SUSTAINABLE TECHNOLOGIES FOR AUXILIARY TRUCK POWER AND TRAILER REFRIGERATION – A REVIEW OF THE EVIDENCE

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INTRODUCTION

Diesel is the main fuel choice for commercial vehicles (Freight Transport Association, 2011a, Hill et al., 2011) and its combustion produces CO_2 which is considered the main contributor to global warming (Barreto et al., 2003, Lee et al., 2011). For this reason, the government has targeted road transport to reduce its carbon footprint and it has developed different policy instruments to achieve this goal, such as the Low Carbon Transport Innovation Strategy (LCTIS) which encourages innovation and technology development in lower carbon transport technologies (DfT, 2007). Lower carbon footprints can benefit road hauliers to some extent, because usually this is achieved by reducing fuel consumption, which in turn decreases operating costs and therefore improves profitability. Nevertheless current technologies are at different stages of maturity and logistics companies considering adopting 'green' technology need to assess each in turn bearing in mind the trade-off between fuel savings and whole life cycle costs. The aim of this paper is to determine the extent to which low-carbon technologies and fuels are being used or could be used in the context of road haulage regarding auxiliary truck power (air conditioning and appliances) and trailer refrigeration units (TRUs).

FREIGHT CARBON EMISSIONS AND GLOBAL WARMING

Transport is more than 98% dependent on oil (Barnier, 2007) with 85% of the world's energy provided by fossil fuels. Their combustion produces harmful gases, including monoxide and dioxide of carbon (CO_x), nitrogen oxides (NO_x), particulate matter (PM_x) and sulphate oxides (SO_x). There is scientific consensus that global warming is producing dangerous climate changes (General Secretariat of the Council, 2009) which may lead to extreme weather and climate events across Europe (McGregor et al., 2005) and if temperature increases are kept under 2°C with respect to pre-industrial levels, the most dangerous consequences could be avoided. This means that developed countries will need to cut their carbon emissions by between 80-95% by 2050 (European Commission, 2010a). As a result, promoting sustainable development and combating climate change have become integral aspects of energy planning, analysis and policy making in many countries (IEA, 2010).

The EU is committed to achieving a series of climate and energy targets by 2020, which include a reduction in EU greenhouse gas emissions of at least 20% below 1990 levels, 20% of EU energy consumption to come from renewable resources, and a 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency (European Commission, 2010b).In the long-term, these objectives are even more ambitious and transport operations seem to be a key focus area where the complete decarbonisation is seen as possible by 2050 (Houtman, 2009).

The UK is the 8th highest emitter of greenhouse gases (GHG) (IEA, 2010) and for this reason, the government has set a long-term framework to tackle climate change and encourage the transition towards a low-carbon economy. The Climate Change Act 2008 establishes a series of carbon budgets that will lead to a carbon emission reduction of at least 80% by 2050. The fourth carbon budget has just been published (Huhne, 2011) setting reductions of at least 34% by 2027.

In the UK, the transport sector contributed to 25% of the UK GHG emissions in 2010 (DECC, 2011) which have increased by 7% since 1990 (AEA, 2011).HGVs and light duty vehicles contributed around 18%and 13% of this respectively (Freight Transport Association, 2011b) and road haulage activity overall represents around 8% of the UK GHG emissions. .

TECHNOLOGY

Vehicle technologies are mainly focused on improving aerodynamics, reducing rolling resistance, and influencing driver behaviour (Baker et al., 2010). The technological development of powertrains are related to better transmissions, engine efficiency and waste heat recovery in the case of conventional internal combustion engines, and the development of alternatives such as electric, hybrid and dual-fuel power trains (Baker et al., 2010). King (2011) reproduces the carbon savings that Ricardo attributes to some technologies (figure 1) and the costs of such solutions (figure 2). Evidence suggests that cheap solutions such as aerodynamics or low rolling resistance can yield appreciable CO_2 reductions.

