management Areas (AQMAs) are needed because of transport emissions[75], and the health cost of urban transport-related air pollution is between £4,5 billion and £10 billion per year.[76]

The social cost of greenhouse gas emissions was calculated as a marginal abatement cost, in other words the cost of avoiding a given amount of emissions by the cheapest means possible. The figure calculated by Ricardo-AEA for the entire EU, and consistent with keeping global warming within 2°C, is €90 per tonne. We used this to calculate the amount society would have to pay to reduce total CO2e emissions (including those from F-gas leakage) by an amount equal to that emitted by transport refrigeration under a business-as-usual scenario.

Countries	PM_{10}	NO_2	Premature death attributable to $PM_{2.5}$
Austria			6 768
Belgium			10 304
Bulgaria			10 806
Croatia			5 437
Cyprus			710
Czech Republic			10 872
Denmark			3 979
Estonia			647
Finland			2 046
France			46 339
Germany			69 762
Greece			10 700
Hungary			15 952
Ireland			1 229
Italy			64 544
Latvia			1 789
Lithuania			2 556
Luxembourg			284
Malta			247
Netherlands			12 634
Poland			42 412
Portugal			5 707
Romania			28 582
Slovakia			6 300
Slovenia			1 938
Spain			25 046
Sweden			4 221
United Kingdom			39 450

