Low Carbon Truck and Refuelling Infrastructure Demonstration Trial Evaluation

Final Report to the DfT

December 2016

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Abbreviations

AST	Appraisal Summary Table	CH_4	Methane
DfT	Department for Transport	NGV	Natural Gas Vehicle
CO_2	Carbon Dioxide	NPV	Net Present Value
CO_2e	Carbon Dioxide Equivalence	NO	Nitric Oxide
CO	Carbon Monoxide	NO_2	Nitrogen Dioxide
CNG	Compressed Natural Gas	OLEV	Office for Low Emission Vehicles
Ded.	Dedicated	OEM	Original Equipment Manufacturer
DF	Dual Fuel	OAH	Over All Height
Gas	Methane	NOx	Oxides of Nitrogen
GGCS	Green Gas Certificate Scheme	PA	Per annum
GHG	Green House Gas	PM	Particulate Matter
GVW	Gross Vehicle Weight	RHI	Renewable Heat Incentive
HGV	Heavy Goods Vehicles	RF	Retro-fit
HPDI	High Pressure Diesel Injection	SDT	Single Deck Trailer
hp	Horsepower	SR	Substitution Ratio
LCNG	Liquid to Compressed Natural Gas	TSB	Technology Strategy Board
LNG	Liquefied Natural Gas	t	Tonne
LC	Low Carbon	TCO	Total Cost of Ownership
LCT	Low Carbon Truck	UCO	Used Cooking Oil
LCTT	Low Carbon Truck Trial		
m	Meter		

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1. Executive Summary

Introduction

The Department for Transport (DfT), the Office for Low Emission Vehicles (OLEV) and Innovate UK (formerly the Technology Strategy Board), co-funded the Low Carbon Truck and Refuelling Infrastructure Demonstration Trial (Low Carbon Truck Trial), through which £11.3m was provided by Government to support the procurement of low emission Heavy Goods Vehicles (HGVs) technologies and their supporting infrastructure. In addition, industry participants have invested £12.1m to create a £23.4m trial.

The funding was made available through a competition initiated by Innovate UK in 2012, which typically covered 50% of the costs of the trial projects, and was paid to participating organisations as grant. Twelve projects were funded which included a majority of dual fuel vehicles, some dedicated gas vehicles and some vehicles running on used cooking oil. Projects also included proposals for refuelling stations. Although the competition was technology neutral and therefore open to electric and hybrid vehicles, no applications for funding for such vehicles were received.

Context

Freight transport is vital to economic growth, but also has significant environmental impacts. HGVs make up around 17%[1] of UK greenhouse gas (GHG) emissions from surface transport. The UK is committed to reducing GHG emission levels by 80% from 1990 levels, by 2050. Reducing emissions from road freight is expected to be very challenging: however, it will be very difficult to meet our 2050 goals without major reductions in GHG emissions from HGVs. A combination of interventions is likely to be needed. However, there is currently a limited evidence base on the cost effectiveness, GHG abatement potential and wider impacts (e.g. air quality) of available interventions. Therefore, the results of this trial will help to inform the evolving evidence base in this area and inform future policy decisions.

Technologies on Trial

The fuels and truck technologies deployed in the Low Carbon Truck Trial (LCTT) are briefly described below.

Fuels	
Natural Gas	Natural gas is a fossil fuel consisting mainly of methane (CH_4). Methane has the lowest carbon intensity of any hydrocarbon, which results in lower CO_2 emissions when the fuel is burnt. Methane is either stored on the vehicle as Compressed Natural Gas (CNG) or as Liquefied Natural Gas (LNG). The term LCNG is used for a refuelling station that stores gas in its liquid state and is able to dispense it as a compressed gas.
Biomethane	Biomethane is produced from biogas released during the decomposition of organic matter. The organic matter is within a sustainable life cycle (e.g. wastes, crop residue) which makes it a renewable fuel with a low carbon footprint.
Used Cooking Oil (UCO)	UCO is a fuel derived from used cooking oils and animal fats where the base feedstock is filtered, washed and treated. As both a renewable and waste derived fuel it has a very low carbon footprint.

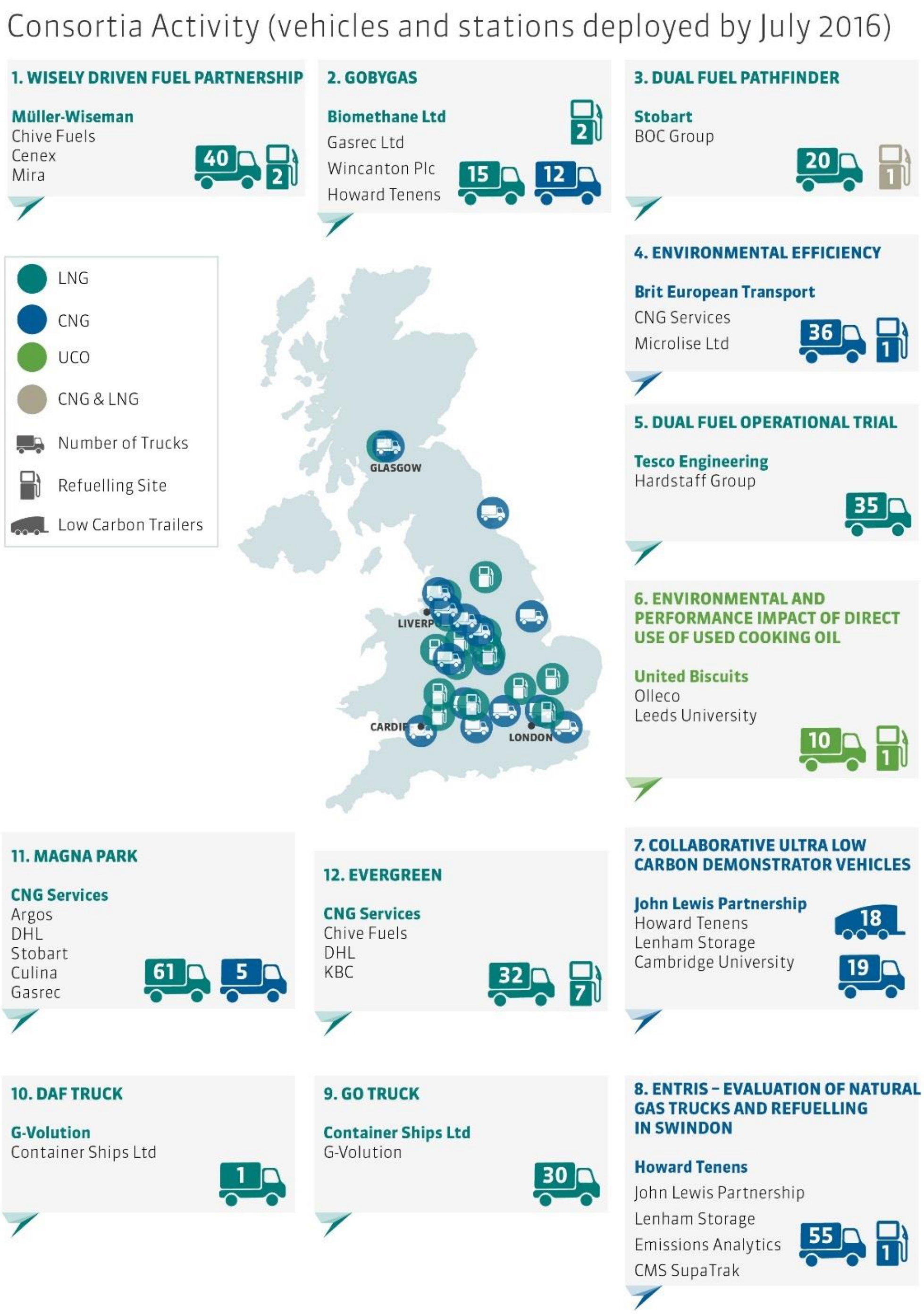
Truck Technologies		
Dedicated Gas	Spark ignition engines that operate on methane gas are used in dedicated gas vehicles. Since these vehicles only run on gas, their operation is restricted within range of appropriate refuelling infrastructure.	
Dual Fuel Diesel/Gas	Dual fuel diesel/gas vehicles simultaneously combust diesel and gas (methane) in a compression ignition engine. The ability to run only on diesel fuel is also retained if a gas station is not available, meaning these vehicles can operate in locations where gas refuelling stations are scarce.	
Dual Fuel Diesel/UCO	This dual fuel system runs a truck on a mix of UCO and diesel. An engine coolant is used to maintain a constant UCO temperature which also prevents any fuel waxing from tank to engine, irrespective of ambient temperature. The system can operate on diesel only in the event that UCO is not available.	
Aerodynamic Trailers	Trailers with sloping roof and boat tail (tapered) rears were used in the trial. Aerodynamic trailers reduce the drag acting on the vehicle and improve fuel consumption.	

[1] Meeting Carbon Budgets – 2016 Progress Report to Parliament, Committee on Climate Change (page 140), June 2016

Trial Projects

The Low Carbon Truck Trial (LCTT) comprised of 12 consortia projects with 35 participating companies (including fleets, emission testing companies, station providers, universities and product developers). By July 2016, 371 vehicles were deployed and 15 refuelling stations were commissioned or upgraded. An overview of the consortia members and vehicles and stations (deployed by July 2016) is shown in Executive Summary Figure 1 below. At the time of writing (August 2016) nine funded trucks and 10 refuelling stations remain to be deployed. These have not been shown in the consortia map below.

Executive Summary Figure 1: Low Carbon Truck Trial Participants

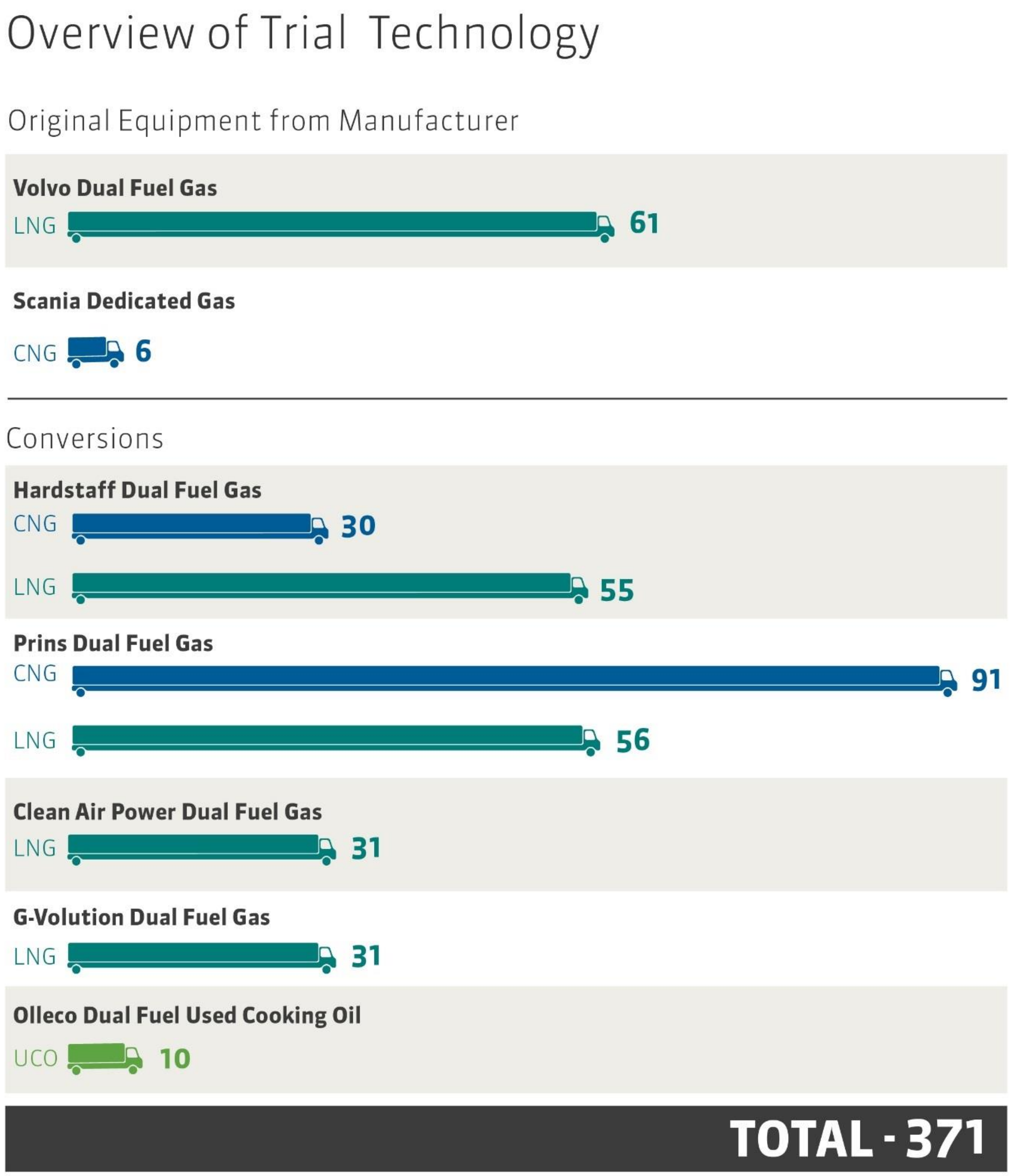


Trial Vehicles

By July 2016, 371 trucks were deployed through the LCTT. Executive Summary Figure 2 below provides a breakdown of the trialled truck technologies. The majority of the trucks (96.5%) operated on dual fuel diesel/gas, 3% operated on dual fuel diesel/UCO and the remainder (1.5%) were dedicated gas vehicles. 82% of the trucks had retro-fit systems and the remaining trucks either had Volvo factory fitted dual fuel systems or were Scania dedicated gas trucks. 95% (353) of the trucks were Euro V, with the remaining 5% (18) being Euro VI.

A further nine G-Volution dual fuel diesel/gas systems were funded and planned to be deployed by September 2016 (after the time of writing), these are not shown in the figure below.

Executive Summary Figure 2: Overview of trial technology (deployed by July 2016)



Refuelling Infrastructure

By July 2016, 15 trial refuelling stations were commissioned. These consisted of seven new and eight upgraded stations. Station upgrades typically consisted of additional gas storage capacity, vent recovery systems and station telemetry. A further ten LCTT gas station deployments are being progressed by consortia and are planned to be deployed throughout the remainder of 2016. Delays in obtaining planning permission, negotiating legal contracts for land use, and optimising station location and technical design were cited as reasons for the delayed refuelling station deployments.

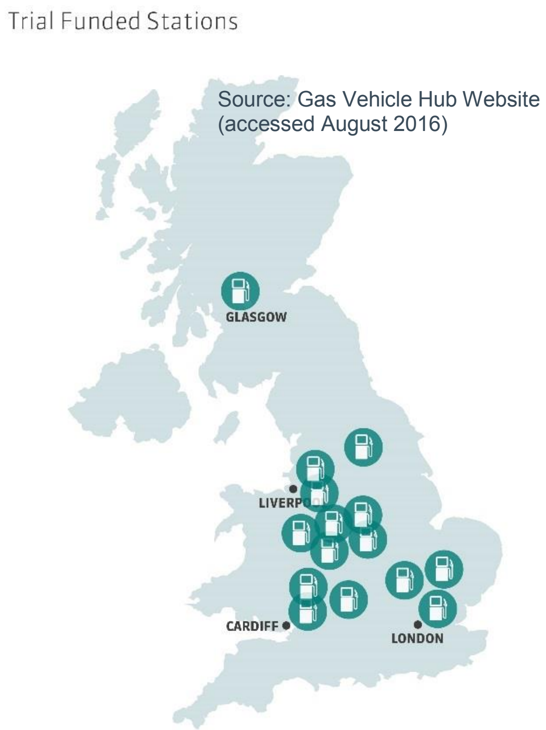
Executive Summary Table 1 below gives a breakdown of the trial stations commissioned by July 2016, with the total planned number of stations shown in brackets.

Executive Summary Table 1 – Trial refuelling stations commissioned (and planned)

Station Type	CNG	LNG	CNG & LNG (Dual Purpose)	UCO
New station	2 (2)	3 (9)	1 (4)	1 (1)
Upgraded station		8 (9)		
Total	15 (25)			

A map detailing commissioned refuelling sites can be found at the Gas Vehicle Hub website[2]. A map of the existing sites is detailed below in Executive Summary Figure 3.

Executive Summary Figure 3: LCT Refuelling Sites



[2] www.gasvehiclehub.com

Truck Emission and Fuel Performance

Mileage and Fuel Use

Throughout the trial a large quantity of information was collected from each vehicle, totalling the mileage and fuel use, which is summarised below.

During the trial:

- 65 million km were travelled.
- The average annual distance covered per truck was 170,000 km (14,000 km per month or 3,300 km per week), ranging from 70,000 to 320,000 km per annum.
- 13 million litres of diesel were consumed.
- 4,300 tonnes of LNG were consumed, with a 5% bio-content.
- 2,553 tonnes of CNG were consumed, with a 5% bio-content.
- 380 tonnes of UCO were consumed, with a 100% bio-content.

Efficiency and Emissions Performance

Definitions
Substitution Ratio (SR) is the percentage of total fuel energy provided by the alternative fuel (either gas or UCO) in place of diesel.
Efficiency Loss represents the additional energy required to drive the alternatively-fuelled truck compared with the diesel comparator vehicles.
Scope 1 or Tank-to-Wheel (TTW) emissions are a measure of CO_2 emissions produced directly from the combustion of a fuel which is outside the natural carbon cycle and increases atmospheric CO_2 levels (i.e. a non-renewable fuel).
All Scope or Well-to-Wheel (WTW) emissions account for the emissions produced during the extraction, processing, delivery and dispensing of the fuel as well as those produced during final combustion on the vehicle. WTW emissions provide a more holistic view of the carbon intensity of fuel use.
Tailpipe emissions are the CO_2 emitted directly from the vehicles tailpipe only. They do not include any other greenhouse gas emissions or any emissions associated with fuel supply.

Executive Summary Table 2 below summarises the performance of the technologies in the truck trial. Whilst there were significant deployments of dual fuel gas trucks in the trial, the data from the UCO and dedicated gas trucks are from individual fleets.

Executive Summary Table 2 – Performance Summary (includes biofuel use)

Performance Variable	LCTT Technology Performance Summary (includes biofuel use)		
	Dual Fuel Gas/Diesel	Dedicated Gas	Dual Fuel UCO/Diesel
Substitution ratio	44% (25 – 52%)	100%	86%
Efficiency loss vs diesel	7% (0 to 25%)	24%	0%
TTW emission saving	3% (-24% to 12%)	11%*	86%
WTW emission saving	0% (-24% to 9%)	10%*	84%

Dual fuel diesel/gas trucks achieved an overall substitution ratio of 44% with an efficiency loss of 7%. Performance between the different dual fuel diesel/gas systems varied greatly with system average SRs ranging from 25% to 52% and efficiency losses from 0% to 25%. The OEM duel fuel truck delivered the best performance operating at a similar efficiency to the diesel comparator trucks with an average SR of 47%. Dual fuel systems with greater levels of integration into the base truck's engine control system showed the highest substitution ratios and lowest efficiency losses. The performance figures shown include any biomethane use in fleets, which on average accounted for 5% of all the gas consumed. However the emission savings do not take account of any emissions of unburned methane (methane slip) experienced by the trial trucks. Independent testing for methane slip was undertaken by some trial consortia. Methane has a global warming potential 25[3] times greater than CO_2, which led to increased CO_2 equivalent emissions in all of the dual fuel

[3] DEFRA/DECC Emission Reporting Guidance, http://www.ukconversionfactorscarbonsmart.co.uk/

diesel/gas trucks tested when compared to a standard diesel truck. In response to concerns highlighted around methane slip the DfT has tested a range of gas and dual fuel trucks under a separate work programme.

***Dedicated gas truck** performance reported in the table above includes a biomethane blend of 15% used by the trial trucks. If this bio-blend were to be removed then the trucks would show an increase in emissions (4% TTW, 3% WTW) mainly due to the reduction in efficiency between a spark ignition dedicated gas truck and the diesel comparator trucks. It should be noted that the trial and comparator vehicles were of different specification (Euro standard, power rating and transmission) meaning this is not a 'like for like' comparison. However, since the diesel comparator vehicle was 400 hp compared to the 340 hp gas vehicle it is unlikely that a more appropriate comparator vehicle would have improved the relative emissions performance of the dedicated gas trucks.

Dual fuel diesel/UCO vehicles achieved very high CO_2 savings because of the high amount (86%) of biofuel (used cooking oil) use.

Aerodynamic trailer performance was reported by one fleet, where the results of a real-world test showed a 7.5% fuel reduction using the low carbon trailer.

Some consortia undertook their own emissions testing using specialist professional testing houses and companies. Further details are provided in *Section 5.6*.

Economic Performance

The consortia agreement with participating fleets precludes the publication of economic data where individual fleet performance can be identified. Therefore, actual trial performance is reported for dual fuel diesel/gas vehicles only.