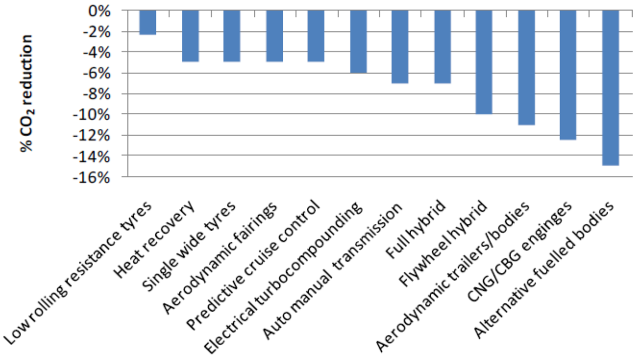


Figure 1.Carbon reductions by using different technologies (King, 2011)

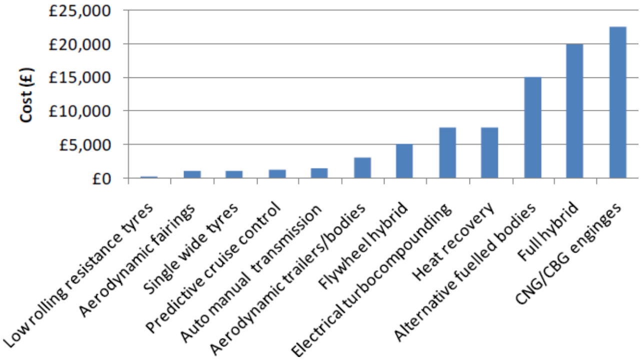


Figure 2.Costs of different technological low-carbon solutions (King, 2011)

VEHICLE TECHNOLOGIES - AUXILIARY POWER UNITS

Studies from the American Transportation Research Institute found that Class 7 trucks spend 200 hr/year idling, Class 8 Non Sleeper (day cabs) 312 hr/year and Class 8 Sleeper trucks up to 1456hr/year (Hennessy, 2010) at an average cost of \$3.00/hr (Baker et al., 2010), producing in the latter case more than 11 tonnes of CO_2/year per truck. Truck idling happens when the engine is continuously running and the truck is not moving. In these cases, energy is needed to power on board 'hotel loads' such as cabin heating, air conditioning, lighting, electronic devices and electrical appliances such as fridges and microwaves. Usually, this energy requirement is powered by the main truck engine or by an auxiliary power unit. In the US there are many states that have legislated excessive idling which has stimulated research and investment in cleaner APU fuel cells, and in Europe, the METSOFC project is developing the next generation of SOFC (Solid Oxide Fuel Cell) stack technology (TOPSOE, 2010).

FUEL CELL AUXILIARY POWER UNITS (APU)

Fuel cells can produce heat and electricity with lower CO_2 emissions. These devices require batteries to store the energy produced, which need to be disposed at the end of their life cycle. Proton Exchange Membrane (PEM) fuel cells convert hydrogen into electricity, heat and water and produce zero emissions as long as hydrogen has been produced sustainably. Solid Oxide Fuel Cells (SOFC) can use natural gas, propane and biogas directly, as they work at very high temperatures or with diesel, gasoline or biodiesel that is converted into syngas with an internal reformer. The reformed fuel is converted into direct-current electricity without combustion, producing water vapour and a small amount of CO_2 as by-products. Rechberger (2009) announced that AVL (a powertrain systems developer) fuel cells were able to reduce CO_2 emissions by 85%, NO_x by 95% and PM_x by 99%. The system efficiency is higher than that found in conventional diesel APU's (Hennessy (2010) recorded system efficiencies of between 40 to 50% and fuel savings of 85% compared to idling the main truck engine). Other advantages include quiet operations (around 55 dB (A)) and low vibration. Rechberger (2009) found that AVL was able to achieve an efficiency of 38% and a total fuel reduction for the truck of between 6-8%.

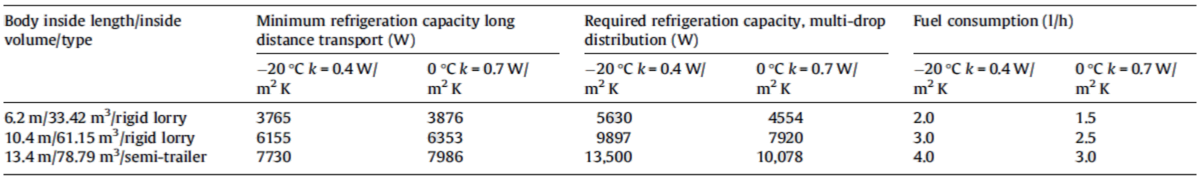
Evidence of Technology Adoption

Delphi, the leading automotive supplier, expects to start a demonstration test in October 2011 in a Peterbilt Class 8 Truck in the US (Hennessy, 2010). AVL plans production of a 3kW SOFC APU by 2014/2015 with a price around 7230\$, that could result in a payback period of 1.2 years (assuming a diesel price of 0.8\$/L). Norrick (2010) divulgated that Cummins Power Generation demonstrated a SOFC APU which was able to deliver 1.1kW with a mere 11% efficiency. Overall, results suggest that there is much work to be done to overcome the technical barriers and improving the power density in W/l and W/kg of such systems.