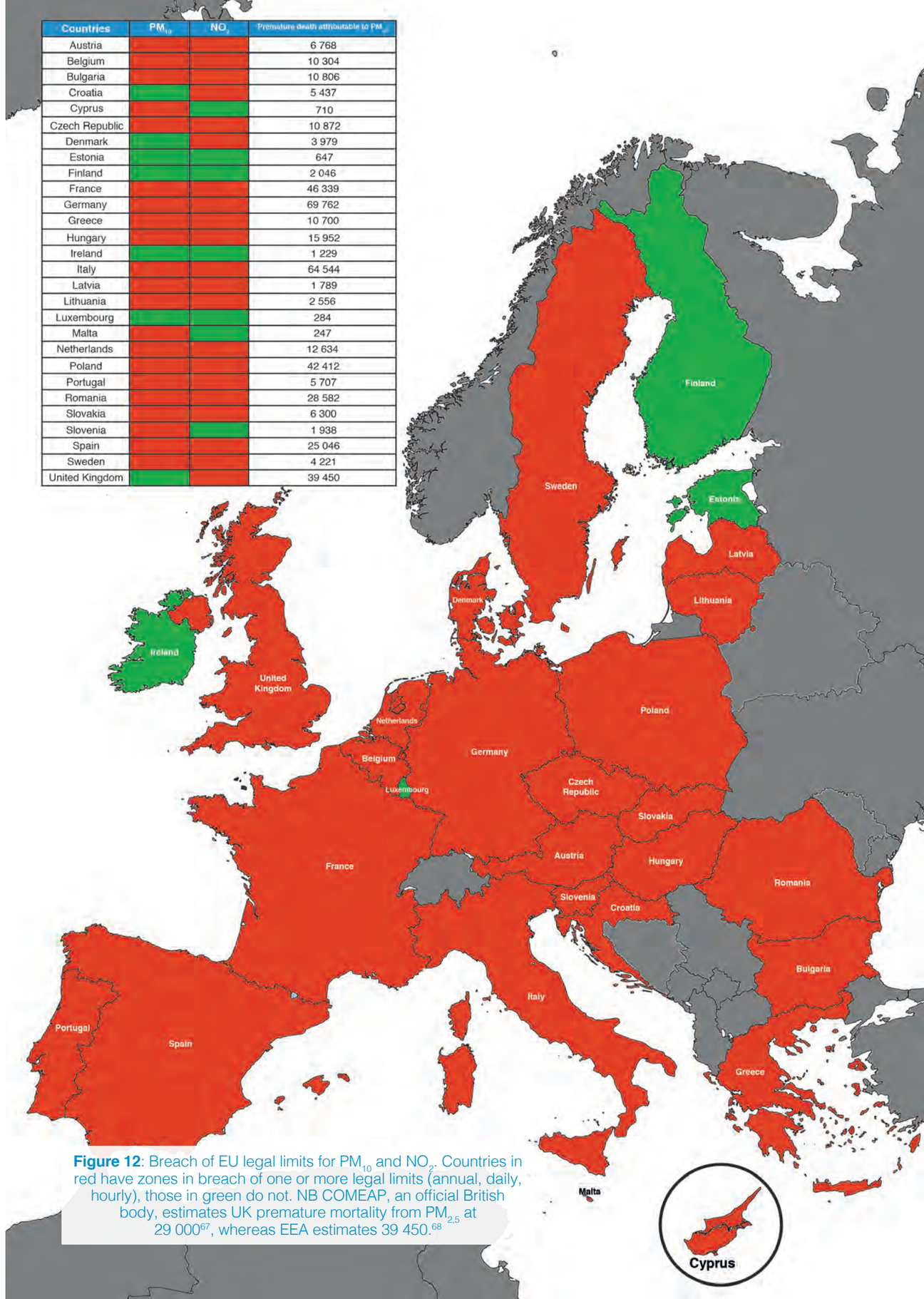


Figure 12: Breach of EU legal limits for PM_{10} and NO_2. Countries in red have zones in breach of one or more legal limits (annual, daily, hourly), those in green do not. NB COMEAP, an official British body, estimates UK premature mortality from $PM_{2.5}$ at 29 000[67], whereas EEA estimates 39 450.[68]

Acronyms

ASU: Air separation unit
ATP: Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage
CO2e: Carbon dioxide equivalent: CO2e allows other greenhouse gas emissions to be expressed in terms of CO_2 based on their relative global warming potential (GWP)
EEA: European Environment Agency
ERTRAC: European Road Transport Research Advisory Council
HFC: Hydrofluorocarbon
GDP: Gross domestic product
GWP: Global warming potential
HGV: Heavy goods vehicle (above 3,5 tonnes)
IEA: International Energy Agency
LGV: Light goods vehicle (under 3,5 tonnes)
LiN: Liquid nitrogen
LNG: Liquefied natural gas
MtCO2: Million tonnes of CO_2
MW: Megawatt
MWh: Megawatt hour
HORIBA MIRA: formerly MIRA, the Motor Industry Research Association
NO_x: Nitrogen oxides
NRMM: Non-Road Mobile Machinery
PM: Particulate matter
TPD: Tonnes per day
TRU: Transport refrigeration unit
HEF: Heat exchange fluid

Technical Terms

Abatement cost: The cost of reducing one more unit of pollution
Alternator: Electrical generator driven by the vehicle's propulsion engine that converts mechanical energy to electrical energy in the form of alternating current
Carbon capture and storage: (CCS) process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere, normally an underground geological formation
Cold chain: A temperature-controlled supply chain of goods such as food or pharmaceutical products
Cryogenic liquid: Gases that have been liquefied and that have a temperature below 120°K (-153°C)
Damage cost: Costs imposed by those pollutants in terms of hospital treatment, premature death, lost life and productivity, and damage to buildings and crops
Energy vector / carrier: a medium of moving, storing, and releasing energy
Grid carbon intensity: The amount of CO_2 that is emitted from the production and consumption of one unit of electricity
Heat exchanger: Equipment built for efficient heat transfer from one medium to another
F-gases: Refrigerant gases
Lifecycle emissions: Emissions associated with all the stages of a product's life from cradle to grave
Liquefaction: The process of cooling a gas to the point of becoming liquid (-194°C for air)
Liquid air: A cryogenic fluid comprising an atmospheric mixture of nitrogen, oxygen and the trace gases
LNG re-gasification: Process by which natural gas that has been liquefied for more convenient shipping is then re-gasified by re-heating
Red diesel: Diesel (or 'gas oil') that carries a lower excise duty than diesel used for road vehicle propulsion
'Wrong-time' electricity: Electricity that is produced by less flexible forms of generation when there is no demand for it, eg. nuclear or wind power produced at night.