Dual fuel diesel/gas systems cost an average purchase premium of £25,500 (range £15,000 - £33,000) with an annual maintenance costs increase of £1,110 (range £500 - £2,500). Dual fuel diesel/gas vehicle economic performance varied significantly with 21% of fleets expected to achieve financial payback within 6 years (i.e. within the average truck ownership period in trial consortiums). Applying trial average fuel costs across the fleet showed the most cost effective system was the OEM dual fuel system which offered average annual running cost savings of £8,500 and an average payback period of 3.5 years (with the best-performing fleet gaining annual savings of £11,900 and a payback period of 2.9 years). The average annual cost saving across all the dual fuel diesel/gas systems was £1,600 per annum. A sensitivity analysis showed the main contributors to poor economic performance were the relative purchase price of gas versus diesel and the large engine efficiency loss apparent in some dual fuel systems.

Fuel price sensitivity: The average cost of diesel and gas over the trial period was £0.99/litre and £0.93/kg respectively. The positive cost difference between diesel and gas prices eroded slowly over the duration of the trial. During 2014 the cost of gas was on average 10% lower than diesel (per unit of fuel purchased) but by the end of the data monitoring period (January 2016) natural gas was on average 3% more expensive than diesel. The cost difference fleets paid for gas varied significantly, by as much as 30p/kg.

Vehicle and Station Reliability

Vehicle reliability: On average the faults attributed to the trial systems caused an increase in unplanned maintenance activity by two events per truck (dual fuel diesel/gas 1.7, dedicated gas 3.5, used cooking oil 2.4) per year increasing downtime by 19% (dual fuel diesel/gas 19%, dedicated gas 122%, used cooking oil 0%). Faults were generally due to the immature nature of the systems used with fault frequency reducing throughout the trial.

Station reliability: The trial-funded gas stations proved to be very reliable, showing an average availability of 99.4% (range 98.7 – 99.8%) equating to two unplanned downtime days per annum. On average ten faults per station were recorded annually. 86% of faults were fixed within one day and 100% of faults fixed within two days. This is in contrast to concerns raised by fleets about the reliability of a number of existing (legacy) gas stations in the UK. The performance of these existing stations was not monitored by the LCTT.

Attitudes

Fleet Manager and Driver Attitudes and Experiences

The LCTT study team surveyed fleet managers and drivers to gather views on the environmental and operational performance of the alternatively-fuelled trucks.

Dual fuel diesel/gas and dedicated gas trucks: 89% of fleet managers were glad they had taken part in the LCTT. 80% stated that operating dual fuel trucks was good for the company's image. 22% of fleets stated that operating the trucks helped them to win new business and 11% had purchased more new dual fuel trucks during the trial period without any grant funding. On average the trial trucks were rated by drivers as having similar performance to a standard diesel truck. Drivers showed no clear preference towards CNG or LNG refuelling as ratings were influenced more by other factors such as the dual-fuel systems in use, refuelling station reliability and the additional distance to travel to refuelling stations.

Dual fuel diesel/UCO trucks: The diesel/UCO trucks were reported to perform comparably to diesel vehicles in all aspects with the exception of emissions, where the fleet manager rated these as much better than diesel.

Barriers to Trialled Trucks

The table below presents the main barriers to the uptake of alternatively-fuelled trucks and potential solutions identified by the trial participants and industry representatives during the LCTT, including through workshops and interviews.

Economic Barriers	
Barriers	**Potential solutions**
• Economic performance is sensitive to diesel cost fluctuations. • Short term support offers limited opportunities for long term change. • High capital cost of stations.	• Create more attractive economic environment through long term subsidised operation (e.g. incentives for lower carbon fuels, and/or grants for low carbon systems). • Offer low interest loans for alternative fuel refuelling stations.
Environmental Barriers	
Barriers	**Potential solutions**

• Variability in CO_2 emission savings across different technologies and retro-fit systems.
• Limited CO_2 savings from some systems.
• Air quality performance uncertainty.
• 'Methane Slip' causing potential overall increases in GHG emissions from some dual fuel (diesel/gas) vehicles.
• Confusion over legitimacy of Green Gas Certificates.
• Lack of biomethane availability.
• Uncontrolled methane venting from some vehicles and stations.
• WTW CO_2 emission factor uncertainty. Conflicting information exists on the carbon intensity of natural gas depending on supply pathway.
	• Facilitate the roll-out and uptake of independent and trusted accreditation scheme developed by the Low Carbon Vehicle Partnership for testing lower carbon truck options, which could:
	  ○ Limit any future operating grants or subsidies to approved low carbon truck systems and technologies.
	  ○ Set environmental thresholds (CO_2, GHG, Air Quality) for approved systems.
	  ○ Factor operators' payment/grant level by CO_2 saving potential.
	• Fund R&D programmes for technical development (e.g. high efficiency dual fuel and dedicated gas systems, more effective methane catalysts). Amend guidance on greenhouse gas reporting to allow fleets to claim the environmental benefits of Green Gas Certificates in transport.
	• Consider incentivising the production of biomethane for use as a road transport fuel above other uses.
	• Legislate the provision of methane vent capture equipment on vehicles and stations.
	• Review WTW performance of the range of pathways for natural gas and biomethane. A recent study[4] suggests current emission report factors may underestimate the WTW impact of natural gas supply.

Operational Barriers (Vehicles)	
Barriers	**Potential solutions**
• Variable performance across retro-fit systems. • Lack of performance knowledge of different fuels and systems. • Limited system availability in Euro VI.	• Low carbon truck system accreditation scheme (see previous comments in environmental section). • Facilitate independent environmental case studies and industry dissemination events on available systems, channel information through trade associations. • Identify opportunities to provide further funding for the development of Euro VI systems meeting defined quality criteria (emission performance).
Operational Barriers (Stations)	
Barriers	**Potential solutions**
• Delays obtaining planning permissions and uncertainty over HSE requirements. • Delays establishing gas network information and requirements. • Lack of refuelling stations.	• Produce standardised guidance for planning authorities, and locate specialised support team within central Government. • Encourage gas network operators to allow station developers better access to network technical information. • Continue funding the deployment of refuelling stations.
Other Considerations	
Barriers	**Potential solutions**
• A limited range of technologies was evaluated within the LCTT.	• Future policy should consider and include technologies which have not been considered in the LCTT. • Future demonstration trial funding requirements should be designed to allow a broader technology spread.

[4] The role of natural gas and biomethane in the transport sector, Riccardo Energy & Environment, 2016 (Issue No 1)

Conclusions

The LCTT met its original key objectives which were to facilitate alternatively fuelled truck learning, product development and the initiation of a publicly accessible UK gas refuelling infrastructure. It has provided a rich and valuable data source to assist policy makers in evaluating the technologies within the trial and provided feedback to the fleet community to give them the knowledge to make informed choices within their fleets.

The trial findings are summarised below, with the following key conclusions by the study team:

Technology Selection was challenging for fleet operators. When looking to make technology purchases (vehicles or stations) fleets reported a lack of independent information on the performance of alternative technologies and a lack of available guidance to assist them in making the right decisions.

Technology Deployment and Learning: Fleets generally considered teething issues with new vehicle technologies acceptable, but reported concerns over the variable quality of support across the retro-fit system suppliers. Significant programme delays were experienced during the deployment of stations. Delays were due to factors such as station design optimisation (especially for new and innovative station designs), assessing the ideal station site locations (to maximise customer throughput), and delays in gaining planning permission, land use agreements, and technical information from the local gas grid operator. Station providers called for standardised guidance for planning authorities, and a specialised support team within central Government.

Environmental

- **CO_2 Performance** - CO_2 performance was variable across the trialled technologies. The best performing dual fuel diesel/gas systems offered CO_2 savings of up 10% TTW and 6% WTW. The biofuel blend of the alternative fuel used by fleets had a significant effect on truck emission performance. When operating using only natural gas, the dedicated gas vehicles and some of the diesel/gas dual fuel systems showed an increase in CO_2 emissions against their real-world diesel comparator vehicles. Biofuel use was a key factor in enabling a step change improvement in CO_2 emission savings. For example, the dual fuel diesel/UCO vehicles provided an 86% TTW and 84% WTW emission saving, and the dedicated gas truck produced real-world emission savings of 11% TTW and 10% WTW when operating on a 15% biomethane blend.
- **Methane Slip** - Emission testing undertaken by consortia highlighted that relatively large amounts of methane were present in the exhaust gas stream of dual fuel diesel/gas vehicles, which resulted in these trucks having higher total GHG emissions. This highlights the need for a better understanding and evaluation of the total GHG and air quality effects of different technologies under real-world driving conditions before policy is set in favour of certain technologies. Policies should also take into account how the environmental impact of retro-fit technologies (which are sold without evidence of Euro emissions compliance) are managed and enforced.
- **Air Quality Performance** – Two consortia provided results of independent air quality emissions testing showing the air quality performance was generally improved from dual fuel diesel/gas systems. One system showed reductions in all air quality pollutants (CO, NO, NO_2, PM, NOx) and another system showed an emissions reduction in some air quality pollutants, but with increases in CO and variable PM performance.

Economics played a crucial role for dual fuel diesel/gas vehicle performance which varied widely by each fleet's operating scenario. 21% of fleets expected to achieve financial payback within 6 years (average truck ownership period in trial consortiums). The main contributors to these results were the reducing cost of diesel throughout the trial period and the large engine efficiency loss apparent in some dual fuel systems. A gas fuel price of around 20p below the diesel price was shown to allow the average gas (dedicated or dual fuel) truck to achieve a payback period of within 3 – 4 years. Achieving and maintaining this fuel cost difference between diesel and gas is key to the success of the gas vehicle industry (assuming there is no reduction in system purchase price) as the current lack of a clear business case was highlighted as a major implementation barrier by fleets, vehicle/system suppliers and station suppliers.

Reliability: The trial systems increased the unplanned downtime of the trucks by 19%. However, this varied significantly by technology type. Reliability was rated as a minor implementation barrier by fleet managers, who generally accepted that the introduction of new technology involves a learning curve for both the fleet operators and system suppliers. New stations funded under the LCTT programme proved to be very reliable achieving an average 99.4% availability. This was in contrast to some legacy gas stations in the UK (which predated the LCTT). Although legacy station performance was not monitored by the trial study team, fleet managers and drivers stated concerns about their reliability. However, anecdotally the reliability of the network stations generally improved as station utilisation and gas demand increased through the trial.

Fleet Manager Views: Fleet managers were glad to have taken place in the LCTT. They rated the performance of the trial trucks similar to that of a diesel truck. Two thirds of the fleet managers were pleased with the performance of the trial trucks, whilst the remaining third cited either refuelling station closures, poor reliability, poor economic performance or concerns over the total greenhouse gas impact of the vehicles due to methane slip as reasons for feeling negatively about the trucks.

Future Developments: At the time of undertaking stakeholder interviews (February 2016) the gas truck industry was experiencing very limited growth, awaiting increases in Euro VI vehicle availability and the recovery of the diesel and gas price differential. The industry and fleets generally felt that alternatively-fuelled truck numbers were set to decline if further financial support was not provided to help bridge the gap to larger scale commercialisation. OEMs and retro-fit technology providers stated that they were actively progressing the supply of more Euro VI products. For example, OEMs are improving the efficiency of dedicated gas vehicles and increasing their product range available in the UK, with 400 hp trucks now available and 450 hp trucks expected in 2017. New gas stations are also continuing to come online. For example, a large capacity CNG refuelling station was opened in Leyland in early 2016, which has provided a step change reduction in gas price.

2. Introduction

2.1. Background – The Low Carbon Truck and Refuelling Infrastructure Demonstration Trial

The Department for Transport (DfT), the Office for Low Emission Vehicles (OLEV) and Innovate UK (formerly the Technology Strategy Board), co-funded the Low Carbon Truck and Refuelling Infrastructure Demonstration Trial (Low Carbon Truck Trial), through which £11.3m was provided by Government to support the procurement of low emission Heavy Goods Vehicles (HGVs) technologies and their supporting infrastructure. In addition, industry participants have invested £12.1m to create a £23.4m trial.

The funding was made available through a competition initiated by Innovate UK in 2012, which typically covered 50% of the costs of the trial projects, and was paid to participating organisations as grant. Twelve projects were funded which included a majority of dual fuel (diesel/gas) vehicles, some dedicated gas vehicles and some vehicles running on used cooking oil (UCO). Projects also included proposals for compressed natural gas (CNG), liquefied natural gas (LNG) and UCO refuelling stations. Although the competition was technology neutral and therefore open to electric and hybrid vehicles, no applications for funding for such vehicles were received.

2.2. Context

Transport is estimated to account for approximately one-fifth of the UK's greenhouse gas (GHG) emissions. The UK government is committed to reducing GHG emission levels by 80% from 1990 levels, by 2050. In the interim the government sets five-yearly carbon budgets to help keep the UK on track to meet the 2050 target. Carbon Budgets 1-4 have been set in legislation and Carbon Budget 5, covering period 2028-2032, is due to be set during 2016. In order to meet these targets, the government is pursuing a range of policy interventions, including measures to reduce GHG emissions from freight.

Freight transport is vital to economic growth, but also has significant environmental impacts. Heavy goods vehicles currently make up around 17%[1] of UK GHG emissions from surface transport. Reducing GHG emissions from road freight is expected to be very challenging: however, it will be very difficult to meet our 2050 goals without major reductions in GHG emissions from HGVs.

A combination of interventions is likely to be needed. However, there is currently a limited evidence base on the cost effectiveness, CO_2 abatement potential and wider impacts (e.g. air quality) of available interventions. Therefore, the results from this trial will help to inform the evolving evidence base in this area to inform future policy decisions.

2.3. Evaluating the Low Carbon Truck Trial

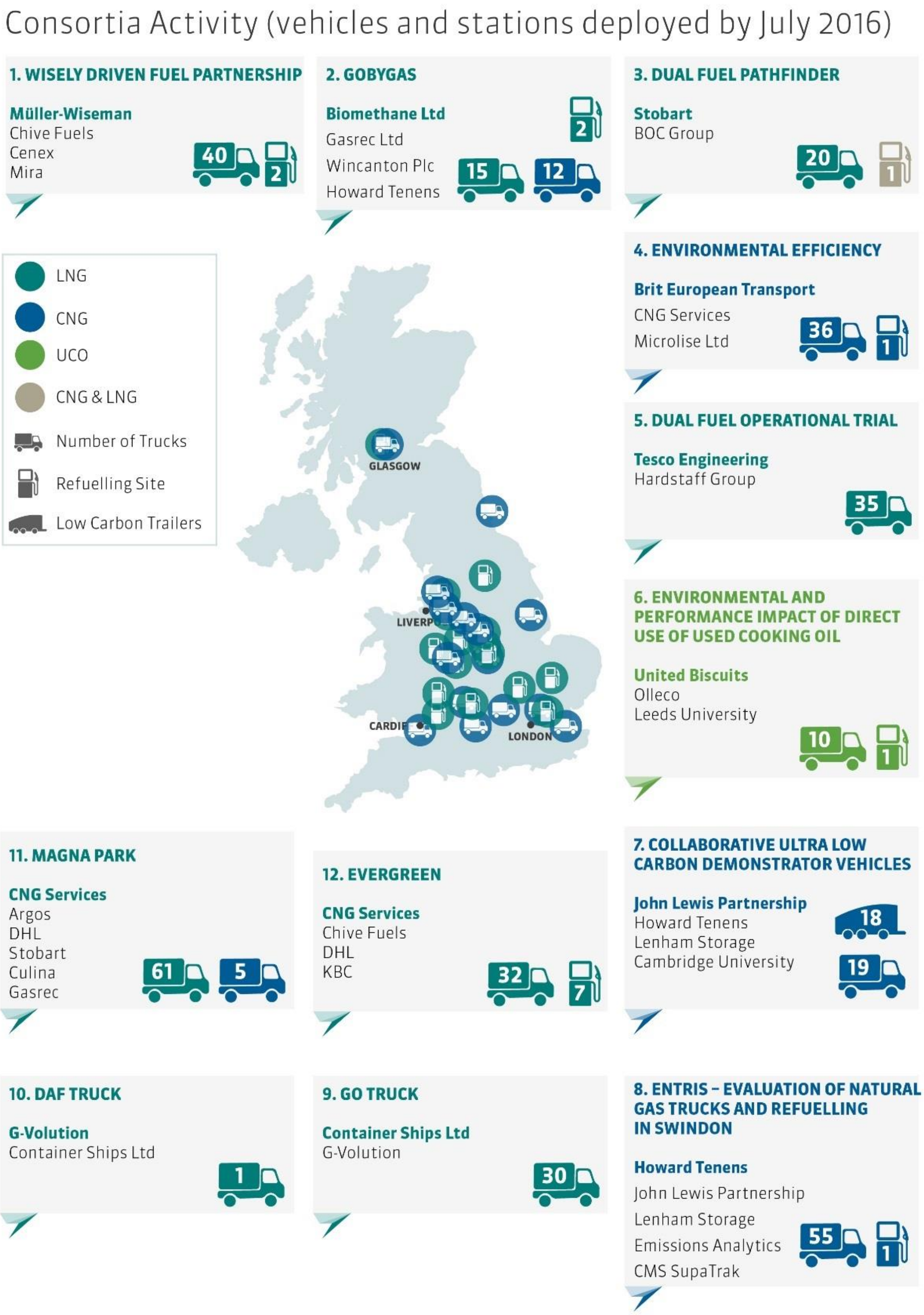
The DfT commissioned Atkins and Cenex to undertake a research project for data collection and analysis to demonstrate the impacts and benefits of using the alternatively fuelled trucks deployed through the trial across a range of freight operations.

3. The Low Carbon Truck Trial

3.1. Trial Participants

The Low Carbon Truck Trial (LCTT) comprised of 12 consortia projects with 35 participating companies (including fleets, emission testing companies, station providers, universities and product developers). An overview of the consortia members and vehicles and stations (deployed by July 2016) are shown in Figure 1.

Figure 1. Low carbon truck trial consortia activity



3.2. Trial Vehicles

By July 2016 371 trucks were deployed through the LCTT. Figure 2 below provides a breakdown of the technologies that were trialled. The majority of the trucks (96.5%) operated on dual fuel diesel/gas, 3% operated on dual fuel diesel/UCO and the remainder (1.5%) were dedicated gas vehicles. 82% of the trucks were retro-fit systems and the remaining trucks either had Volvo factory fitted dual fuel systems or were Scania dedicated gas trucks. 95% (353) of the trucks were Euro V, with the remaining 5% (18) being Euro VI.

A further nine G-Volution dual fuel diesel/gas systems were funded and are planned to be deployed by September 2016. These are not shown in the figure below.

Figure 2. Overview of vehicle technology (deployed by July 2016)

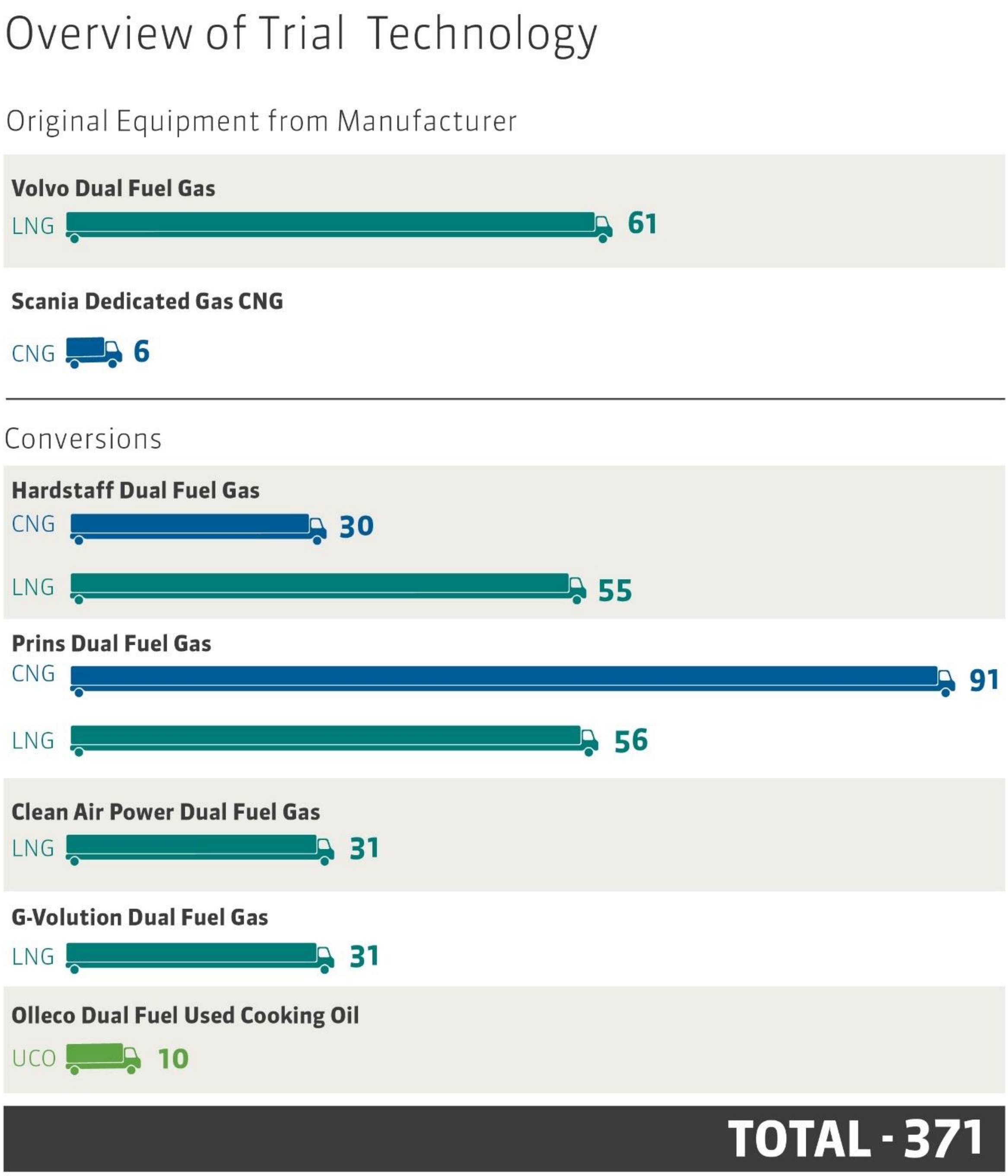


Table 1 below shows that the majority (85%) of trial vehicles were in the 40-44 tonnes gross vehicle weight (GVW) class.