VEHICLE TECHNOLOGIES- REFRIGERATED TRAILERS

The most common refrigeration system for transport refrigeration units is mechanical refrigeration though a refrigerated transport vapour compression system. The system is typically driven by direct belt drive, vehicle alternator unit or auxiliary alternator unit. Typically, auxiliary diesel engines are the most common refrigeration units for HGVs. Road haulage of food represents between 1.8% (Smith et al., 2005) and 2.5% (Garnett, 2003) of the UK's total CO_2 emissions. According to Defra (2011), around 9% of GHG emissions in the UK food chain are attributed to commercial transportation of food for UK consumption (this does not currently include refrigeration from transportation). From this percentage, UK HGV's accounted for 28% of the emissions in 2009, with a further 11% from overseas HGV's (Defra, 2011). Keystone Distribution who manages McDonald's supply chain, indicated that during multi-drop deliveries, multi-temperature diesel powered refrigeration units consumed 2.5 l/hr (Keystone Distribution UK, 2011) on average (over 24hrs) which contradicts the results from (Tassou et al., 2009), Table 1. Even so, this lower fuel consumption represented around 48 tonnes of CO_2/ year per trailer. These figures suggest that reducing the carbon footprint of refrigerated trailers can make a contribution towards the decarbonisation of the sector.

Table 1 Refrigeration duties and fuel consumption of self-contained mechanical transport food refrigeration units (Source: Tassou et al. (2009))



Body inside length/inside volume/type	Minimum refrigeration capacity long distance transport (W)		Required refrigeration capacity, multi-drop distribution (W)		Fuel consumption (l/h)	
	–20 °C $k = 0.4$ W/ m^2 K	0 °C $k = 0.7$ W/ m^2 K	–20 °C $k = 0.4$ W/ m^2 K	0 °C $k = 0.7$ W/ m^2 K	–20 °C $k = 0.4$ W/ m^2 K	0 °C $k = 0.7$ W/ m^2 K
6.2 m/33.42 m^3/rigid lorry	3765	3876	5630	4554	2.0	1.5
10.4 m/61.15 m^3/rigid lorry	6155	6353	9897	7920	3.0	2.5
13.4 m/78.79 m^3/semi-trailer	7730	7986	13,500	10,078	4.0	3.0

CRYOGENIC REFRIGERATION: LIQUID NITROGEN

This system uses very cold liquid nitrogen that is stored in tanks which is sprayed along the trailer or multi-temperature compartments. The fluid vaporises quickly and reduces the temperature of the container uniformly cooling down the cargo faster than conventional systems (Tassou et al., 2009). Nitrogen refrigeration does not produce emissions at point of use and is very quiet (under 60dB (A)) which allows operators to potentially access previously restricted low-emission urban areas during out-of-hours periods. Because no engine or evaporator is needed, fewer mobile parts reduce maintenance costs up to 65% (Logistics Manager.com, 2008). This influences the whole life cycle cost because around half of these comprise fuel costs, downtime costs, repair and servicing costs and service delivery failures (DfT, 2010a). Other benefits include reduced top freezing and more consistent set point temperatures compared to conventional systems (EcoFridge, 2009). If Nitrogen is generated renewably it completely eliminates the carbon footprint of food refrigerated transport (ecoFridge, 2009b) but there are concerns related to safety.

Evidence of Technology Adoption

Ukram Technologies is the company that develops the cryogenic refrigeration system EcoFridge (EcoFridge, 2009). Its customers include Carrefour (France), Safeway (US), Woolworths (South Africa) and Asda (UK). ASDA is currently conducting a 5 year trial (to 2012) with 7 nitrogen-cooled ecoFridge units (DfT, 2010a) for chilled trailers. ASDA saved almost 83 tonnes of carbon during the first 10 months of the trial (EcoFridge, 2009). ASDA operates around 2500 trailers (DfT, 2010a) and if the trials prove satisfactory they could reduce carbon emissions by 14 tonnes per truck per year.