Endnotes can be found at www.dearman.co.uk

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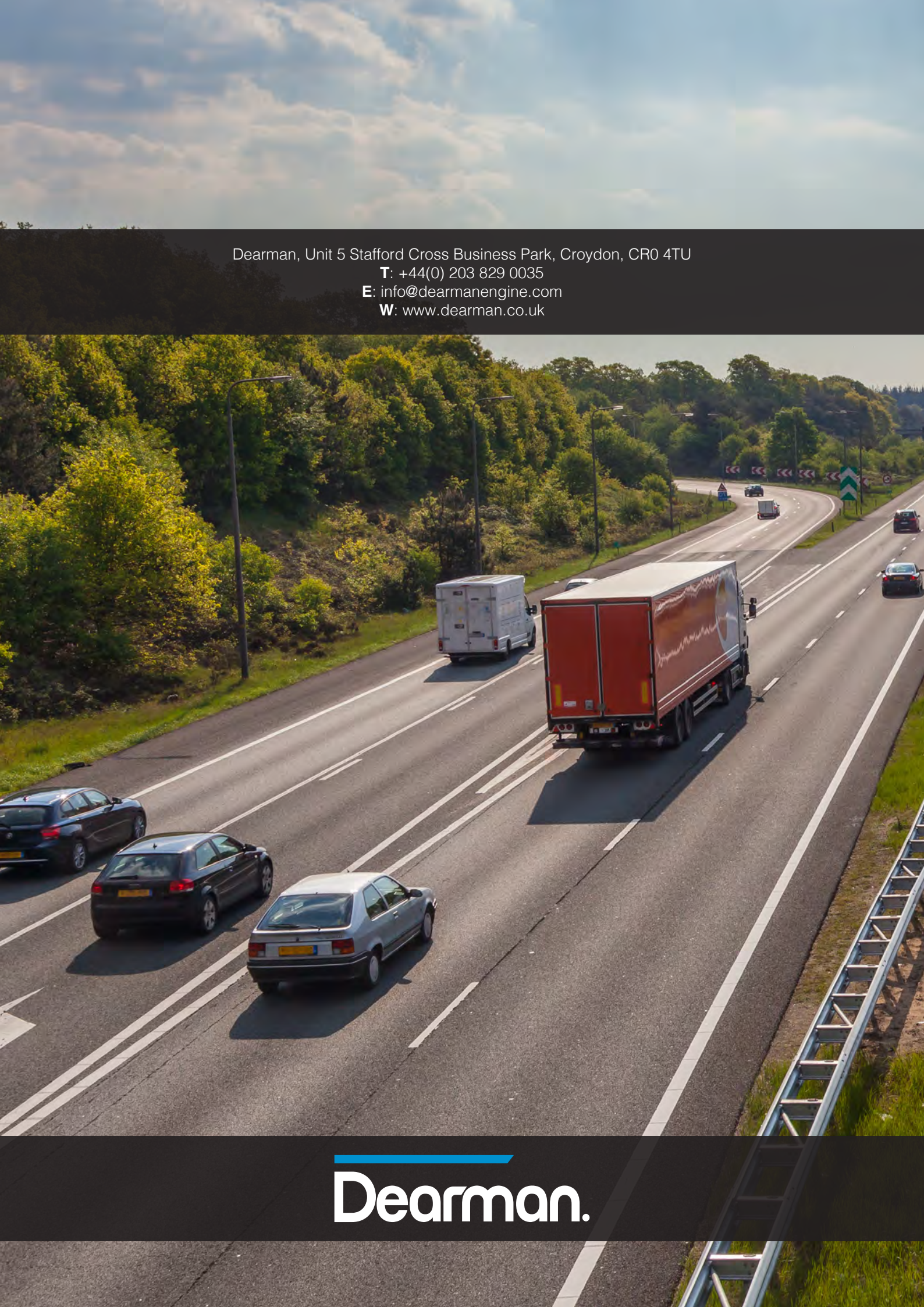
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