Table 1. Overview of gross vehicle weight

Rigid units	Tractor units	
26 tonnes	**28-38 tonnes**	**40-44t**
10 vehicles (3%)	46 vehicles (12%)	315 vehicles (85%)

3.2.1. Low Carbon Trailers

The John Lewis-led consortium operated a number of low carbon trailers, which included aerodynamic features such as sloping roofs, boat-tail rears and low height tractor and trailer combinations (see Figure 3 below). The trailers in use comprised of:

- Six Grey and Adams ultra-low height 13.6m refrigerated trailers with sloping roof and boat tail rear, operated by the John Lewis Partnership;
- Two 15.6m Over All Height (OAH) tri-axle trailers with sloping roof and boat-tail rear, operated by Lenham Storage;
- Two 10.8m OAH low height urban tandem trailers with sloping roof, boat tail rear on low height tractor units, operated by Lenham Storage;
- Two 15.6m OAH low height low weight trailers with sloping roof and boat-tail rear, operated by Lenham Storage;
- Two 12.2m Single Deck Trailer (SDT) trailers with aerodynamic package, operated by Howard Tenens;
- Two 15.6m SDT trailers with boat tail rear, operated by Howard Tenens; and
- Two 15.6m Grey and Adams refrigerated trailers with sloping roof and boat tail rear, operated by Howard Tenens.

Figure 3. Low carbon trailer

3.3. Refuelling Infrastructure

By July 2016, 15 trial refuelling stations were commissioned. These consisted of seven new and eight upgraded stations. Station upgrades typically consisted of additional gas storage capacity, vent recovery systems and station telemetry. At the time of writing, a further ten LCTT gas station deployments were being progressed and were planned to be deployed by the end of 2016. Delays in obtaining planning permission, negotiating legal contracts for land use, and optimising station location and technical design were cited as common reasons for the delayed refuelling station deployments.

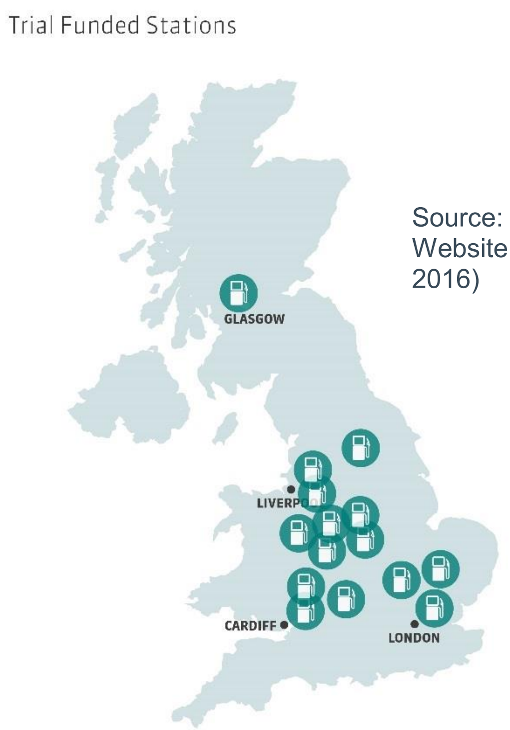
Table 2 below gives a breakdown of the trial stations commissioned by July 2016, with the total planned number of stations shown in brackets.

Table 2 - Trial refuelling stations commissioned

Station Type	CNG	LNG	CNG & LNG (Dual Purpose)	UCO
New station	2 (2)	3 (9)	1 (4)	1 (1)
Upgraded station		8 (9)		
Total	15 (25)			

A map detailing commissioned refuelling sites funded through the Low Carbon Truck Trial (LCTT) can be found at the Gas Vehicle Hub website[5]. A map of the existing sites is detailed below in Figure 4.

Figure 4. LCT refuelling sites



Source: Gas Vehicle Hub Website (accessed August 2016)

5 http://gasvehiclehub.org/low-carbon-truck-trial?sid=284:Trial-Funded-Stations

3.4. Technologies on Trial

The truck and refuelling station technologies deployed (by July 2016) in the LCTT are briefly described below.

3.4.1. Truck Technologies

Technology Type: **Dedicated Gas**

Systems in LCT Trial: Scania 340 hp, 38t GVW, Euro VI (6 Vehicles)

Spark ignition engines which operate on 100% methane gas are used in dedicated gas vehicles. They usually produce less noise, particulate matter and NOx emissions compared to their diesel counterparts. Methane fuel can be stored on-board in compressed or liquefied form. Since these vehicles function on gas fuel only, their operation is restricted within range of appropriate refuelling infrastructure. Manufacturers of dedicated gas vehicles offer various tank capacity options to tailor the vehicle range to customer requirements.

Source: Scania

Technology Type: **Dual Fuel Diesel/Gas**

Systems in LCT Trial:
OEM Systems: Volvo Methane Diesel; 40 – 44t GVW; Euro V (61 vehicles)
Retro-fit Systems:
Hardstaff: 44t GVW, Euro V (85 systems)
Prins: 26 – 44t GVW, Euro V (145 systems) & Euro VI (2 systems)
Clean Air Power: 44t GVW, Euro V (31 systems)
G-Volution: 44t GVW, Euro V (21 systems) & Euro VI (10 systems)

Dual fuel diesel/gas vehicles simultaneously combust diesel and gas (methane) in a compression ignition engine. These vehicles can retain a similar efficiency to their diesel equivalents and theoretically provide emission savings due to the lower carbon content of methane compared to diesel. Further CO_2 emissions savings can be attained through the use of biomethane. The quantity of methane utilisation in the engine increases with engine speed and load, and therefore dual fuel vehicles are most suited to trunking operations. The ability to run only on diesel fuel is also retained if a gas station is not available, meaning these vehicles can operate in locations where gas refuelling stations are scarce. The main technical difference between the dual fuel systems in the LCTT was the level of intergration with the base truck engine control unit, with more integrated systems generally offering higher levels of efficiency and higher substitution ratios.

OEM Volvo Methane Diesel truck with LNG tank. Source: Eddie Stobart

Technology Type: **Dual Fuel Diesel/UCO**

Systems in LCT Trial: Retro-fit system by Olleco (10 systems)

This dual fuel system runs the truck on a mix of diesel and UCO via a split/dual fuel tank which feeds to a mixing system. The onboard fuel management system increases the blend of UCO as the engine load and operating temperature increase. The engine coolant is used to maintain a constant fuel temperature and also prevents any fuel waxing from tank to engine, irrespective of ambient temperature. The system can operate on diesel only in the event that UCO is not available.

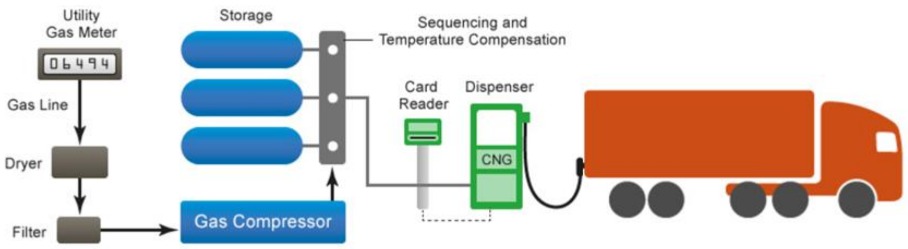
Source: United Biscuits

3.4.2. Refuelling Stations

Station Type: **Grid Connected CNG Station**

Systems in LCT Trial: Howard Tenens (1 station)

Natural gas is extracted from the gas network then conditioned for use in a vehicle. Typically, any moisture and contamination is removed from the utility gas and then compressed to 250 bar ready to be dispensed into a vehicle. Access is controlled via ID card recognition and the filling process is optimised through controlled sequencing of low, medium and high pressure banks with temperature compensation to ensure a constant fill pressure.

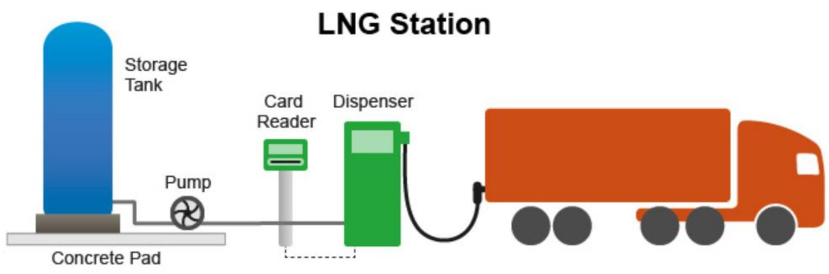


Grid connected CNG station. Source: US Environmental Protection Agency

Station Type: **LNG Station**

Systems in LCT Trial: Chive Fuels (9 stations); Gasrec (2 stations)

LNG stations are not connected to the gas network. Instead liquefied methane is stored cryogenically in low pressure insulated tanks at site which are refilled by gas suppliers. These stations can dispense to the vehicle with the aid of a cryogenic pump or are naturally fed using the pressure difference between the station and vehicle storage tank.



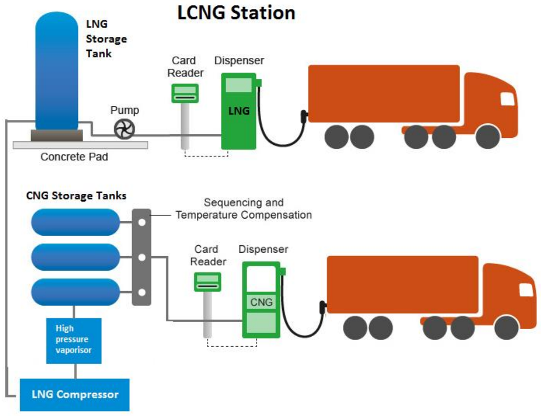
LNG Station. Source: US Environmental Protection Agency

To reduce the loss of methane to atmosphere during refuelling, well designed LNG stations incorporate vent capture equipment. This captures any methane vented from the vehicle tank and returns it to the station. Gas venting from the vehicle tank is required during refuelling if for example the vehicle tank pressure is greater than the refuelling tank pressure, or the cryogenic vehicle tank is warm. Different methods of managing the vented gas exist such as re-liquefying this gas using the station thermal management system, or storing the gas in pressurised cylinders and returning the gas to the LNG delivery tanker.

Station Type: **LCNG Station**

Systems in LCT Trial: BoC (1 station)

A station is referred to as a LCNG station when it dispenses CNG, but is not connected to the gas network. Instead LNG is stored at site and used to make the CNG using an LNG evaporator and compressor. Some LCNG stations, such as that shown here and those deployed through the Low Carbon Truck trial, also have the capability to dispense the fuel as LNG.



LCNG Station. Source: US Environmental Protection Agency

Station Type: **Mother-Daughter Station**

Systems in LCT Trial: Brit European (1 Station)

This station consists of a CNG tube trailer which is coupled to a dispenser. When the station gas is depleted, the tube trailer is transported to and refuelled at a 'Mother' station, which is normally a local large grid connected CNG station. The mother-daughter station has proven to be an economical solution for locations without access to the gas network, particularly for those fleets that do not use enough gas to justify the infrastructure cost.

This 5000 kg daughter station is refuelled weekly supplying gas to the Brit European fleet. Source: Brit European

Station Type: **UCO**

Systems in LCT Trial: Olleco (1 Station)

The UCO station consists of a heated tank which maintains the temperature of the Ultra biofuel at 20 degs. C to ensure good flow characteristics through the station valves and metering equipment. The station is integrated with the fleet web based telemetry system which provides remote driver usage and fuel contents data.

3.4.3. Fuels

The alternative fuels deployed in the LCTT are briefly described below.

Fuel Type: **Natural Gas**
Natural gas is a fossil fuel. It consists mainly of methane (CH_4) and small quantities of other hydrocarbon fuels such as ethane, propane and butane. Methane has the lowest carbon intensity of any hydrocarbon, which results in lower CO_2 emission when the fuel is burnt when compared to diesel. It should be noted that when released into the atmosphere unburnt, methane's impact on global warming is around 25 times greater than CO_2. As a result, if used for transport it must be managed to prevent leakage. The UK's extensive national gas grid provides an abundant source of methane which can be extracted, compressed and used in vehicles as a fuel. Compressed natural gas is stored on the vehicle in high-pressure tanks at circa 200 to 250 bar. During the LCTT LNG was mostly provided from an LNG production facility at Avonmouth or imported by tanker from European ports. A new high capacity LNG import terminal at the Isle of Grain with a truck loading facility was opened by the National Grid in November 2015. This took over operations from the Avonmouth facility which closed on the 30th April 2016.
Fuel Type: **Biomethane**
Biomethane is produced from the methane released during the recent decomposition of organic matter which makes it a renewable source of energy. The major benefit of biomethane is that it is carbon neutral. The carbon dioxide emitted during the combustion of the gas is equal to that absorbed by the organic matter during its growth.  **Gasrec supplied biomethane to the LCT trial which was created from waste in landfill. Source: Gasrec** Biomethane is typically more expensive to supply than natural gas - but on a well-to-wheel emission comparison to diesel, CO_2 savings of around 35 – 80% are available, depending on biomethane supply route[6]. Biomethane can be supplied and used directly in a vehicle. Alternatively, some companies opt to purchase Green Gas Certificates[7] from suppliers that inject biomethane into the gas grid. However, at the time of writing, Green Gas Certificates are not currently accepted as a legitimate method of claiming carbon reduction under the UK Government carbon reporting guidance. All biomethane used directly by trucks in the LCTT was supplied by Gasrec (pictured) from their landfill gas upgrading plant in Surrey.
Fuel Type: **UCO**
UCO is a fuel derived from used cooking oils and animal fats where the base feedstock undergoes a proprietary refining process. The final product complies with DIN 51 623, the German fuel standard for pure plant oils and fats. As both a renewable and waste derived fuel it has a very low carbon footprint. The UCO used in the LCTT was supplied by Olleco. The trade name of Olleco's refined UCO product is Ultra biofuel.

[6] The role of natural gas and biomethane in the transport sector, 2016, Ricardo Energy and Environment

[7] Popular Green Gas Certifications schemes include http://greengastrading.co.uk/ or http://www.greengas.org.uk/

4. Trial Data Collection

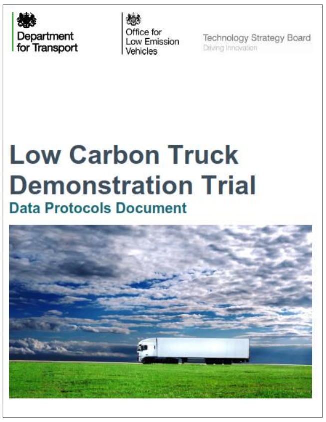
Key Points

- Data on the performance of the trial trucks and stations were submitted to the study team on a quarterly basis. A summary of key statistics was returned to the fleets to ensure the data held were considered representative of fleet performance.
- Each fleet declared a set of data from diesel comparator trucks to allow performance comparisons.

4.1. Data Collection Protocols

In collaboration with the trial funders and the participating fleets, the study team developed the Low Carbon Truck Trial Data Protocols. This document defined the information to be submitted by each consortium. The data were split into two types.

- **Descriptive Data:** this defined information to be submitted regarding the specifications of equipment (vehicles, stations and telemetry) used in the trial. Descriptive data were normally provided at the outset of the trial and only updated if a significant alteration in equipment deployment took place.
- **Performance Data:** this information was submitted on a quarterly basis by each consortium and covered ongoing performance data such as fuel consumption, mileage, fuel costs and reliability.


Department for Transport
Office for Low Emission Vehicles
Technology Strategy Board
Low Carbon Truck Demonstration Trial
Data Protocols Document

On receipt, the information was loaded into the Cenex Vehicle Performance Database and screened and analysed, with a summary of performance data sent to each fleet to confirm the accuracy of the study team's assessment.

4.2. Comparator Trucks

Each fleet declared and submitted data from a set of diesel comparator trucks. The data were used to understand the relative emission and cost performance of the trial trucks.

Ideally the comparator trucks were conventional diesel trucks of the same make and model undertaking similar duty cycles and operating concurrently to the trial trucks. In some instances, the comparator truck criteria could not be met, and in these cases, fleets either:

(i) Declared comparator vehicles from different depots which had similar duty cycles and trucks;
(ii) Provided historic data from the diesel trucks operating previously to the trial trucks; or
(iii) Had experienced sufficient time periods where the trial trucks had operated in diesel only mode due to vehicle or refuelling station faults that the 'diesel only' MPG could be used as the comparator data.

Although the comparator data for diesel trucks clearly incorporates real-world variation outside of the study team's control, it can be considered as broadly representative of comparator diesel truck performance and also represents the comparator data which a fleet would have available to them to measure performance and to inform investment decisions.

5. Trial Truck Performance Data

Key Points

Mileage and Fuel Use

The key trial mileage and fuel consumption statistics are below.

- 65 million km were travelled by the LCTT fleet.
- The average annual distance covered per truck was 170,000 km (14,000 km per month or 3,300 km per week), ranging from 70,000 to 320,000 km per annum.
- 13 million litres of diesel were consumed.
- 4,300 tonnes of LNG were consumed, with a 5% bio-content.
- 2,553 tonnes of CNG were consumed, with a 5% bio-content.
- 380 tonnes of UCO were consumed, with a 100% bio-content.

Substitution Ratio and Efficiency

- The dual fuel diesel/gas systems showed substitution ratios of up to 52%. The average substitution ratio across all systems was 44%, with an average efficiency loss of 7%.
- The dedicated gas trucks showed an efficiency drop of 24% against the comparator diesel vehicles.
- The dual fuel diesel/used cooking oil vehicles achieved a substitution ratio of 86% with no observed efficiency loss.

Environmental Performance

- The dual fuel diesel/gas systems showed tank-to-wheel (TTW) CO_2 emission savings of up to 12% and well-to-wheel (WTW) CO_2 emission savings of up to 9%. The average emission performance across all dual fuel diesel/gas systems resulted in a 3% TTW and 0% WTW emissions saving. This includes an average biomethane blend of 5% which was used by the trial trucks.
- The dedicated gas vehicles showed TTW emissions savings of 11% and WTW emissions savings of up to 10%. This includes a biomethane blend of 15% used by the trial trucks. If this bio-blend were to be removed then the trucks would show an increase in emissions (4% TTW, 3% WTW) mainly due to the reduction in efficiency between the spark ignition dedicated gas trucks and the diesel comparator trucks. However, the trial and comparator vehicles were of different specification (Euro standard, power rating and transmission) meaning this is not a 'like for like' comparison.
- The dual fuel used cooking oil/diesel vehicles achieved a TTW emissions saving of 86% and WTW emissions saving of 84%. The high CO_2 saving can be attributed to the high use of biofuel in these trucks.
- A sensitivity analysis showed the impact of substitution ratio, efficiency loss and biomethane blend on environmental performance in dual fuel diesel/gas trucks. This showed that the increase in emission savings resulting from some systems in the trial was primarily caused by high engine efficiency losses. The analysis also showed that using a 30% biomethane blend in the best performing dual fuel diesel/gas system could offer well-to-wheel CO_2 savings of 20%.

Independent Emissions and Noise Testing

Some consortia undertook their own emissions testing using specialist professional testing houses and companies. Key findings are summarised below.