VEHICLE TECHNOLOGIES - SOLAR PANELS

A photovoltaic array mounted on the roof of a trailer can generate enough power to fulfil the energy requirements of a refrigeration unit. The system requires batteries to store the energy and they need to be replaced at the end of their life cycle. The energy produced powers the transport refrigeration unit. This requires lower maintenance than diesel generators and extends its operating life. A solar trailer does not consume fuel; therefore the operating costs are lower. The advantages include zero emissions (if the emissions of manufacturing the solar panels are not included), noiseless operations and low vibration. Bahaj (2000) demonstrated that it was feasible to produce enough energy to power a multi-temperature chilled food refrigerated delivery trailer, even during months of very low irradiance. The 35m^2 roof of the trailer was able to generate 4.4 kW of maximum output which was enough for chilling (+7^{o}C) fresh food. Multi-drop multi-temperature frozen food transport requires much lower temperatures (-20^{o}C) and due to the high thermal load (the difference between the external temperature and the set point) more power is necessary. Photovoltaic panels can make a significant contribution in reducing energy consumption but they cannot provide an autonomous solution, unless their efficiency significantly improves. Thin film technology provides even lower efficiencies and does not represent a realistic alternative. One of the key barriers of a ‘solar trailer’ is the long payback period which has been estimated to be around 15 years (Bahaj and James, 2002). This figure may now be overly pessimistic as more recent findings suggest that reductions in non-silicon costs and silicon usage drive annual module cost reductions of 13-17% (Ernst & Young LLP, 2011).

VEHICLE-TO-GRID

When haulage vehicles are parked during the day and not generating income, ‘solar trailers’ could generate additional streams of revenue by selling their energy surplus to the grid, taking advantage of the UK Feed-in Tariffs (FiT) and the trade of Renewable Obligation Certificates (ROC). This would shorten the payback period of the investment, making ‘solar trailers’ a more feasible alternative. This Vehicle-to-Grid (V2G) technology is still under development and requires a smart grid and a well-defined regulatory framework. The UK has more than 140,000 goods vehicles over 26 tonnes (DfT, 2010b). It could be inferred that due to their size, they have a roof big enough to generate sufficient solar power for auxiliary systems, chilling applications and eventually feed-in the surplus into the grid. This would contribute towards the stabilisation of the national grid by providing good quality energy in terms of frequency and voltage.

Evidence of Technology Adoption

Krone’s “Cool Liner” provides solar panels for trailers that ‘will support in the future’ the energy supply of the cooling device (Krone, 2011). Currently, these solar panels only prevent the battery of the refrigerator motor from going flat. In the US, Sundanzer manufactures commercial solar refrigerator containers and freezer hybrid container models for the US Army, NASA and the US DOE sponsored clients (Sundanzer, 2011).

ALTERNATIVE SOURCES OF ENERGY- HYDROGEN

Hydrogen is a very abundant element that is found as part of other molecules such as water and hydrocarbons. As such, it is widely available and it could ensure energy security in an oil scarce and geopolitical challenging future. Hydrogen has great potential in transportation because it could power vehicles, transport refrigeration units and other auxiliary systems with virtually zero emissions and noise. This can be done though fuel cells, hydrogen internal combustion engines or dual fuel systems. Unless hydrogen is generated sustainably, its carbon footprint has to be evaluated in a well-to-wheel basis bearing in mind how it is generated. Hydrogen for automotive purposes is usually stored at 350 or 700 bar to occupy a reasonable space in the vehicle. This is a highly energy intensive process which in addition requires stronger, larger and heavier fuel tanks than conventional diesel. This increases costs and reduces the truck payload. Another major issue is the lack of infrastructure. There is a chicken-and-egg cycle in which there is no hydrogen demand because there is no infrastructure and there is no infrastructure because there is not enough demand (Farrell et al., 2003). Hydrogen is not a realistic alternative to reduce the carbon footprint in logistics operations in the short and medium term, and the main logistics niche applications will be initially APU and lift trucks. The HyWays Roadmap (2008) estimates that Hydrogen could reduce oil consumption in road transport by 40% by 2050.