- Unburnt methane (methane slip) from the exhausts of dual fuel diesel/gas vehicles has the potential to eliminate any GHG benefit. Methane has a global warming potential 25 times greater than CO_2. Testing undertaken by consortia showed that methane emitted from the dual fuel vehicles tested resulted in the trucks having greater CO_2 equivalent emissions when compared to a standard diesel truck. This occurred both in vehicles with and without methane catalysts installed. The same issue was not highlighted as a concern for dedicated gas trucks which are designed to allow a more complete methane burn.
- In response to concerns around methane release from vehicles the DfT commissioned a separate GHG emissions testing programme, which is being managed by the Low Carbon Vehicle Partnership

to test the total GHG emissions from a range of gas and dual fuel vehicles. The results of this testing are due to be reported in winter 2016. Dual fuel diesel/gas system suppliers are also looking to develop effective solutions to methane emissions for Euro VI dual fuel products, with some Innovate UK-funded projects currently underway.

- The dual fuel diesel/gas systems were reported to achieve tailpipe[8] CO_2 emission savings of between 9 – 16%. Emissions recorded by testing facilities are generally regarded as more accurate than real-world CO_2 emission measurements since they are conducted under controlled conditions using specialist equipment to directly measure CO_2 emissions.
- Air quality performance was variable with some systems showing reductions in all air quality pollutants (CO, NO, NO2, PM, NOx) and other systems showing increases in CO and variable PM performance.
- Results from testing undertaken on the diesel/UCO trucks showed that PM10 and PM2.5 emissions were reduced by 45% and 65% respectively and that NOx emissions were similar between the diesel and UCO vehicles.
- Test results showed that the dual fuel diesel/gas trucks were significantly quieter, circa 3 dB(A), in dual fuel mode during low speed drive and acceleration events. The trucks were also quieter, 0.5 - 1.2 dB(A), under idle and hot engine start conditions in dual fuel mode when compared to diesel only operation.

The results presented here for each trial system came from different populations of truck make and model, with differing specifications, undertaking varying duty cycles in real-world conditions. The appropriate comparator diesel trucks were defined by the participating fleets. The study team consider the data presented here to be a fair and reasonable representation of trial truck performance and the data is broadly comparable across the different alternative fuel systems. It should be noted that the performance presented is not from back-to-back emission tests over repeatable and reproducible driving cycles in a controlled environment. The average results shown are weighted by the total distance travelled.

Where possible the performance of the trial trucks has been separated and reported in six groups as described below in Table 3.

Table 3. Trial truck groups

Truck Group Code	Truck Group Description
RF DF UCO	Retro-fit Dual Fuel Diesel/Used Cooking Oil Truck.
RF DF Gas 1	Retro-fit Dual Fuel Diesel/Methane Truck. The retro-fit trucks are reported as a separate group per system to allow the variation in performance between the different suppliers to be understood. At the time of reporting minimal performance data were available from the fourth retro-fit dual fuel system on trial (by G-Volution). Therefore, this system has not been reported on.
RF DF Gas 2	
RF DF Gas 3	
OEM DF Gas	OEM Dual Fuel Diesel/Methane Truck.
OEM Ded. Gas	OEM Dedicated Methane Truck.

[8] Actual CO_2 released from the tailpipe only, not accounting for methane slip.

5.1. Data Grouping, Screening and Verification

The trial trucks deployed by each fleet were grouped by common technical specifications, depot location and duty cycle. Dual fuel systems which were in a state of development were removed from the data set along with instances where the participating fleets were unable to confirm the accuracy of the study team's data. The resulting data is then presented in two ways, where appropriate, throughout this report.

- **Trial Performance:** this shows the 'warts and all' performance of the trial trucks during the trial period and includes fleets that experienced low gas use due to poor access to gas refuelling stations.
- **Potential Performance:** this scenario shows the performance of the trial trucks where deployments with poor access to gas refuelling infrastructure are removed from the data set. This enables truck performance to be shown with minimal negative bias due to refuelling stations availability issues.

The default performance figures presented in this report represent the Potential Performance of the trial vehicles, but reference is made to the Trial Performance where applicable.

5.2. Substitution Ratio and Efficiency

Useful Definitions
Substitution Ratio (SR)
The SR is the percentage of total fuel energy provided by the alternative fuel (either gas or UCO).
Efficiency Loss
The efficiency loss represents the additional energy required to drive the alternatively-fuelled truck compared with the diesel comparator vehicles.
Miles per Gallon (MPG)
MPG is a measure of a vehicle's fuel efficiency. It indicates the number of miles a vehicle travels using one gallon of fuel.
Miles per Gallon Equivalent (MPGe)
MPGe represents the energy efficiency of multi-fuel trucks, based on diesel-energy miles per gallon equivalence. This allows direct efficiency comparisons between differently fuelled truck technologies.

Table 4 below shows the average and range in SR and efficiency of the different systems in the LCTT. Due to the large variation in performance between the different systems, the dual fuel diesel/gas systems have been shown separated by each system provider.

Table 4. Potential system substitution ratio and efficiency

System	Substitution Ratio (%)	Efficiency Loss (%)
RF DF UCO	**86%**	**-3%**
Dual Fuel Diesel/Gas (total)	**44%**	**7%**
RF DF Gas 1	47% (45 - 47%)	4% (0 – 4%)
RF DF Gas 2	45% (36 – 52%)	18% (9% - 19%)
RF DF Gas 3	33% (25 – 43%)	7% (0 – 20%)
OEM DF Gas	47% (46 – 49%)	0% (0 – 4%)
OEM Ded. Gas	**100%**	**24%**

5.2.1. Dual Fuel Diesel/Gas Vehicles

The dual fuel diesel/gas vehicles achieved an overall average SR of 44% with an efficiency loss of 7%. Performance between the different dual fuel diesel/gas systems varied greatly with system average SRs ranging from 25% to 52% and efficiency losses from 0% to 20%. The OEM DF Gas truck delivered the best performance operating at a similar efficiency to the diesel comparator trucks with an average SR of 47%. Dual fuel systems with greater levels of integration into the base truck's engine control system showed higher substitution ratios and lower efficiency losses[9]. In a dual fuel truck the efficiency loss mainly represents unburnt fuel passing through the engine and is generally attributed to the system's design where methane is introduced in the inlet manifold, rather than injected directly into the cylinder where its containment can be better controlled before fuel combustion occurs.

5.2.2. Dedicated Gas Vehicles

The OEM Ded. Gas truck showed a 24% efficiency reduction compared to its diesel comparator. This may be a cumulative effect of both the efficiency reduction inherent in moving from a compression ignition to a spark ignition engine and in the different specification between the gas and diesel vehicles. The diesel truck used an automated manual box and the gas vehicles had a fully automatic transmission. In addition to the difference in transmission the dedicated gas vehicle on trial was a Euro VI 340 hp vehicle and the diesel comparator a Euro V 400hp vehicle. The duty cycles (route and vehicle loading) between the vehicles were however well controlled and comparable.

5.2.3. UCO Vehicles

The RF DF UCO system achieved a substitution ratio of 86% and an increase in efficiency of 3%. This means the RF DF UCO trucks consumed 3% less energy than the diesel comparator vehicles. Whilst this result is unexpected, and likely to be due to non-ideal comparator data, an independent test report by HORIBA-MIRA showed that an RF DF UCO system installed on a Euro VI truck (outside of the LCTT) consumed 2.8% less energy when operating in DF mode compared to diesel mode on a trunking drive cycle.

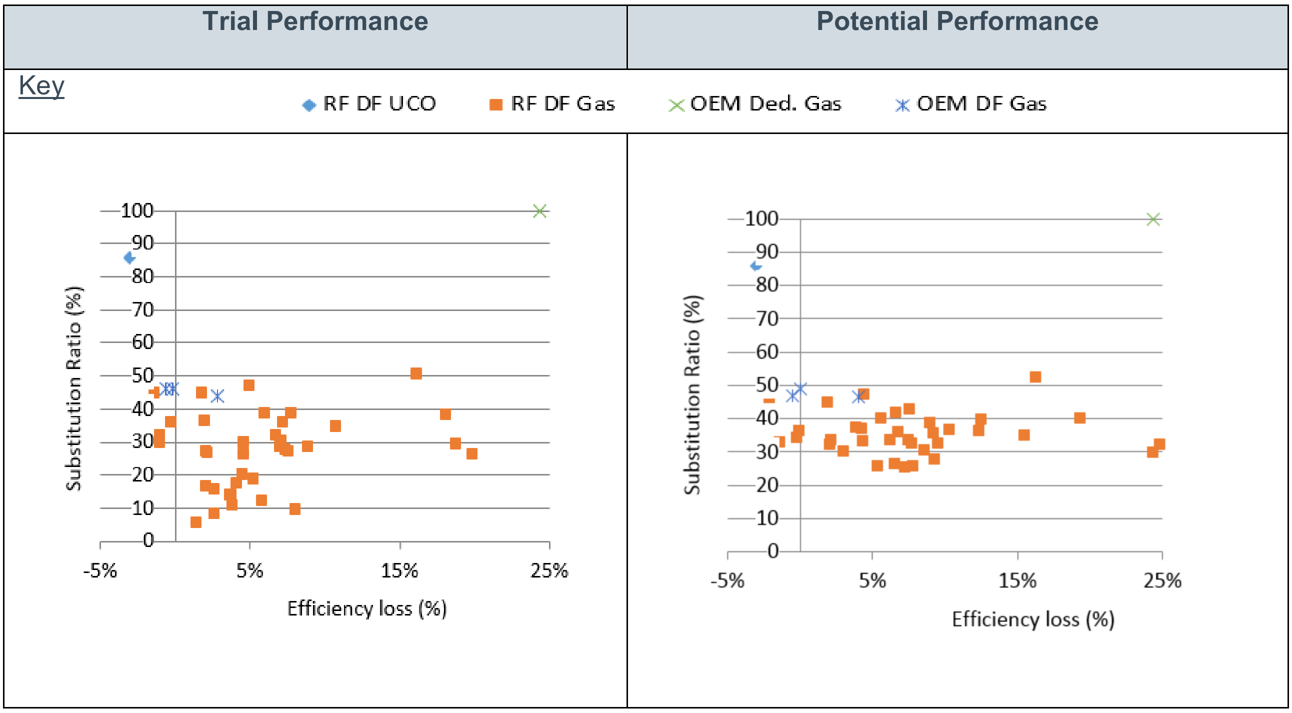
[9] The system integration level was assessed by the study team through confidential discussions with each dual fuel system supplier.

5.2.4. Trial Performance

As discussed in *Section 5.1* above, deployment periods encompassing poor station access were removed from the data to allow a reasonable performance comparison between the different systems. Gas station availability was a significant issue for some fleets which resulted in periods (typically up to 12 months) of little gas use.

Figure 5 below shows the distribution of SR and efficiency loss per fleet vehicle group in both the Trial Performance and Potential Performance scenarios[10].

Figure 5. Scatter plot of SR vs efficiency loss in the LCTT fleet



The scatter plot above shows the variation in reported performance across the vehicle groups. Once time periods of poor refuelling access had been removed the lowest SR experienced by a fleet group was 25%. The Trial Performance data set has a lower average efficiency loss due to the inclusion of diesel only running time in the dual fuel vehicles. The two dual fuel deployments which show a circa. 25% efficiency loss both initially delivered into the London area, and were later redeployed to more appropriate operational duty cycles by the fleets.

[10] Negative efficiency losses shown were rounded up to zero when presenting the trial result summary table for dual fuel vehicles as these are likely to be a factor of the duty cycle variation inherent in the trial and comparator diesel truck data provided.

5.3. Mileage and Fuel Use

The key trial mileage and fuel consumption stats are below.

- 65 million km were travelled by the LCTT fleet.
- The average annual distance covered per truck was 170,000 km (14,000 km per month or 3,300 km per week), ranging from 70,000 to 320,000 km per annum.
- 13 million litres of diesel were consumed.
- 4,300 tonnes of LNG were consumed, with a 5% bio-content.
- 2,553 tonnes of CNG were consumed, with a 5% bio-content.
- 380 tonnes of UCO were consumed, with a 100% bio-content.

5.4. Environmental Performance

Definitions
CO_2
Carbon dioxide is the most common greenhouse gas and is emitted during the combustion of hydrocarbon based fuels.
CO_2e
Carbon dioxide equivalent is an emission rating that includes all the different greenhouse gases on a carbon dioxide equivalence basis.
Tank-to-Wheel (Scope 1)
Scope 1 or Tank-to-Wheel (TTW) emissions are a measure of CO_2 emissions produced directly from the combustion of a fuel which is outside the natural carbon cycle and increases atmospheric CO_2 levels (i.e. a non-renewable fuel). Hence for the combustion of a renewable fuel the TTW CO_2 emissions are zero. Under UK emissions reporting guidance[11],TTW emissions only are the responsibility of the transport operator.
Well-to-Wheel (All Scopes)
All Scope or Well-to-Wheel (WTW) emissions account for the emissions produced during the extraction, processing, delivery and dispensing of the fuel as well as those produced during final combustion on the vehicle. WTW emissions provide a more holistic view of the carbon intensity of fuel use.
Tailpipe
Tailpipe emissions are the CO_2 emitted directly from the vehicles tailpipe only. They do not include any other greenhouse gas emissions stated on a CO_2 equivalence factor.

Emissions were calculated directly from vehicle fuel consumption by applying the appropriate emission factors from the 2015 Defra/DECC Emission Factors for Company Reporting guidance[11]. All biomethane used in the trial was supplied by Gasrec, and a specific emission factor for the Gasrec plant (as declared in their RTFO submissions) was used[12].

There is no factor applied to the data to account for any additional 'methane slip' from the dual fuel vehicles. Work is being undertaken in a separate DfT-funded programme to measure methane emissions from a range of gas and dual fuel trucks, which is discussed further in *Section 5.6.1.*

Table 5 below shows the emissions performance of the trial trucks. It should be noted that the performance shown is relative to the fuel type (CNG/LNG) and other operational factors of the fleets in each group. This includes any biomethane use declared by the fleets[13]. Therefore, the results shown are not directly comparable. The effects of operational factors on truck emissions performance are examined in *Section 5.5*.

[11] DEFRA/DECC Emission Reporting Guidance, http://www.ukconversionfactorscarbonsmart.co.uk/

[12] Gasrec RTFO emission factor 2015, 0.4775 kg CO_2 / kg biomethane

[13] In line with DEFRA/DECC Emission Reporting Guidance, this includes direct use of biomethane only. It does not include an emissions benefit associated with the use of any Green Gas Certificates (GGCs) purchased by fleets. No fleets declared the purchase of GGCs to the trial study team.

Table 5. Trial truck CO_2 emission performance (including biofuel use)

System	TTW Performance				WTW Performance			
	TTW Emission Savings (%)	TTW Emissions (kg/km)	Total TTW Emissions (tonnes CO_2)	Total TTW Emission Savings (tonnes CO_2)	WTW Emission Savings (%)	WTW Emissions (kg/km)	Total WTW Emissions (tonnes CO_2)	Total WTW Emission Savings (tonnes CO_2)
RF DF UCO	86%	0.118	153	926	84%	0.851	215	1107
Dual Fuel Diesel/Gas (total)	3%	0.777	41624	1243	0%	-0.001	52534	-28
RF DF Gas 1	8%	0.697	3448	286	3%	0.029	4432	142
RF DF Gas 2	-6%	0.868	14645	-772	-8%	-0.081	18357	-1364
RF DF Gas 3	1%	0.783	8984	86	0%	0.001	11096	13
OEM DF Gas	9%	0.718	14547	1643	6%	0.058	18650	1180
OEM Ded. Gas	11%	0.551	117	15	10%	0.080	145	17
Total				3427				1068

5.4.1. Dual Fuel Diesel/Gas Vehicles

The dual fuel diesel/gas vehicles achieved an average TTW emission saving of 3% and WTW saving of 0%. This included an average of 5% biomethane blend declared by fleets. Emissions performance varied across the different systems, and was influenced mainly by the efficiency losses experienced by individual systems. The OEM DF Gas system, which operated at a similar efficiency to a diesel vehicle achieved the best emission savings (9% TTW, 6% WTW), whereas the RF DF Gas 2 system, which operated at an 18% efficiency loss actually increased fleet emissions (6% TTW, 8% WTW). Factors affecting emission savings in dual fuel vehicles are explored further in *Section 5.5*.

5.4.2. Dedicated Gas Vehicles

The dedicated gas vehicles on trial achieved TTW emissions savings of 11% and WTW emissions savings of 10%. This includes a biomethane blend of 15% used by the trial trucks. If this bio-blend were to be removed then the trucks would show an increase in emissions (4% TTW, 3% WTW) mainly due to the reduction in efficiency between a spark ignition dedicated gas truck and the diesel comparator trucks. ***However, the trial and comparator vehicles were of different specification (Euro standard, power rating and transmission) meaning this is not a 'like for like' comparison.*** However, since the diesel comparator vehicle was 400 hp compared to the 340 hp gas vehicle it is unlikely that a more appropriate comparator vehicle would have improved the gas trucks' relative emissions performance.

5.4.3. Dual Fuel Diesel/UCO Vehicles

The dual fuel Diesel/UCO vehicles achieved a TTW emission saving of 86% and WTW emission saving of 84%. The high CO_2 saving is due to the high use of biofuel in these trucks.

5.5. Environmental Performance Sensitivity

The emissions performance of the technologies presented in *Section 5.4* represent the performance of the trial trucks using a biomethane blend and fuel types declared by the fleets, and therefore do not allow a direct comparison of the performance of the different technologies trialled. This section examines the factors which influence emission savings in gas trucks.

5.5.1. Dual Fuel Diesel/Gas Vehicles

In dual fuel diesel/gas vehicles, emissions savings are mostly influenced by substitution ratio (SR), efficiency loss and biomethane blend, as explained below.

i) Gas Substitution Ratio

The SR is the percentage of energy provided by the alternative fuel as opposed to diesel. Because natural gas is a lower carbon fuel than diesel, the higher the substitution ratio, the greater the CO_2 saving will be, as long as the amount of energy required to drive the truck is the same in both dual fuel mode and diesel only mode. Table 6 below shows the TTW and WTW CO_2 emissions compared to diesel (per unit of energy provided). This table shows the carbon intensity of the fuel only. However, an efficiency loss is normally observed in dual fuel systems. This causes a higher energy requirement and requires greater fuel consumption, thereby reducing emission savings per km.

Table 6. Emissions per unit of energy for different fuels

Emission Types	Fuel	Emissions per unit of energy (g CO_2e/MJ)[11]	Emission savings compared to diesel
TTW	Diesel	71.9	NA
	CNG & LNG	56.9	21%
	Biomethane	0	100%
WTW	Diesel	88.1	NA
	LNG	78.0	11%
	CNG	68.7	22%
	Biomethane	14.0	84%

ii) Efficiency Loss

As discussed previously, most dual fuel diesel/gas vehicles require greater fuel consumption than their diesel counterparts because the mixture of gaseous and diesel fuel is combusted less efficiently when the truck is operating in dual fuel mode. This efficiency loss means that more fuel is required to drive the same distance as an equivalent diesel truck, which reduces the GHG emission savings from using methane.

iii) Biomethane Blend

Biomethane is a renewable fuel and is very low carbon (as shown in Table 6). Therefore high biomethane blends can deliver greater GHG emission savings. Biomethane fuel is interchangeable with natural gas in a vehicle.

Emissions factors

It should be noted that the emissions factors used in this analysis are those provided by the UK Government[14] for emissions reporting. Examining the differences in WTW emission savings through varying natural gas supply scenarios further is not within the scope of this report.

[14] DEFRA/DECC Emission Reporting Guidance, http://www.ukconversionfactorscarbonsmart.co.uk/

Comparison of Emissions Savings

The 'traffic-light' tables below show an analysis of different scenarios depending on the aforementioned variables affecting emissions savings. The tables show the emissions savings for a dual fuel truck compared to a diesel truck under the following sensitivities:

- **Gas substitution ratio** has been varied from 10% to 50%.
- **Efficiency loss** has been varied between 0% to 15% representing the majority of efficiency losses in data observed in the LCT trial.
- **Biomethane** blend has been varied by the following three scenarios:
    - **0%** no biomethane blended in natural gas.
    - **5%** this was the average biomethane blend used across the LCTT.
    - **30%** to give a high use scenario.

Table 7. TTW emission savings available from dual fuel trucks using CNG and LNG

TTW		0% Biomethane				5% Biomethane				30% Biomethane			
		Efficiency loss				Efficiency loss				Efficiency loss			
		0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
Gas substitution ratio	10%	2%	-3%	-8%	-13%	2%	-2%	-7%	-12%	4%	0%	-5%	-10%
	20%	4%	-1%	-5%	-10%	5%	0%	-5%	-9%	9%	4%	0%	-5%
	30%	6%	2%	-3%	-8%	7%	3%	-2%	-6%	13%	9%	5%	0%
	40%	8%	4%	-1%	-5%	10%	5%	1%	-4%	18%	14%	10%	5%
	50%	10%	6%	1%	-3%	12%	8%	4%	-1%	22%	18%	15%	11%

Table 8. WTW Emission savings available from dual fuel trucks using LNG

WTW for LNG		0% Biomethane				5% Biomethane				30% Biomethane			
		Efficiency loss				Efficiency loss				Efficiency loss			
		0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
Gas substitution ratio	10%	1%	-4%	-9%	-14%	2%	-3%	-8%	-13%	3%	-2%	-6%	-11%
	20%	2%	-3%	-7%	-12%	3%	-2%	-7%	-12%	7%	2%	-3%	-7%
	30%	3%	-1%	-6%	-11%	5%	0%	-5%	-10%	10%	5%	1%	-4%
	40%	5%	0%	-5%	-10%	6%	1%	-3%	-8%	13%	9%	5%	0%
	50%	6%	1%	-4%	-8%	8%	3%	-2%	-6%	17%	12%	8%	4%

Table 9. WTW Emission savings available from dual fuel trucks using CNG

WTW for CNG		0% Biomethane				5% Biomethane				30% Biomethane			
		Efficiency loss				Efficiency loss				Efficiency loss			
		0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
Gas substitution ratio	10%	2%	-3%	-8%	-12%	3%	-2%	-7%	-12%	4%	-1%	-6%	-10%
	20%	4%	0%	-5%	-10%	5%	0%	-4%	-9%	8%	4%	-1%	-6%
	30%	7%	2%	-3%	-7%	8%	3%	-2%	-6%	12%	8%	3%	-1%
	40%	9%	4%	0%	-5%	10%	6%	1%	-3%	16%	12%	8%	4%
	50%	11%	7%	2%	-2%	13%	8%	4%	-1%	20%	16%	12%	8%

For each of these cases, the emission savings (both TTW and WTW) increase as the efficiency loss decreases and the gas substitution ratio improves. It can also be seen that emission savings increase considerably with biomethane blend (for the same efficiency loss and substitution ratio), and CNG has a lower WTW carbon intensity than LNG.

Comparison of Emissions Savings by Conversion System

In order to show the emissions performance from the different conversion systems employed in the LCTT, the average values of efficiency penalty and substitution ratio for each of the systems were considered, as shown in the tables below for both LNG and CNG fuels.

Key

OEM DF Gas (red) · RF DF Gas 1 (blue) · RF DF Gas 2 (purple) · RF DF Gas 3 (black)

Table 10. TTW emission savings per conversion system using CNG and LNG

TTW		0% Biomethane				5% Biomethane				30% Biomethane			
		Efficiency loss				Efficiency loss				Efficiency loss			
		0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
Gas substitution ratio	10%	2%	-3%	-8%	-13%	2%	-2%	-7%	-12%	4%	0%	-5%	-10%
	20%	4%	-1%	-5%	-10%	5%	0%	-5%	-9%	9%	4%	0%	-5%
	30%	6%	2%	-3%	-8%	7%	3%	-2%	-6%	13%	9%	5%	0%
	40%	8%	4%	-1%	-5%	10%	5%	1%	-4%	18%	14%	10%	5%
	50%	10%	6%	1%	-3%	12%	8%	4%	-1%	22%	18%	15%	11%

Table 11. WTW emission savings per conversion system using LNG

WTW for LNG		0% Biomethane				5% Biomethane				30% Biomethane			
		Efficiency loss				Efficiency loss				Efficiency loss			
		0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
Gas substitution ratio	10%	1%	-4%	-9%	-14%	2%	-3%	-8%	-13%	3%	-2%	-6%	-11%
	20%	2%	-3%	-7%	-12%	3%	-2%	-7%	-12%	7%	2%	-3%	-7%
	30%	3%	-1%	-6%	-11%	5%	0%	-5%	-10%	10%	5%	1%	-4%
	40%	5%	0%	-5%	-10%	6%	1%	-3%	-8%	13%	9%	5%	0%
	50%	6%	1%	-4%	-8%	8%	3%	-2%	-6%	17%	12%	8%	4%

Table 12. WTW emission savings per conversion system using CNG

WTW for CNG		0% Biomethane				5% Biomethane				30% Biomethane			
		Efficiency loss				Efficiency loss				Efficiency loss			
		0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
Gas substitution ratio	10%	2%	-3%	-8%	-12%	3%	-2%	-7%	-12%	4%	-1%	-6%	-10%
	20%	4%	0%	-5%	-10%	5%	0%	-4%	-9%	8%	4%	-1%	-6%
	30%	7%	2%	-3%	-7%	8%	3%	-2%	-6%	12%	8%	3%	-1%
	40%	9%	4%	0%	-5%	10%	6%	1%	-3%	16%	12%	8%	4%
	50%	11%	7%	2%	-2%	13%	8%	4%	-1%	20%	16%	12%	8%

The OEM DF Gas system presents the most satisfactory emissions savings performance due to its low efficiency loss and good substitution ratio. RF DF Gas 2 shows poor performance due to its high efficiency loss, with RF DF Gas 1 and 3 systems in-between, with an intermediate efficiency loss.

In the 30% bio-blend scenario all systems produce an emission saving.

5.6. Consortia Testing Results

Some consortia undertook their own testing of the trial vehicles. Whist this testing was not under the control or influence of the study team, the high level results reported by these consortia during the course of the trial are summarised below.

5.6.1. Unburnt Hydrocarbon and Methane Emissions

Consortia testing of dual fuel diesel/gas vehicles showed that unburnt hydrocarbons (a proxy for methane) increase when operating in dual fuel mode. Methane is a powerful greenhouse gas, which can reduce or eliminate any carbon savings from the vehicles when 'methane slip' occurs during operation. Testing undertaken by consortia showed that methane emitted from the dual fuel vehicles resulted in the trucks having greater CO_2 equivalent emissions when compared to a standard diesel truck. This occurred both in vehicles with and without methane catalysts installed. However, it was not possible to estimate the effectiveness of the catalyst on methane emissions as the vehicles tested and the testing processes used by the different consortia were not comparable.

In response to concerns around methane release from some of the dual fuel vehicles the DfT commissioned a separate HGV emissions testing programme that is being managed by the LowCVP to test GHG emissions from a range of gas and dual fuel commercial vehicles. The results of this testing are due to be reported in winter 2016. Dual fuel diesel/gas system suppliers are also looking to develop effective solutions to methane emissions for Euro VI dual fuel products.

It should be noted that the testing of a dedicated gas truck was not undertaken as part of the LCTT. However, methane from dedicated gas trucks is a regulated emission and not expected to be significant. For example, emission testing of a Euro V 26t GVW dedicated gas truck undertaken by Cenex as part of the Coca-Cola Enterprises gas vehicle trial showed that the unburnt hydrocarbons emitted added just 3gCO2/km on a CO_2 equivalence basis (an increase of 0.3% compared to CO_2 only emissions)[15]. Results from the DfT's HGV Emissions Testing programme also found levels of methane slip from the dedicated gas trucks tested to be very low.

5.6.2. Aerodynamic Testing

Fleets using the aerodynamic trailers were unable to track fuel consumption to trailer use and due to operational restrictions were also unable to match trailers to tractor units for prolonged time periods. Therefore, very limited data on the performance of the trailers were received. One fleet reported the results of a real-world test which achieved a 7.5% fuel reduction using the low carbon trailer.

5.6.3. CO_2 and Air Quality Emissions

The dual fuel diesel/gas systems were reported to achieve tailpipe CO_2 emission savings of between 9 – 16%. Emission levels recorded by testing facilities are generally regarded as more accurate than real-world CO_2 emission measurements since they are conducted under controlled conditions using specialist equipment to directly measure CO_2 emissions. Air quality performance was variable with some systems showing reductions in all air quality pollutants (CO, NO, NO_2, PM, NOx) and other systems showing increases in CO and variable PM performance.

Results from testing undertaken on the UCO trucks showed that ultrafine PM emissions were reduced by approximately 40% and that NOx emissions were similar between the diesel and UCO vehicles. A comparison between the trucks running on UCO and diesel showed that UCO use resulted in lower fuel injector deposit formation. Chemical analysis of fuel injector deposits showed that the composition of deposits between diesel and biofuel is similar. Controlled fuel consumption testing at HORIBA-MIRA proving ground showed that a EURO VI vehicle operating on UCO had no efficiency loss when compared to diesel only operation. In fact, fuel consumption improved by 2.8% over a trunking drive cycle.

No external testing of the OEM Ded. Gas vehicle was undertaken as part of the LCTT.

5.6.4. Noise and Acceleration Testing

One consortium was able to share results from noise and performance testing. Test results showed that the dual fuel diesel/gas truck tested was significantly quieter, circa 3 dB(A), in dual fuel mode during low speed drive and acceleration events. The truck was also quieter, 0.5 - 1.2 dB(A), under idle and hot engine start conditions in dual fuel mode when compared to diesel only operation. Acceleration tests showed that the truck tested was 6 seconds (12%) slower when accelerating to 50 mph in dual fuel mode compared with diesel only mode. The change in acceleration performance was not noticed by the drivers.

[15] Cenex 2012, http://www.cenex.co.uk/wp-content/uploads/2014/02/CCE-biomethane-trial-report-1_3.pdf

6. Issues and Lessons Learned, as Reported by Trial Participants

The LCTT process included regular performance reporting to the study team and a series of workshops designed to facilitate joint information sharing and learning between the trial participants. Associated workshop reports are available for download from the Resource Centre of the Gas Vehicle Hub (www.gasvehiclehub.com/resources). Below is a summary of the key experiences and learnings reported during the trial period.

6.1. Performance Improvements

- **Vehicle performance** – Although most consortia identified teething issues early in the trial, these were generally addressed by the manufacturer/conversion provider throughout the trial with the majority of fleet managers reporting a good level of performance from the trucks by trial completion.
- **Vehicle deployment** – Fleets redeployed vehicles to areas where they could improve technical and economic performance. Dual fuel diesel/gas vehicles were relocated to higher mileage and speed haulage operations and to areas of the country where lower cost gas was available.
- **Vehicle venting** – Fleets with previous experience of Euro III and IV dual fuel diesel/gas trucks reported that the new generation of trial trucks had fewer issues with the need to vent methane while refuelling due to the addition of methane vent capture equipment at the majority of stations. Many fleets implemented a ‘no vent’ policy to ensure refuelling issues were reported and addressed.
- **Driver and depot engagement** - Successful refuelling and operation of the vehicles was strongly linked to driver and depot management training and engagement programmes. Fleets reported variation in the performance of the trucks depending on how well they were embraced amongst staff at different depots.
- **Station venting** – Anecdotal evidence from trial participants showed a reduction in the number of station venting events, due mainly to newer technology (including programmes to retro-fit vent capture equipment at existing stations) and more efficient use of station facilities (i.e. increase in refuelling events and optimisation of station gas deliveries).
- **Availability of refuelling stations** – The number of stations available either publicly or through private agreements increased by a significant number over the trial period.

Case Study – Improving Performance through Vehicle Relocation
Economic performance of dual fuel vehicles is heavily dependent on the duty cycle, fuel prices and fuel substitution ratios achieved. These factors need to be optimised in order to maximise cost savings and for this reason trial participants had to be flexible in the location of trucks. In 2015 Howard Tenens moved all their London-based vehicles to Swindon in order to achieve better mpg performance, increased mileage and higher substitution ratios. All John Lewis Bracknell fleet vehicles were moved to Leyland in anticipation of the new refuelling site opening in December 2015. This move provided lower cost CNG to the fleet and ensured the dual fuel vehicles retained an economic advantage over diesel.
Collaborative Ultra Low Carbon Demonstrator Vehicles - This consortium consists of John Lewis Partnership as the lead partner with Lenham Storage and Howard Tenens plus Cambridge University providing emissions testing. The trial has delivered 19 vehicles on the road consisting of 17 CNG Dual Fuel – DAF Prins Conversions and 2 CNG Dual Fuel – Mercedes Benz Prins Conversion. The trial has also delivered 18 Low Carbon Trailers. **Evaluation of Natural Gas Trucks and Refuelling in Swindon -** This consortium consists of Howard Tenens as lead partner with Lenham Storage and John Lewis Partnership. Emissions Analytics have provided emissions testing with CMS Supatrack providing telemetry. This trial has delivered 55 vehicles on the road and one refuelling site.

Refuelling at CNG Fuels, Leyland

Dual fuel diesel/gas truck and low carbon trailer combination operated by Waitrose

6.2. Areas for Concern

- **Uncertainty around technology choice** – Fleets reported having insufficient information to make informed choices, and were unclear whether to operate CNG/LNG or which technology would be most appropriate for them.
- **First fill** – Fleets reported difficulties on the first fill of cryogenic vehicle tanks, or when cryogenic vehicle tanks had to be refuelled from empty. LNG vaporises quickly in a warm vehicle tank and therefore should be refuelled from stations with vent capture equipment. However, fleets reported being turned away from refuelling stations when they did not have the capacity to manage large quantities of vented gas.
- **Delays in station commissioning** – There were significant delays in station commissioning throughout the trial, linked to site issues, planning permission processes, legal and technical issues. Delays have had an impact on the performance of the gas trucks causing lower than expected substitution rates. In some cases, additional mileage was undertaken by the trial trucks diverting to off-route gas refuelling stations. Station operators reported a lack of experience by planning departments, and reported that the process for approving and assessing gas station applications was not consistent between planning authorities. Station providers asked for a single set of procedures and guidance to be developed for authorities and a central expert team to be set up in Government which could advise local planners.
- **Station siting** – One station provider called for a national information system for gas pressure and capacity information which would help overcome delays in station siting associated with needing to await information from utilities providers.

- **Station closures linked to HSE prohibition notices** - In 2014, several stations commissioned outside the trial were served with prohibition notices due to a lack of compliance with the Control of Major Accident and Hazards (COMAH) regulations. The development of industry guidance and standards (such as the recently published *Code of Practice on The Storage of Cryogenic Flammable Fluids 2016*) should assist in the simplification of appropriate station design advice and ease the planning approval process. Additionally, station owners called for an approved list of gas infrastructure maintenance contractors to help simplify the contractor selection process.
- **Vehicle tank pressure –** Public CNG stations in the UK generally dispense gas at 250 bar, whereas in the EU 200 bar is more common. One operator reported that they were unaware of the correct tank pressure when ordering the trucks and were refuelling their CNG tanks to above their rated capacity.
- **Station closures** – Four gas refuelling stations, which were not funded through the LCTT, closed during the trial period. While most fleets had the flexibility to redeploy vehicles onto new routes which allowed gas refuelling, some fleets were unable to redeploy vehicles and therefore needed to operate their dual fuel trucks in diesel only mode.

Case Study – Delivering Refuelling Infrastructure

Environmental Efficiency sought to commission a “daughter” station to the CNG Mother station in Crewe by June 2013. In July 2014 planning permission at a location in Derbyshire was refused and a new site was identified outside of Scunthorpe. The daughter station became operational in November 2015 and operates with one tube trailer, with an option for hiring a second trailer if required. Refuelling requires a 10 hour round trip to Crewe.

In total it took 18 months to obtain planning permission (through change of site, issues with 3rd parties and the planning process). In learning lessons from this process Environmental Efficiency have highlighted the need to plan for earlier engagement with local communities to explain how the technology works in order to overcome objections relating to concerns about an increase in vehicle movements and the perceived safety of the technology. Mitigation measures such as vehicle curfews and educational videos have been developed to help with this.

Due to these delays the vehicles used in this trial (purchased for a specific contract and operating on fixed routes) returned very low substitution ratios due to the lack of station availability until the opening of their Scunthorpe station.

Consortia Overview – Environmental Efficiency

The trial has delivered 36 vehicles on the road consisting of 30 CNG Dual Fuel Mercedes Hardstaff Conversions plus 6 CNG Dual Fuel MAN Prins Conversions. CNG Services have provided refuelling infrastructure with Microlise providing telemetry.

Brit European report that their trial has delivered the world’s first dual fuel car transporter with innovative thinking at the heart of providing an engineering solution to locating the CNG tank on the vehicles.

CNG ‘daughter’ tube trailer used by Brit European

Dual fuel diesel/gas car transporter

6.3. Areas of Uncertainty

- **Biomethane reporting** - Trial participants wanted to use more biomethane to reduce their environmental impact, but the appropriate use of biomethane in the transport sector remains unclear. Participants wanted to see a change in the UK Government GHG Reporting Guidelines so that carbon savings from virtual biomethane schemes can be taken into account.
- **Methane venting** – Whilst in general methane venting from stations and vehicles was reported to be minimal, fleets were unsure how to measure or account for venting within emission reporting and evaluation.
- **Methane slip** – Fleets expressed concern over reports of methane slip from vehicles, and were unsure whether this applied to their technology or conversion type.

7. Economic Performance of Trial Trucks

Key Points

Capital, Maintenance and Fuel Costs

- The dual fuel diesel/gas systems cost an average purchase premium of £25,500 (range £15,000 - £33,000) with an annual maintenance costs increase of £1110 (range £500 - £2500). Increases in maintenance costs were due to additional gas injector and gas filter replacements along with an increase in inspections and checks of the gas fuel containment and delivery system. Using trial average fuel costs, the dual fuel diesel/gas trucks showed a fuel saving of 1.7 ppkm, which varied depending on the dual fuel system from -1.7ppkm to +4.3ppkm.
- The average cost of diesel and natural gas over the trial period was £0.99/litre and £0.93/kg respectively. The positive cost difference between diesel and gas prices eroded slowly over the duration of the trial, with the cost of diesel reducing by 24% between December 2012 and December 2015 with gas reducing by 20% (LNG) and 9% (CNG) over the same period.
- During 2014 the cost of gas was on average 10% lower than diesel but by the end of the trial monitoring period (January 2016) natural gas was on average 3% more expensive than diesel per unit of fuel. The price that different fleets paid for gas varied by as much as 30p/kg.
- The long term residual value of the trial trucks is uncertain. The costs of removing a dual fuel diesel/gas system range from between £1500 and £2500, so that the truck can then maintain the same residual value as a diesel truck. An OEM dedicated gas product is estimated to attract a reduction in residual value of between 30 – 50% until the infrastructure provision in the UK improves[16].

Trial Truck Payback

- Payback was calculated against commercial technology costs for the systems and did <u>not</u> include the grant offered for the trial system.
- Dual fuel diesel/gas vehicle economic performance varied widely by each fleet's operating scenario with just 21% of fleets expected to achieve financial payback within 6 years (average truck ownership period in trial consortiums). Applying trial average fuel costs across the fleet showed the most cost effective system was the OEM DF Gas system which offered average annual running cost savings of £8.5k and an average payback period of 3.5 years (with the best performing fleet gaining annual savings of £11.9k and a payback period of 2.9 years). The average annual cost saving across all the dual fuel diesel/gas systems was just £1.6k per annum. The main contributors to these results were the reducing cost of diesel throughout the trial period and the large engine efficiency loss apparent in some dual fuel systems.
- A sensitivity analysis showed that for the gas trucks the main contributors to economic success were the diesel and gas price difference, followed by system efficiency and annual mileage. The most influentially positive factor which is directly under the control of the fleet is the ownership period, where longer periods allow the annual fuel cost savings to make a greater impact on total cost of ownership (TCO). The most detrimental effect on economic performance across all the trial systems was the price difference between gas and diesel.
- The average cost of purchasing Green Gas Certificates (+3 ppkg) had a small impact on the truck payback period when compared to the other factors assessed.
- A fuel price differential of around 20p was required to allow the average dual fuel diesel/gas and dedicated gas vehicles to achieve a payback of within 3 – 4 years.

The cost data submitted by the participating fleets are summarised and discussed in the tables below. The cost data was provided directly from the fleet operators. All cost data excludes VAT.

The price data and payback periods presented DO NOT include any LCTT funding received by the consortia. The trial agreement with participating fleets precludes the publication of economic data where individual fleet performance can be identified. Therefore, actual economic information is reported for dual fuel diesel/gas

[16] Based on discussion with OEMs and leasing providers.

vehicles only. Economic analysis provided on the dedicated gas vehicle can be considered representative of a typical deployment.

7.1. Vehicle Ownership Costs

Table 13. Dual fuel gas truck ownership costs

Dual Fuel Diesel/Gas Trucks		
Cost factor	**Average cost**	**Cost range and notes**
System cost	£25,500	Range £15,000 to £33,000. System costs differed between suppliers and were influenced mainly by the complexity of the DF control systems and engine interaction, the number of gas injectors per cylinder, the complexity of vehicle integration (i.e. how much space was available for the tanks as vehicles can require modification to allow room for the gas containment system) and the number of gas tanks supplied.
Warranty	(included in purchase cost)	The base truck and retro-fit devices are covered by each manufacturer's standard warranty. Third party warranties are required for retro-fit systems to cover incidental damage to the truck caused by the dual fuel system. The costs of these warranties were generally included in the purchase cost of the retro-fit system, and can cost up to £800 per year depending on the level of warranty cover specified.
Maintenance	£1110	Range £500 - £2,500. Additional maintenance for gas vehicles includes fuel filter changes, general inspection, torqueing of tank straps, diagnostics and gas injector replacement. The main factor affecting maintenance costs was related to the gas injector replacement frequency. Systems varied between having one injector per cylinder with replacement required every 500,000 km whilst others had two per cylinder requiring replacement every 250,000 km.
Other	£60	Range £0 - £300. Additional costs for training and equipment were minimal. Most vehicle providers supplied free workshop and driver training. Fleets either had no mechanism to estimate additional costs associated with the management of gas vehicles, or stated that these costs were minimal.