Evidence of Technology Adoption

In the context of freight, hydrogen will be more suitable for light duty than for heavy duty vehicles. The only trial in the UK of hydrogen freight has been carried out by the Post Office in Stornoway (Hebrides Archipelago) where two Ford Transit vans have been adapted to run on petrol or hydrogen fuel cells. Until the technology is more mature, dual fuel powertrains such as those trialled by Iveco with Hydro-Methane, a mix of natural gas with 30% of sustainable hydrogen (Iveco, 2011) will be the norm. Other approaches include the injection of hydrogen (produced from distilled water) into the engine's air induction tract, which results in the engine burning the fuel more efficiently (h2gogo, 2011). Grundon Waste Management (2010) is conducting three trials of the HRN3 Hydrogen Generator from h2gogo and they expect to increase fuel efficiency by between 3-5% on its 44 tonnes GVW vehicles. Because this solution can be retrofitted to any diesel engine, it could be applied to APU and diesel powered refrigeration systems.

ALTERNATIVE SOURCES OF ENERGY - BIODIESEL

Biodiesel has very similar properties to conventional diesel. Fazel et al. (2011) indicate that biodiesel presents better lubrication however, there are some disadvantages such as enhanced corrosion and material degradation. Because the same engines and distribution network can be employed, there are less technical and economic challenges than with other alternative fuels such as hydrogen. Biodiesel presents better environmental credentials than diesel because it is "renewable, biodegradable and nontoxic" (Fazal et al., 2011). However, according to Schenk et al. (2008), if all arable land would be dedicated to produce biofuels, this would cover less than half of the world's energy demand and he puts forward second generation biofuel technologies as an option with huge potential.

BIODIESEL FIRST GENERATION

First generation biodiesel is produced from animal fats and vegetable oils, through a transesterification process in which the fats and methanol produce fatty acid methyl ester (FAME) and glycerine as by-product. According to Ricardo (2010), FAME is "economically viable" if the oil price is over 80$/barrel. Biofuels can reduce well-to-wheel CO_2 emissions between 5 and 90% depending on the feedstock, production process and the distance between source and consumption points (Baker et al., 2010). It is accepted that biodiesel used in diesel engines reduces hydrocarbons, CO, PM_x and SO_x emissions while increasing NO_x emissions (Baker et al., 2010, Fazal et al., 2011).FAME presents challenges such as waxing that might lead to the clogging of lines and filters under low temperatures which imply shorter service intervals (oil and filter changes) and therefore higher maintenance costs. Higher FAME blends of biofuel might require the adaptation of conventional diesel engines and Ricardo (2010) has detected compatibility issues with existing injection systems. As only oil sugars and starch are used, this generation of biodiesel is less efficient than the second generation where the whole plant is used.

Evidence of Technology Adoption

In 2006, Keystone Distribution started to move all its fleet from conventional diesel to 100% biodiesel. Their biodiesel is generated from waste cooking oil from McDonald's restaurants which otherwise would go to landfill. According to Keystone (2008) this strategy reduced their CO_2 emissions by 5,795 tonnes and it saved them £750,000 off fuel costs over the first year only. Nowadays, higher fuel costs result in even bigger costs savings and with more than half of their fleet running on biodiesel more than 9,400 tonnes of CO_2 emissions are saved each year.

BIODIESEL SECOND GENERATION

Second generation biodiesel can be obtained through BTL (Biomass-To-Liquid) or HVO (Hydrogenated Vegetable Oil) processes. In the BTL process, biomass is converted into liquid and according to Choren (2011) the synthetic fuel can achieve CO_2 savings between 60-90% on WTW basis and PM_x emissions savings of 30-50%. However, real field tests with a Mercedes-Benz Euro 3 engine OM 906 LA, have revealed PM_x emission savings of just 20% (Krahl et al., 2007). In the HVO process, vegetable oils and animal fats are hydrogenated and isomerised, yielding hydrocarbons with excellent combustion properties and good storage stability (European Expert Group, 2011) as they are free of aromatics, oxygen and sulphur and have high cetane numbers (Aatola et al., 2008). According to Aatola et al. (2008) HVO avoids the main problems of FAME oil such as deposit formation, storage stability, fast wear of the engine oil or poor performance in cold temperature. Neste Oil claims their HVO product delivers 40-60% GHG savings compared to conventional diesel and reductions in hydrocarbons and NOx emissions (Aatola et al., 2008).The second generation of biodiesel produces a higher energy yield per hectare than the 1st generation because the whole plant can be used and harvesting in less fertile soils could be suitable for feedstock.