Table 14. Dedicated gas truck ownership costs

Dedicated Gas		
Cost factor	**Average cost**	**Cost range and notes**
System cost	£25,000 to £31,000	Typical cost range for a circa 300 HP dedicated gas truck based on discussions with OEMs.
Warranty	£0	Vehicle covered by OEM warranty.
Maintenance	£400	Represents circa 7% increase in annual maintenance cost for gas vehicles (Ref. Cenex CCE trial 2012).

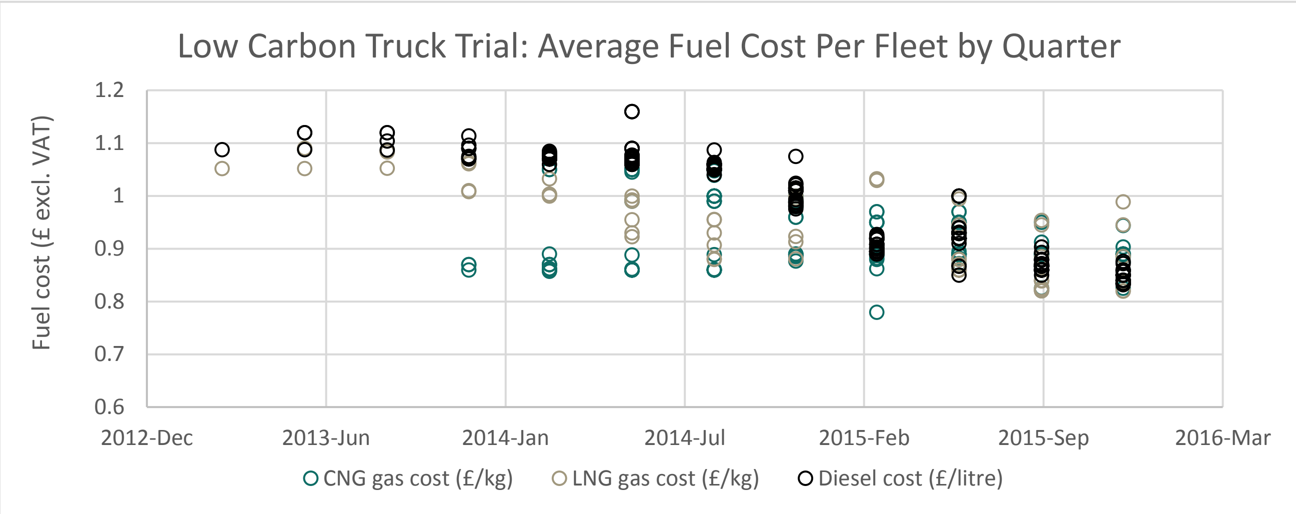
7.2. Fuel Costs

Participating fleets provided data on fuel costs on a quarterly basis. Fuel costs varied significantly by fleet, mainly due to the station type, contract supply volume and fleet negotiating power.

7.2.1. Quarterly Fuel Cost Trend

Figure 6 below shows the average fuel cost per fleet by quarter.

Figure 6. Quarterly average fuel price



The price that different fleets paid for gas varied by as much as 30p/kg. This variation was both volume and station dependent. Lower cost gas was generally available from higher capacity stations and grid connected CNG stations. Due to the low level of infrastructure available fleets had little flexibility to refuel from cheaper gas stations. During the trial a number of fleets relocated vehicles to depots which had access to lower cost gas. The positive cost differential between diesel and gas prices eroded slowly over the duration of the trial, with the cost of diesel reducing by 24% between December 2012 and December 2015 with gas reducing by 20% (LNG) and 9% (CNG) over the same period. During 2014 the cost of natural gas was on average 10% lower than diesel but by the end of the trial monitoring period (December 2015) natural gas was on average 3% more expensive than diesel. This correlates with anecdotal evidence from the fleets which towards the end of 2014 had started reporting greater running costs from the trial trucks.

7.2.2. Fuel Costs by Station Type

Table 15 below shows how fuel costs varied by station type during the trial. CNG grid connected stations provided the lowest cost fuel. They also provided the greatest variance in gas cost which ranged from £0.75 to £1.05 per kg. The cost of LNG, either delivered directly as LNG or converted to CNG was similar, with direct LNG being marginally lower cost than LCNG.

Table 15. Fuel costs by station type

	Diesel (£/litre)	Grid CNG (£/kg)	LCNG (£/kg)	LNG (£/kg)
Min	0.83	0.75*	0.83	0.82
Max	1.16	1.05	1.07	1.09
Min/Max Diff (%)	28%	39%	23%	25%
Average	**0.99**	**0.91**	**0.95**	**0.94**

*Subsequent to the data reporting period in this report, a new CNG station has opened in Leyland which advertises a CNG cost of circa. 65ppkg (July 2016), providing a step change reduction in the UK price from public refuelling stations.

7.3. Trial Running Cost and Payback Period

The additional capital costs of the trial trucks would ideally be paid back through fuel savings over the trucks lifetime, offering a total cost of ownership saving to the fleet operator. The fuel costs per km and the payback period of the trial trucks reported in this section represent the economics experienced by the fleets under their own unique different operating patterns and cost parameters. Therefore, the data is not directly comparable. A sensitivity analysis conducted in *Section 7.4* shows how different operating parameters impact the economic performance of the trucks.

Table 16 below shows the fuel costs reported by each LCTT fleet, summarised by system type. The savings are shown in two formats.

1. **Trial Fuel Costs** – These represent the economic experiences of the individual fleets over the trial period using each fleet's bespoke fuel costs.
2. **Levelled Fuel Costs** – This scenario represents the economic experiences of the fleets when trial average fuel costs are applied (£0.99 p/litre diesel, 0.93p/kg gas).

Table 16. Fuel costs by conversion system

System	Fuel Cost (ppkm)					
	Trial Fuel Costs (ppkm)			Levelled Fuel Cost (Diesel £0.99 / litre, Gas £0.93 / kg) (ppkm)		
	Diesel	Trial Truck	Savings	Diesel	Trial Truck	Savings
Dual Fuel Diesel/Gas (total)	**30.5**	**28.8**	**1.7**	**30.7**	**29.0**	**1.7**
RF DF Gas 1	28.5	25.6	2.9	28.9	25.8	3.1
RF DF Gas 2	30.6	32.0	-1.4	31.5	33.2	-1.7
RF DF Gas 3	28.9	28.3	0.6	30.3	29.2	1.1
OEM DF Gas	31.7	27.3	4.4	30.6	26.3	4.3
OEM Ded. Gas	**25.1**	**20.2**	**4.9**	**23.8**	**22.0**	**1.8**

Table 17 below show the average additional capital, annual running costs and payback period of each system type.

Table 17. Economic analysis for trial fuel cost scenario

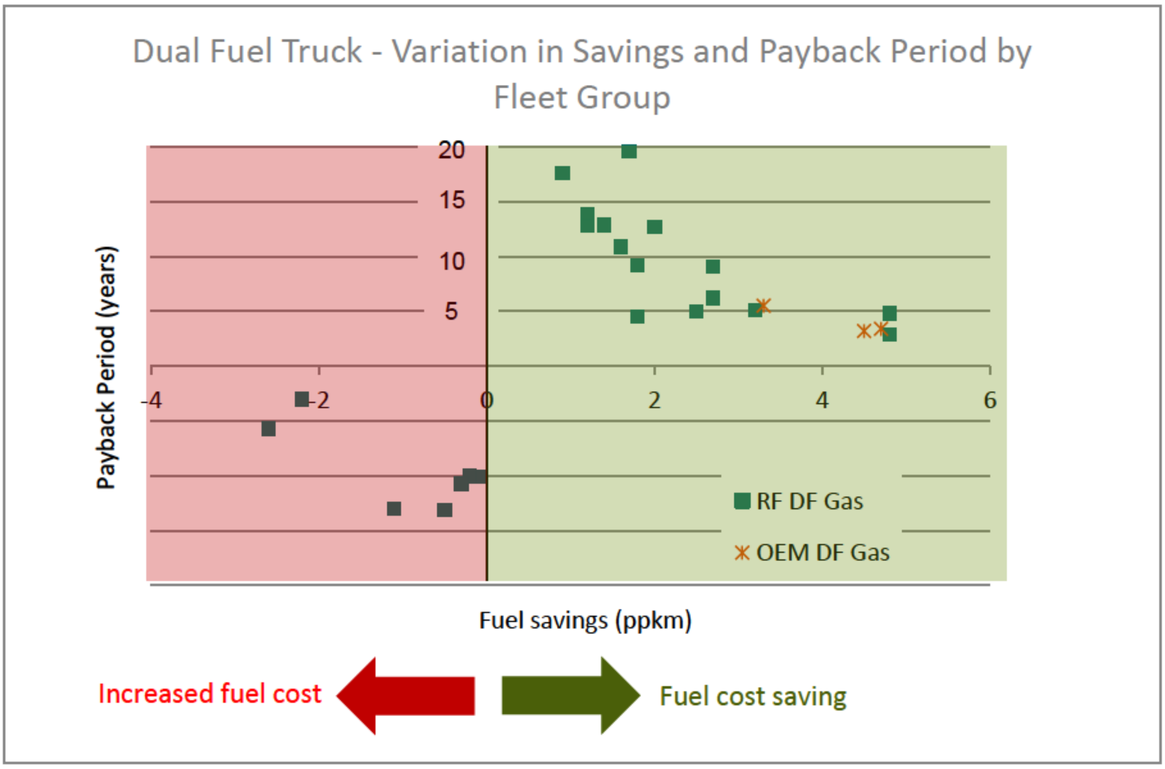
Additional Costs and Payback Period					
System	**DF Gas**	RF DF 1	RF DF 2	RF DF 3	OEM DF
Capital costs[8] (£)	**+25592**	+27560	+28842	+20853	+29667
Annual maintenance costs (£)	**+1110**	+736	+1254	+729	+1873
Annual fuel costs (£)	**-2526**	-6669	+1284	-549	-9967
Annual adblue cost (£)	**-218**	-285	-182	-157	-361
Total annual savings (£)	**1634**	6218	-2355	-23	8455
Payback period (years)	**15.7**	4.4	NA	NA	3.5

7.3.1. Dual Fuel Diesel/Gas

The most economic dual fuel system (OEM DF) offered average annual running cost savings of £8,500 and an average payback period of 3.5 years (with one fleet gaining annual savings of £11,900 and a payback period of 2.9 years). However, there was much variation with the worse performing system increasing costs by an average of £2,400 per annum. On average the dual fuel systems gave £1,600 annual savings over the trial. This was not sufficient to payback the initial capital investment cost of the system.

Figure 7 below shows the variation in payback periods across the dual fuel diesel/gas systems. Whilst most systems offer some ppkm savings, some increased fuel costs. 21% of fleets are expected to achieve a financial payback within the anticipated 6-year average ownership period of the trucks (using the actual fuel costs paid by each fleet).

Figure 7. Savings and payback for dual fuel diesel/gas vehicles



7.4. Economic Sensitivity Analysis

A sensitivity analysis was conducted to demonstrate the effect of performance variation in the trial technologies. Whilst data on real-world performance variation was available from the trial on the dual fuel diesel/gas technologies, there was very limited deployment variation from the dedicated gas vehicle. Therefore, following a review of other performance data outside of the LCTT the study team estimated the potential performance variation from dedicated gas trucks.

7.4.1. Dual Fuel Diesel/Gas Truck Sensitivity

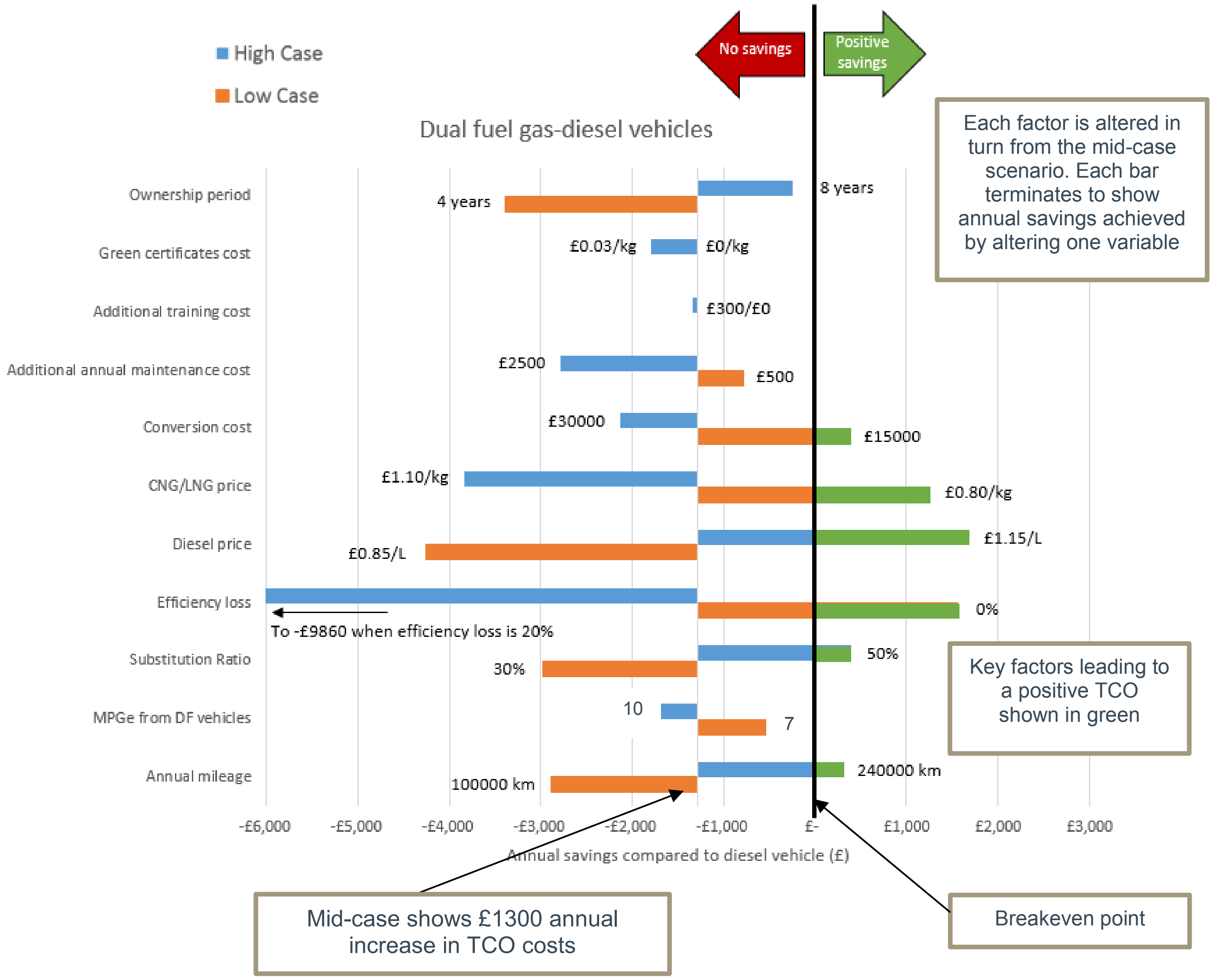
The key factors affecting the economic performance of the dual fuel trucks are shown in Table 18 below. Each factor was given a low, medium and high analysis case which broadly represented the average case (mid case) and variation in performance across the LCTT.

Table 18. Scenarios for dual fuel diesel/gas vehicles

Input	Low Case	Mid Case	High Case
Annual mileage (km)	100000	170000	240000
Trial MPG	7	8.5	10
Substitution ratio (%)	30	40	50
Efficiency loss (%)	0	5	20
Diesel price (£/litre)	0.85	1	1.15
Gas price (£/kg)	0.80	0.95	1.1
Conversion cost (£)	15000	25000	30000
Additional annual maintenance cost (£/annum)	500	1000	2500
Additional training cost (£0	0	50	300
Green certificates cost (£/kg)	0	0	0.03
Ownership period (years)	4	6	8
Other inputs (fixed)	Adblue set at 21.5 ppl used 5% in diesel. Fuel energy as per DEFRA 2015 Emission Factors.		

Figure 8 below shows the sensitivity of applying each high and low parameter in turn to the mid-case scenario and the resultant annual total cost of ownership (TCO) savings. It should be noted that the TCO annual savings shown in this analysis assume payback of the system in line with the stated ownership period, and are therefore different to the running cost savings reported in *Section 7.3.*

Figure 8. Sensitivity analysis for dual fuel diesel/gas vehicles



The figure above shows that the average dual fuel diesel/gas deployment delivered a total cost of ownership (TCO) increase of £1,300 per annum per vehicle. Fleets which achieved TCO savings tended to be those with low conversion costs, paying a low gas price, using efficient dual fuel systems experiencing high substitution ratios and undertaking high annual mileages. The main contributors to economic success were the diesel and gas price differential, followed by system efficiency and annual mileage. The most influentially positive factor which is directly under the control of a fleet is the ownership period, where longer periods allow the annual fuel cost savings to make a greater impact on TCO. The most detrimental factor to economic performance was operating dual fuel systems at a high efficiency loss. This tended to be system specific and duty cycle specific.

7.4.2. Dedicated Gas Truck Sensitivity

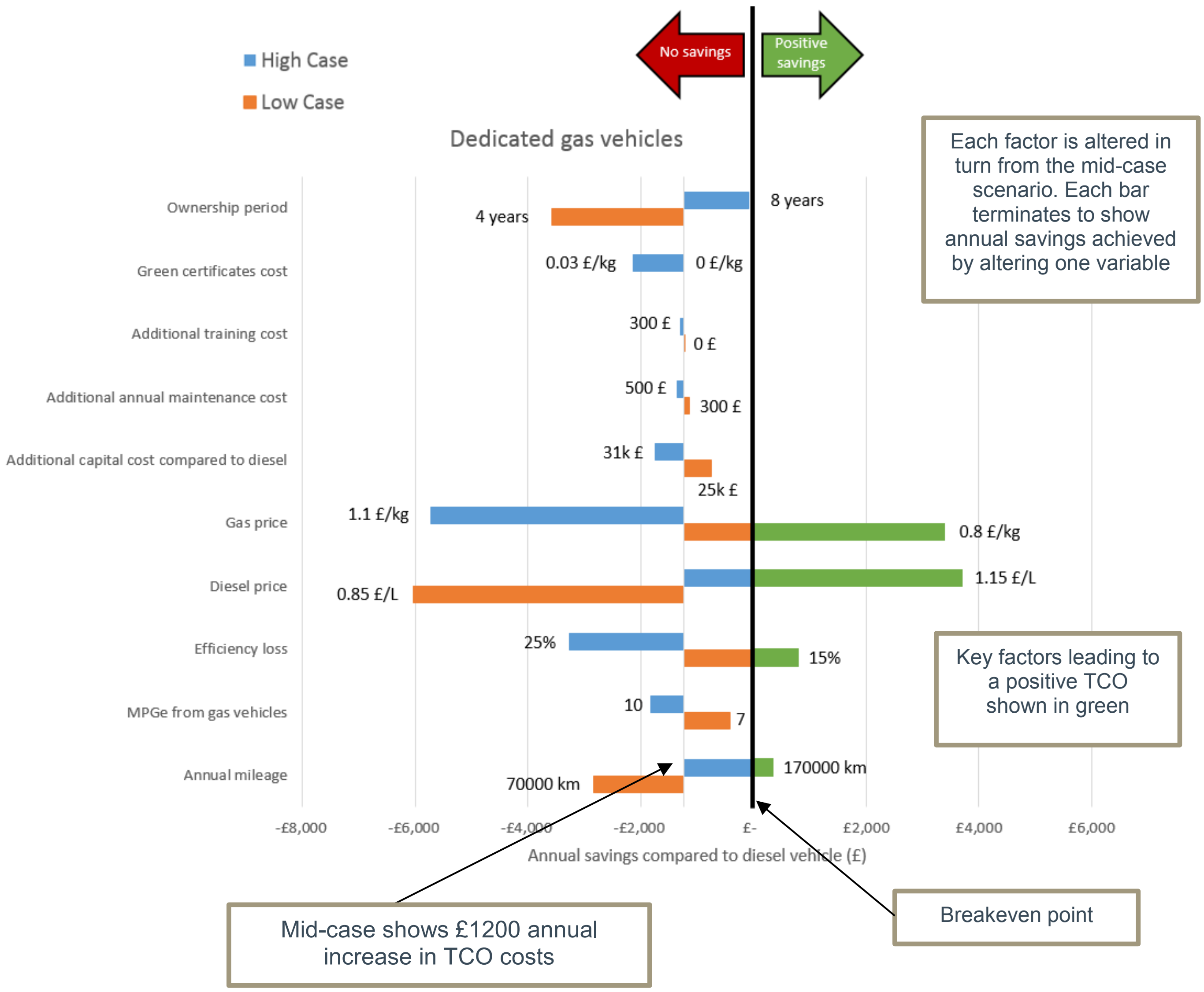
The key factors affecting the economic performance of dedicated gas trucks are shown in Table 19 below. Here the scenarios are based more broadly on general truck operating performance variation rather than specific fleet variation in the trial, due to the low population of data available on dedicated gas trucks in the LCTT.

Table 19. Scenarios for dedicated gas vehicles

Input	Low Case	Mid Case	High Case	Comments
Annual mileage (km)	70000	120000	170000	Reduced mileage due to lower range/travel radius of dedicated gas trucks.
Trial MPGe	7	8.5	10	Representative of LCTT performance.
Efficiency loss (%)	15	20	25	Mid case typical of normal efficiency loss in gas engines.
Diesel price (£/litre)	0.85	1	1.15	Representative of LCTT performance.
Gas price (£/kg)	0.80	0.95	1.1	
Additional capital cost compared to diesel (£)	25000	28000	31000	Representative of cost range across different manufactures and configuration options.
Additional annual maintenance cost (£/annum)	300	400	500	7% increase for gas vehicles (Ref. Cenex CCE trial 2012)
Additional training cost (£)	0	50	300	Representative of general LCTT performance.
Green certificates cost (£/kg)	0	0	0.03	
Ownership period (years)	4	6	8	
Other inputs (fixed)	AdBlue set at 21.5 ppl used 5% in diesel. Fuel energy as per DEFRA 2015 Emission Factors.			

Figure 9 below shows the sensitivity of applying each high and low parameter in turn to the mid case scenario and the resultant annual TCO savings.

Figure 9. Sensitivity analysis for dedicated gas vehicles



The mid case scenario shows an annual TCO cost increase of around £1,200. The economic conclusions for dedicated gas vehicles are the same as dual fuel diesel/gas vehicles. The main contributors to economic success were the diesel and gas price differential, followed by system efficiency and annual mileage. The most influentially positive factor directly under the control of the fleet is the ownership period, where longer periods allow the annual fuel cost savings to make a greater impact on TCO. The most detrimental effect on economic performance is the price difference between gas and diesel.

7.4.3. Fuel Cost Sensitivity

This section further examines the effect fuel cost variation had on truck payback period throughout the trial. The factors within this analysis are explained below.

- Operational scenario: The mid case scenario, as reported in *Section 7.4.1* was used (except fuel costs).
- Fuel cost sensitivity: Fuel costs were varied under the following scenarios.
  - Diesel cost per litre (represents spread of diesel costs throughout the trial).
    - High £1.15
    - Medium £1
    - Low £0.85
  - Gas costs per kg (represents spread of gas costs throughout the trial).
    - High £1.10
    - Medium £0.95
    - Low £0.80
    - Low Low £0.65 (represents costs of new CNG station opened in Leyland post-trial reporting period).

The results are shown in the following three scenarios:

- Dual Fuel Diesel/Gas - Representative of average trial dual fuel diesel/gas truck performance.
- Dedicated Gas - Considered representative of current dedicated gas truck performance.
- Dedicated Gas Potential - Shows near future potential performance considering the same annual mileage performance as a dual fuel truck (representative of two refuels per day, or use of an LNG tank) and a 5% improvement in efficiency expected from new generation of dedicated gas trucks[17].

Key to payback tables	
Red	Payback not available
Orange	Payback between ~3 – 6 years (acceptable to some fleets)
Green	Payback in less than ~3 years (acceptable to most fleets)

Table 20. Dual Fuel Gas Payback Period by Fuel Price

Dual Fuel Truck Payback Period by Fuel Price (years) (170000 KPA, 40%SR, 8.5 MPG, £25k Capital Cost, £1k maint. premium p.a.)					
		Gas Price (£/kg)			
		£0.65	£0.80	£0.95	£1.10
Diesel Price (£/litre)	0.85	5	NA	NA	NA
	1	3.1	4.6	NA	NA
	1.15	2.3	3	4.3	NA

Table 21. Dedicated Gas Payback Period by Fuel Price

Dedicated Gas Truck Payback Period by Fuel Price (years) (120000 KPA, 8.5 MPG, £28k Capital Cost, £400 maint. premium p.a., 20% eff. loss)					
		Gas Price (£/kg)			
		£0.65	£0.80	£0.95	£1.10
Diesel Price (£/litre)	0.85	3.7	NA	NA	NA
	1	2.3	3.5	NA	NA
	1.15	1.6	2.2	3.4	NA

[17] Iveco estimated that their dedicated gas vehicle range being introduced in 2016/17 with automated manual gearboxes would improve the efficiency of current dedicated gas vehicles by approximately 5%.

Table 22. Potential Dedicated Gas Payback Period by Fuel Price

Potential Dedicated Gas Truck Payback Period by Fuel Price (years) (170000 KPA, 8.5 MPG, £28k Capital Cost, £400 maint. premium p.a., 15% eff. loss)					
		Gas Price (£/kg)			
		£0.65	£0.80	£0.95	£1.10
Diesel Price (£/litre)	0.85	2.1	4	NA	NA
	1	1.4	2	3.6	NA
	1.15	1	1.3	1.9	3.2

The analysis above shows that for the mid-case trial performance scenario for both dual fuel and dedicated gas trucks a fuel price difference of around 20p (per unit) was required to allow the dual fuel and dedicated gas vehicles to achieve a payback within 3 – 4 years.

When looking at the potential of some 2016 model dedicated gas vehicles, if the same annual mileage as a dual fuel truck (representative of two CNG refuels per day, or the use of an LNG tank) is achieved and a 5% improvement in efficiency (as expected from the new generation of dedicated gas trucks) can be achieved then payback within the 6-year ownership lifetime is achieved with just a 5p per unit fuel cost differential between diesel and gas, with a 20p difference resulting in 2 year payback periods.

As shown in *Sections 7.4.1* and *7.4.2,* other factors not varied in this analysis can also have a significant effect on the trial truck economics.

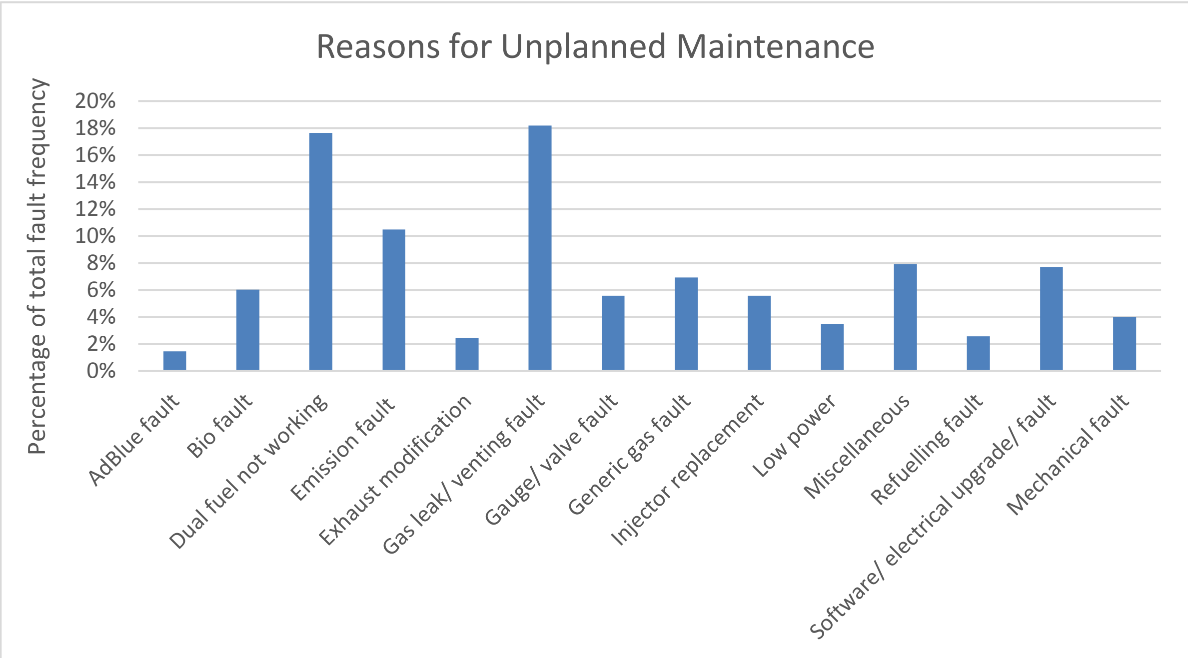
8. Vehicle Reliability

Key Points

- Overall the trial trucks experienced increased unplanned maintenance activity by 2 events per truck (dual fuel diesel/gas 1.7, dedicated gas 3.5, dual fuel diesel/used cooking oil 2.4) per year increasing downtime duration by 19% (dual fuel diesel/gas 19%, dedicated gas 122%, used cooking oil 0%). The high downtime figure for the dedicated gas vehicle is not typical for this type of truck and was due to bedding in issues cause by faulty fuel gauges and emission warning lights.
- Faults were generally due to the immature nature of the trial systems used with the fault frequency reducing throughout the trial.
- The most frequently occurring fault in dual fuel diesel/gas vehicles was ‘dual fuel system inactive’ (18%) and ‘gas leaking or venting faults’ (18%).
- The dual fuel diesel/used cooking oil vehicles mainly experienced ‘bio-faults’ which required a filter replacement to rectify.
- The OEM dual fuel diesel/gas vehicles had the lowest occurrence of faults, adding just one unplanned maintenance event per year. The dual fuel diesel/used cooking oil system caused the least additional unplanned downtime adding just 0.4 hours of unplanned maintenance per truck per year.

Fleet operators were required to report unplanned maintenance events from the trial trucks. A total of nearly 900 events were reported, which are shown in in Figure 10 below.

Figure 10. Faults reported during the truck trial



A description of each fault code and the main failure causes is given in Table 23 below.

Table 23. Fault code descriptions

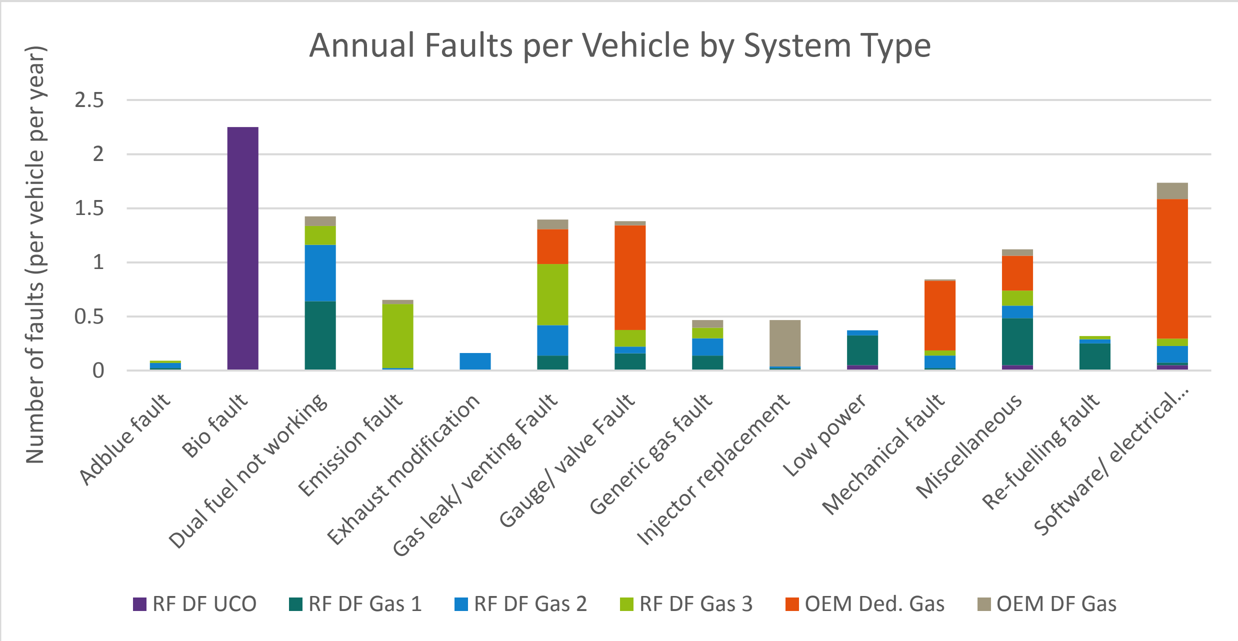
Fault description	Percentage of faults	Comment / typical fault reasons
Gas leak/ venting fault	18%	Leaking pipework, valves and fittings, caused mainly by initial installation faults or poor maintenance of securing straps/brackets.
Dual fuel not working	18%	Trucks not switching to dual fuel gas mode. This fault did not typically inhibit truck operation since they could function purely on diesel alone.
Emission fault	12%	Emission warning light displayed in cab. Normally resolved through DF control system recalibration.
Miscellaneous	9%	Miscellaneous one-off faults.
Software/ electrical upgrade/ fault	7%	Electrical faults (e.g. fault lights, wiring loom fault, damaged wires, sensor failure) or software reprogramming.
Generic gas fault	7%	Gas warning light on dash.
Injector replacement	6%	Unscheduled gas injector replacement required.
Gauge/ valve fault	6%	Pressure gauge showing incorrect readings. Valve not functioning correctly, sticking solenoids.
Bio fault	6%	Low fuel pressure, filter replacement required. Most faults were caused by isolated delivery of contaminated fuel. Relevant to the RF DF UCO system only.
Mechanical fault	4%	Bracket / securing mechanism failure.
Exhaust modification	3%	Modification to exhaust required due to fouling components.
Low power	3%	Poor performance when operating on gas (low power).
Re-fuelling fault	3%	Faulty refuelling equipment on vehicle (connectors or connector nozzle caps).
Adblue fault	1%	Adblue leak or truck not using adblue.

The majority of the faults represent the learnings associated with the relative immaturity of the dual fuel systems, with faults caused by both dual fuel system integration issues and training of maintenance technicians. Many of the faults were due to isolated issues regarding certain systems and installations.

8.1. Faults by Conversion System Type

In Figure 11 below the data is normalised by trial duration and truck numbers and shown on an 'annual number of faults per truck' basis.

Figure 11. Faults reported by system



The key points to note in the chart above are described in Table 24 below, along with overall fault statistics.

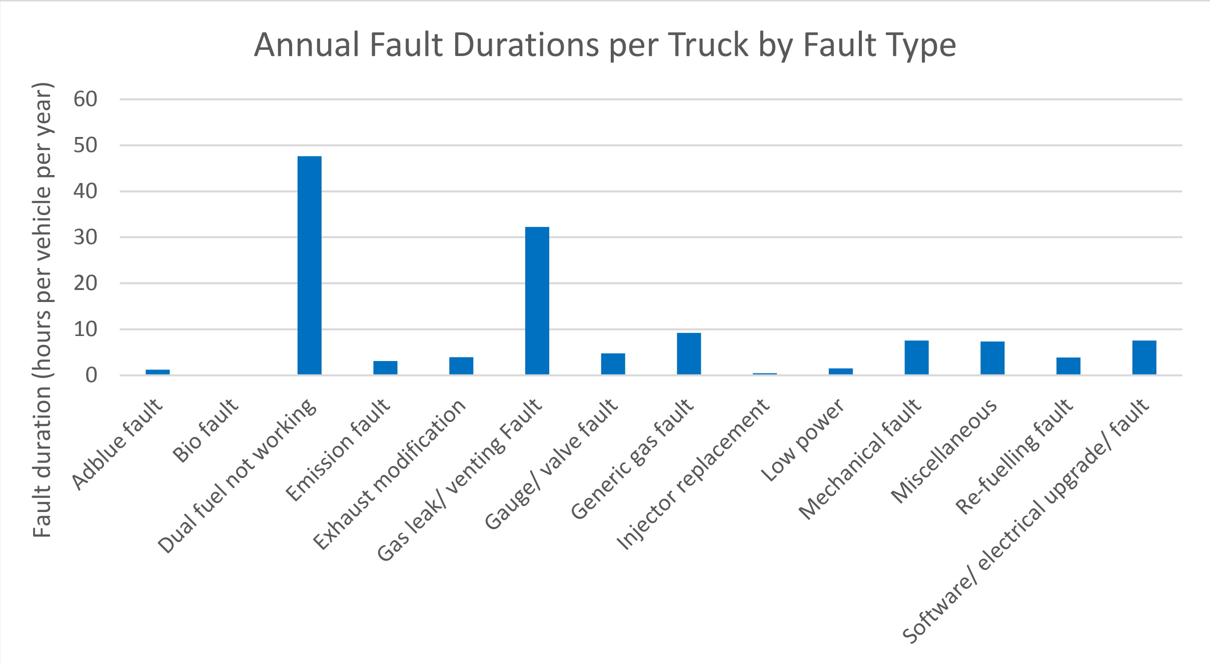
Table 24. Notes on faults per conversion system

<table>
<tr><td rowspan="2">RF DF Gas</td><td>Faults/Year/Truck</td><td>Weighted % of Total Faults</td></tr>
<tr><td>2.1 (RF DF 1) 1.7 (RF DF 2) 1.9 (RF DF 3)</td><td>17% (RF DF 1) 14% (RF DF 2) 15% (RF DF 3)</td></tr>
<tr><td colspan="3">Whilst some faults were common across the three retro-fit gas dual fuel systems, many were unique to the characteristics of a certain system or deployment. For example, 93% of the Emission Faults were due to RF DF Gas 3 and 100% of the Exhaust Modification faults due to RF DF Gas 2.</td></tr>
<tr><td rowspan="2">OEM Ded.Gas</td><td>Faults/Year/Truck</td><td>Weighted % of Total Faults</td></tr>
<tr><td>3.5</td><td>28%</td></tr>
<tr><td colspan="3">The OEM Ded. Gas trucks represented the highest percentage of faults per vehicle. However, OEM Ded. Gas trucks were deployed towards the end of the trial. As a result, the fault percentage presumably represents initial teething issues with the technology rather than the long term reliability of the trucks.</td></tr>
<tr><td rowspan="2">OEM DF Gas</td><td>Faults/Year/Truck</td><td>Weighted % of Total Faults</td></tr>
<tr><td>1.0</td><td>8%</td></tr>
<tr><td colspan="3">The OEM DF Gas system experienced the least faults amongst the trial systems. The majority of the downtime was related to injector failures. Injector replacement is normally a standard maintenance activity. However, maintenance frequencies were not understood and defined at the initial stages of the trial causing injector failure in service.</td></tr>
<tr><td rowspan="2">RF DF UCO</td><td>Faults/Year/Truck</td><td>Weighted % of Total Faults</td></tr>
<tr><td>2.4</td><td>19%</td></tr>
<tr><td colspan="3">UCO trucks experienced two unplanned faults per year. The majority were due to one isolated incident in 2014 Q3 where a contaminated tanker delivered the fuel to the depot. The contaminated fuel clogged fuel filters in turn causing the trucks' ECU (engine control unit) to request a filter replacement. It should be noted that the downtime associated with these faults was minimal.</td></tr>
</table>

8.2. Fault Duration

Some fleets were able to provide the precise start and end times of unplanned maintenance events allowing the duration of the faults to be calculated. This is shown below in Figure 12 and the data has been normalised to give annual fault time per truck. **In many cases the trucks were still operated whist the fault was active and awaiting repair. The actual downtime caused by the faults are recorded in Figure 13.**

Figure 12. Annual fault durations per vehicle



The majority of the fault time recorded was due to ‘Dual fuel not working’ (37%). This equated to 48 hours per truck annually, and reduced by 15% per annum through the trial period. 65% of these faults were due to RF DF 2 systems. However, it should be noted that this includes some long fault durations (up to 5 months) causing affected trucks to operate in diesel only mode for extended periods. Other common causes of faults were ‘Gas Leak / Venting Fault’ (25%) and ‘Generic Gas Faults’ (7%). The actual downtime caused by the faults are recorded in Figure 13 below.

8.3. Unplanned Downtime Duration by Fault Code

The average unplanned downtime per truck due to the trial system was 36 hrs per annum. A breakdown of the faults along with their contribution to annual down time per truck is shown below in Figure 13.