ALTERNATIVE SOURCES OF ENERGY – BIOGAS & NATURAL GAS

CNG trucks produce 10-15% lower GHG emissions compared to diesel vehicles (Baker et al., 2010) and CO_2 savings around 20-25% compared to gasoline, despite the trucks being 20-25% more expensive than their diesel counterparts (Baker et al., 2010), the differential between gas and diesel shortens with high oil prices because of lower gas prices and taxation (OECD/IEA, 2011), revealing considerable costs savings if the whole life cycle of the vehicle is considered. Noise emissions from gas vehicles are much lower. The main issue with Natural Gas Vehicles (NGV) is that the lack of infrastructure limits the range of operations making them more suitable for city logistics. Larger volume fuel tank might reduce payload.

Biomethane presents additional advantages. Its sources are abundant and include sewage treatment plants, landfill waste, cleaning of organic waste streams and animal and agricultural waste. Compared with diesel, PM_x and NO_x emissions are lower and GHG emissions savings are around 60% (Baker et al., 2010). The UK Government issues 'Renewable Transport Fuel Certificates (RTFC) for producing Compressed Biomethane (CBM) and this is worth around 10 p per KG of CBM. Under the EU Renewable Energy Directive, double RTFCs are given for transport fuel made from waste. This means that 1000 tonnes of CBM has RTFC worth £100k, while the equivalent in Renewable Heat Incentive (RHI) would generate £700k and Feed-in-Tariffs £600k (Baldwin, 2011). This suggests that generating biomethane for transportation will not occur imminently.

Evidence of Technology Adoption

Howard Tenens has decided to use dual fuel vehicles (diesel and natural gas) to meet its commitment with sustainability (Cope, 2011). This gives its HGVs a range of 630 miles and CO_2 savings of 15%. This technology is considered a stepping stone for the company until biomethane is widely available. Due to the lack of natural gas infrastructure, the company has deployed so far, 3 refuelling stations at different sites in England, with more on plan, at a cost of £3 million. As the company realises that this is a niche technology at the moment, they have decided to open their refuelling stations to other logistics providers in order to create a demand that might steer a competitive market that could lead to lower fuel costs and a larger distribution network that will allow them to extend their range of operations.

Truck manufacturers that have dual fuel diesel-natural gas models include Iveco, Mercedes, Renault and Volvo. Scania has models that run on natural gas only, as well as Kenworth and Peterbilt in the US. Dual fuel hydrogen-gas is a new alternative that Iveco has presented in 2011 (e.g. Iveco Hydromethane). This suggests that there is a growing interest in manufacturing dual fuel technologies. Among the organisations that are involved in evaluations of CNG, BioMethane or Diesel-Natural Gas in the UK are Howard Tenens and its customers (Coca-Cola and Mars), Eddie Stobart, Sainsbury's and Candem Council. There is no evidence of adoption of gas for transport refrigeration in the UK. CleanAirPower (2011), one UK manufacturer of dual fuel systems, said that it would be technically feasible to use dual fuel truck engines to produce energy for auxiliary power, however the alternator would not be powerful enough for refrigerated applications.

CONCLUSIONS

In the ambit of refrigerated transport, liquid nitrogen indicates lower whole life costs than diesel transport refrigeration units with near zero emissions, as long as nitrogen is generated renewably. Alternatively, “solar trailers” can provide enough energy for chilling applications but they need the support of another technology when working under multi-drop, multi-temperature frozen transport. The combination of ‘solar trailers’ with V2G technologies can reduce the payback period of the investment and can make refrigerated transport less carbon intensive.

In the context of auxiliary power units for cabin hotel loads, Solid Oxide Fuel Cells are a better solution than Proton Exchange Membrane Fuel Cells for eliminating idling and CO_2 emissions; however, the technology is not mature yet and different trials will start this year. All these technologies present different levels of carbon savings and need to be considered in a wider context with other actions and technologies. Power trains have not been reviewed but the feedback from operators was that electric trucks batteries are excessively expensive and constrained to vehicles up to 12 tonnes GVW.
Research carried out for this study suggests that cost, availability and lack of information are the main barriers to the wider adoption of green fleet technologies. Operators appear willing to consider using alternative fuel technologies in their freight operations with small increases in fuel prices and with the implementation of a compulsory carbon trade emission scheme. Road haulage companies appear to be very dynamic and keen to explore alternatives, not only to achieve cost savings but also to improve their external image. Government policies should support this willingness to improve by investing in the research and development of low carbon technologies and subsidizing the deployment of the initial refuelling infrastructure that will support the early adopters, while working with haulage associations to raise awareness of the different alternatives and their benefits.

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