Figure 13. Annual unplanned downtime per vehicle

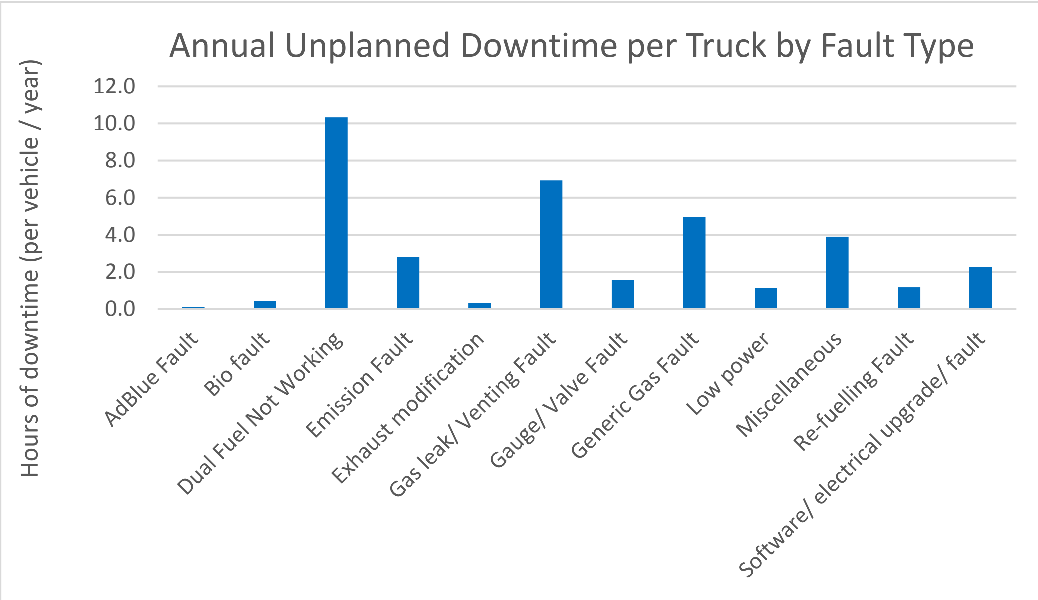


Table 25 below shows a breakdown of downtime per trial system and how this compares to the annual unplanned downtime for diesel system faults. On average the trial systems increased down time by 19%. This ranged from a 0% increase (with just 0.4 hrs downtime per truck) for the UCO system to a 122% increase (with 235 hrs downtime per truck) for the OEM Ded. Gas system.

Table 25. Summary of downtime per system

Trial System	Annual trial system downtime per vehicle (hrs/truck/annum)	Downtime increase due to trial system
RF DF UCO	**0.4**	**0%**
RF DF Gas	**36**	**19%**
RF DF Gas 1	32	17%
RF DF Gas 2	58	30%
RF DF Gas 3	41	21%
OEM DF Gas	0.6	0%
OEM Ded. Gas	**235**	**122%**

9. Station Reliability

Key Points

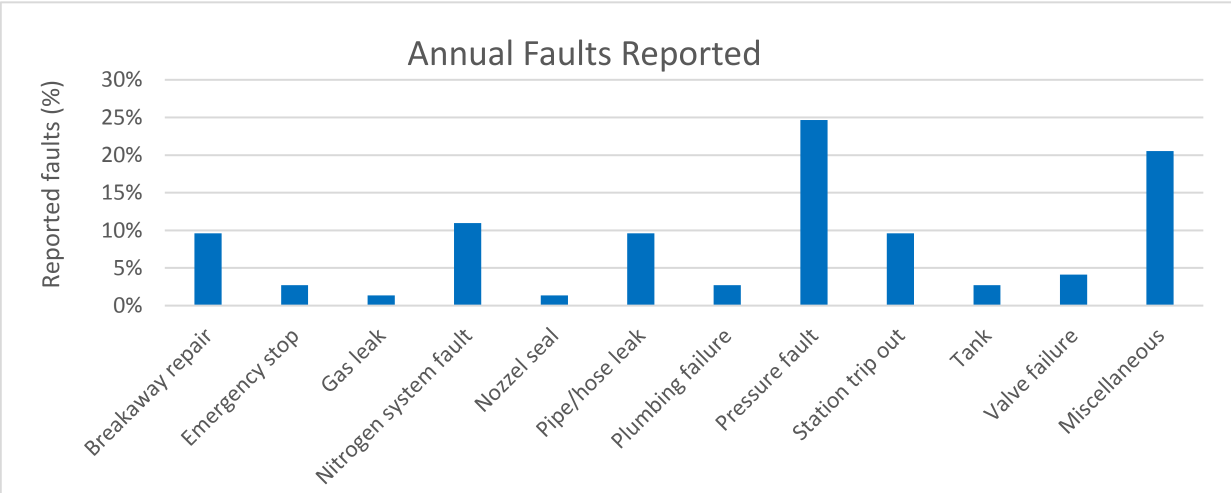
- The trial funded gas stations proved to be very reliable, showing an average availability of 99.4% (range 98.7 – 99.8%).
- On average 10 faults per station were recorded annually from the trial gas stations. 86% of faults were fixed within 1 day and 100% of faults fixed within 2 days. The majority of faults were related to pressure alarms (25%) followed by leaking pipes and connectors (10%), repair to break-away valves (10%) and general station trip out events.
- One fault per annum was recorded from the used cooking oil station which related to the station heating system and was rectified within 24 hours.

9.1. Gas Station Reliability

Five gas station operators (1 x CNG, 4 x LNG) were able to provide data on station faults throughout the trial. The stations were new facilities which received grant funding. No reliability data were available for non-trial funded stations or legacy stations that had received trial funding for upgrades only.

The new trial funded gas stations proved to be very reliable showing an average availability of 99.4% (range 98.7 – 99.8%) equating to nearly two unplanned downtime days per annum. On average 10 faults per station were recorded annually. 86% of faults were fixed within 1 day and 100% of faults fixed within 2 days. Figure 14 below shows the gas station faults reported over the trial.

Figure 14. Station faults



The main cause of faults were high/low pressure alarms (25%). Other common faults were stations tripping out due to electrical/mechanical parameters being out of limit (10%), repair to breakaway valves (10%) due to damage caused by a vehicle driving away whilst still connected to the refuelling hose and gas leaks from connectors and hoses (10%). Nitrogen system faults were specific to LNG stations which utilised nitrogen cooling loops to maintain ideal LNG temperature.

9.2. UCO Station Reliability

On average just one fault was recorded annually from the UCO refuelling stations showing an average availability of 99.7%. The faults were related to malfunction of the UCO heating system which maintains the oil at 35 degrees C. The fault was rectified within 24 hours.

10. Station Providers' Views

Key Points

Six gas station providers were interviewed to ascertain the effect of the Low Carbon Truck Trial on the industry and the main barriers to wider adoption of the technology. Station providers informed us of the following:

- The LCTT clearly contributed to the increase in demand for methane fuel and the number of stations and gas suppliers in the UK, which was paralleled by slow growth in the wider industry.
- Methane fuel costs decreased throughout the LCTT, with estimates ranging from a 5% to 30% decrease since 2012. However, the effect of this price decrease has not been sufficient to promote a significant market change due to a concurrent decrease in oil and diesel prices.
- Biomethane supply has not increased, with gas suppliers citing that poor market incentives for production and lack of legislative requirements for fleets to reduce transport emissions combined to limit the supply and demand for the fuel.
- Methane demand is likely to decrease in the short term due to the current lack of clear business case (due to low diesel prices) and the lack of Euro VI gas products on the market.
- Access to low rate borrowing for gas refuelling stations would make infrastructure installation more attractive to fleets.

10.1. Demand for Methane and its Effect on the Supply Chain

Six organisations (five of which were participants in the LCTT) that supply methane as a road transport fuel were interviewed to understand the effect of the LCTT on the following:

- The demand for methane and its effect on the supply chain.
- The cost of methane.
- The impact on green gas supply mechanisms and schemes.
- The impact on the production and supply of biogas and biomethane.
- Other issues/barriers.

All organisations that responded to the questionnaire reported that the LCTT has increased UK demand for methane as a vehicle fuel, and has also increased the number of players involved in the supply chain. This demand is clearly related to the deployment of trucks and infrastructure as part of the trial. Quotes from interviewees include:

'As the capex of the trucks was reduced, teething issues were more acceptable and customers were willing to push along.'

'A number of new station providers, such as CNG Fuels, ENN, BOC have now entered the refuelling station market, signifying a clear interest in the future provision of infrastructure. There are a number of stations under development through the UK, and several planned as part of EU funding success.'

'Our organisation has benefited from the LCTT, although part of the market growth would have happened anyway.'

As alluded to in the last comment, the growth in methane supply as part of the LCTT has been paralleled by a slow growth in the wider natural gas vehicle (NGV) fuel market, although it was noted that natural gas as a vehicle fuel remains a small, niche market for gas suppliers, with one interviewee commenting:

'We have seen slow growth on the remainder of our customer base [outside of the LCTT] and subsequently feel the same in the market.'

One respondent highlighted the opening of the Isle of Grain as a significant development for future UK LNG supply for vehicles as it means that UK companies no longer have to go to the European mainland to source supplies.

10.2. The Cost of Methane as a Vehicle Fuel

Most respondents agreed that methane costs have decreased since the start of the LCTT, with estimates ranging from a 5-7% to a 30% decrease since 2012. However, the effect of this price decrease has not been sufficient to promote a significant market change due to a concurrent decrease in oil and diesel prices:

'The impact of the low oil and diesel price has not provided the market with the appropriate differentiation [to promote faster growth].'

10.3. Biomethane and Green Gas Supply Mechanisms

All respondents indicated that biomethane (particularly liquefied biomethane) vehicle fuel supply has not increased since 2012, and that if anything supplies have decreased in that time; and that further incentives are needed to encourage its use in transport:

'The additional cost of producing and liquefying biomethane is making the customer business case even harder to make.'

10.4. Issues and Barriers Identified by Suppliers

Following on from the structured questions on the effect of the LCTT on methane demand in the UK, station suppliers identified a number of aspects they considered were holding back growth in the gas vehicle market.

Table 26. Station providers' issues and barriers to methane based transport

The lack of a clear evidenced business case is hampering market growth Suppliers highlighted that gas vehicles did not always offer an attractive business case	*'The business case relies on showing huge savings relative to diesel. Our customers are asking to see evidence of payback periods of two years if possible, three years at the outside, otherwise their accounting people will make the case for other uses of capital outlay that is more profitable for the business.'* *'With oil/diesel price being so low and unpredictable, the [cost] differential is not as big as is required to make a business case work. When you factor in the engine conversion and private plant investment it actually costs customers more to convert to LNG. The infrastructure is growing in the UK and some good faith in the market that "if we build it, they will come" but customers need a lot of work to completely convince. Especially in industries where margins are low – (i.e. haulage).'*
The lack of Euro VI dual fuel offerings has effectively frozen the development of the vehicle market at present Suppliers highlighted a decline in gas sales is expected as dual fuel Euro VI vehicles are not available	*'Although demand has been hampered by the shift to Euro VI, and the lack of a reliable solution for dual fuel, several of the trial participants are now investigating new OEM dedicated vehicles. The use of dual fuel engines has bridged the technology gap between diesel and dedicated gas. A reliable Euro VI dual fuel solution will still be required for some time as fleets educate themselves over the transition, and as Euro V diesel conversions move through their useful life, there may be periods where gas vehicle numbers in the country decrease before they progress further.'* *'Lack of vehicles and therefore lack of demand is the biggest problem we are facing. We will suffer with the lack of Euro VI dual fuel solutions.'*
Incentives need to level the playing field Suppliers highlighted that biogas sold to the transport	*'Gas grid injection is not a problem, however the choice of where the gas is recognised as being used is the important point. Producers should be able to choose to sell their kgs to heat, transport, etc., without it being a financially costly decision.'*

sector is not appropriately recognised	
The emissions benefit of cleaner trucks needs to be clarified and valued by Government Suppliers highlighted that there are no legislative mechanisms compelling hauliers to reduce their emissions which undermines the value of biomethane	*'There are two benefits for LNG conversion – CO_2 reduction and cost reduction. CO_2 reductions in fossil LNG are tenuous and the current [incentives landscape] for biomethane makes LBM for transport not commercially feasible. Until the government brings in legislation that focuses on vehicle emissions, LBM will not become mainstream.'*
Additional support would be welcomed – not just funding	*'More government support would help, as there is significant competition and limited funds when looking for European support, especially now that cohesion countries are going to take a lot of the remaining rollout funds.* *Support from the government to back lending by financial institutions would be a far more useful policy. Where debt could be obtained at reasonable rates with the credit underwritten by the government. Banks have little or no interest in supporting development at a station level, and large banks such as the European Investment Bank have minimums of €25m, which is far too large to be helpful.'*

11. Vehicle System Manufacturers' Views

Key Points

Seven truck system suppliers were interviewed to ascertain the effect of the LCTT on the industry and the main barriers to wider adoption of the technologies trialled. This included five retro-fit system suppliers and two OEMs.

- Retro-fit system suppliers generally reported increases in sales volumes (up to 100%) due to the LCTT enabling product development and increased workforce. Whilst OEM providers stated the LCTT has had little effect on overall sales volumes.
- Retro-fit system suppliers that reported sales increases of over 50% also reported cost reductions (of up to 20%) over the trial period in their products due to increased sales volumes.
- OEMs are committed to increasing the range of dedicated gas vehicles available, with variants up to 450 hp expected in 2017.
- Retro-fit dual fuel manufacturers stated they are working on numerous innovations focused on reducing methane slip and increasing system efficiency, with the majority of systems undertaking fleet trials in 2016 with general release expected in 2017.
- Vehicle manufacturers rated the uncertain business case due to the low diesel cost experienced during the trial period as the main barrier to fleet adoption. Methane slip, the need for a long term fuel duty differential, and lack of infrastructure were cited as major barriers.
- Regarding the UCO vehicles, the main barrier to wider uptake was deemed to be cost with fuel duty or purchase grant support required to allow fleets to achieve significant GHG reductions at a similar or lower total cost of ownership.

11.1. Demand for Vehicles and its Effect on the Supply Chain

The majority of retro-fit system suppliers reported that the LCTT helped them to increase sales (in some cases by up to 100%), expand their workforce and to grow business opportunities. They stated that the trial came at the right time when customer interest was increasing and it helped turn interest into firm orders.

For OEMs the increase in sales volumes due to the trial was negligible, but the OEMs still sighted the value in the trial being the legacy of refuelling infrastructure, market awareness and the networking opportunities gained through the trial workshops and events.

'the trial had a very positive effect on our business. The significant increase in orders enabled us to locate to bigger premises, hire more staff and develop our products. The revenue generated was reinvested in the local area and created [nine] new jobs.'

'once we had sold systems to a few large blue chip customers, this acted as a qualifier for our system and opened the door to more and more customer interest. Suddenly we were talking to all the major fleets and were accepted as a good quality supplier.'

Two respondents commented that sales of Euro V systems were negatively impacted due to the trial as customers engaged in the competition process before trialling vehicles which delayed purchasing decisions and ultimately pushed some purchasing decisions beyond Euro V vehicle availability.

11.2. Cost of Vehicles and Systems

Retro-fit gas system suppliers that reported sales increases of over 50% during the trial period also stated that system costs reduced by 10 to 20% over the same period due to the development of low cost gas containment systems. Minimal cost difference in vehicle maintenance was reported, although one supplier commented that the costs of their inclusive maintenance package reduced over the trial period as the maintenance risks (due to unknown service life of components) reduced with experience.

'We managed to reduce costs through working with a Chinese supplier to develop a bespoke LNG tank. This development all comes from having volume orders through the truck trial.'

All manufacturers stated the gas tanks were the highest cost component accounting for 35 – 50% of the total system costs. Two respondents estimated a 50% reduction in tank costs could be achieved if mass produced (~25,000 units per annum).

'with the exception of the tanks, if designed for mass manufacture the remaining components of a dedicated gas vehicle could be supplied at a lower cost than diesel components'

11.3. Euro VI Vehicles and Future Technology Development

OEM manufactures stated that they were fully committed to the supply of direct injection methane engines (dedicated gas or high pressure diesel/gas injection) to support Euro VI demand. Dedicated gas spark ignited vehicles are currently (July 2016) available from suppliers in power configurations between 260 - 400 hp (Iveco, Mercedes, Scania, Volvo), with 450 hp variants expected to appear in 2017 (Iveco). Volvo are developing a High Pressure Direct Injection (HPDI) engine which uses diesel fuel as a pilot in a compression ignition engine. This vehicle is expected to achieve gas substitution ratios greater than 95% with no loss of engine efficiency. However, there is currently no release date available for this vehicle.

Retro-fit dual fuel manufacturers stated that they are working on innovations (some funded through Innovate UK) focused on reducing methane slip and increasing efficiency, such as more effective catalysts, improved gas combustion techniques and systems to convert diesel engines to operate on 100% gas. One supplier has a Euro VI retro-fit system currently available, but most new systems are expected to be trialled during 2016 coming to market in 2017.

'we have [Euro VI dual fuel] orders pending, awaiting confirmation that our new catalyst is removing methane from the exhaust stream'

11.4. Lessons Learned from Other Countries

The UK was seen as an attractive market place for product development, with low levels of regulation on retro-fitted systems reducing the costs to bring systems to market. System suppliers stated that successful policies in other countries which helped to create a strong market for natural gas vehicles include a consistent long term fuel duty policy and sustained support for infrastructure deployment and legislative requirements mandating service fleets to adopt gas (primarily for air quality benefit).

11.5. Issues and Barriers Identified by Truck Trial System Suppliers

Following on from the structured questions system suppliers identified a number of aspects they considered were holding back growth in the gas vehicle market.

Table 27. Vehicle manufacturers' issues and barriers to methane based transport

The lack of a clear evidenced business case is hampering market growth Suppliers highlighted that gas vehicles did not always offer an attractive business case	*'Diesel price is the main barrier; this has killed it [the business case] over the last 12 months.'*
Methane slip is a major barrier for some fleet customers	*'we have [Euro VI dual fuel] orders pending, awaiting confirmation that our new catalyst is removing methane from the exhaust stream'* *'methane slip is a major barrier'* *'methane slip reduces the credibility of dual fuel vehicles'*
Further support is required to maintain the growth of natural gas vehicles Suppliers highlighted the need for assistance to support the development of systems and stations	*'Pump money into conversion systems, station providers will put stations in at their own cost if fleets are buying vehicles. The industry will have suffered another false start if subsidies are not continued'* *'Grant funding is useful, but it can stall the market with organisations waiting for funding to become available'* *'The government should continue to support R&D …improve infrastructure and have a consistent strategy'*

12. Fleet Manager Attitudes and Experiences

Key Points

Dual fuel diesel/gas trucks

- Fleet managers were sent surveys to quantify their attitudes towards the vehicles and stations used during the trial.
- 89% of fleet managers were glad they took part in the LCTT. They enjoyed working with other like-minded companies and 80% stated that operating dual fuel trucks was good for the company's image. 22% of fleets stated that operating the trucks helped them to win new business and 11% had purchased more new dual fuel trucks during the trial period without any grant funding.
- Two thirds of fleet managers felt positively about the dual fuel diesel/gas trucks. The remaining third cited either refuelling station closures, reliability, economic performance or concerns over the total greenhouse gas impact of the vehicles due to methane slip as reasons for feeling negatively about the trucks.
- Fleet managers generally viewed the performance of the dual fuel diesel/gas trucks to be broadly similar to that of a diesel truck (9% reduced performance perception observed). Emissions, noise, fuel use, fuel costs and range on full tanks of fuel were rated as marginally better than a standard diesel truck. Purchase price, unplanned maintenance costs, payload and refuelling time were rated as worse than a standard diesel truck.

Dual fuel diesel/UCO trucks

- Just one fleet operated UCO vehicles within the trial. The UCO trucks were reported to perform comparably to diesel vehicles in all aspects with the exception of emissions, where the fleet manager rated these as much better than diesel vehicles. The performance of the station was rated lower than a comparable diesel refuelling station due to some teething problems with the station metering system and nozzle design.

12.1. Fleet Manger Surveys – Dual Fuel Diesel/Gas

Ten fleet managers responded to a survey that sought to quantify their attitudes towards the vehicles and stations used during the trial. The respondents covered both LNG (5 respondents) and CNG (5 respondents) dual fuel systems.

12.1.1. Dual Fuel Truck and Refuelling Station Performance

Truck Performance: Fleet managers generally viewed the performance of the dual fuel diesel/gas trucks to be broadly similar to that of a diesel truck (9% reduced performance perception observed). Emissions, noise, fuel use, fuel costs and range provided by full tanks of fuel were rated as marginally better than a standard diesel truck. Purchase price, unplanned maintenance costs, payload and refuelling time were rated as worse than a standard diesel truck.

44% of fleet managers agreed with the statement that the dual fuel diesel/gas trucks had saved them money over the trial, and 33% were in disagreement, with the remainder being uncertain.

'there has been fuel cost savings, but not to the extent hoped for, due to both limited fuelling stations and reduced cost of diesel recently '

56% of fleet managers stated that the dual fuel diesel/gas trucks had helped them to reduce fleet emissions, whilst 33% were unsure due to either uncertainty over methane slip or because CO_2 emissions were not analysed within the company.

Refuelling Stations: 67% of fleet managers felt positively or neutrally towards the refuelling stations at the end of the trial, with many fleet managers commenting on the poor reliability of the existing UK gas stations (as opposed to the new stations funded by the LCTT which achieved an average relaibility of 99.4%).

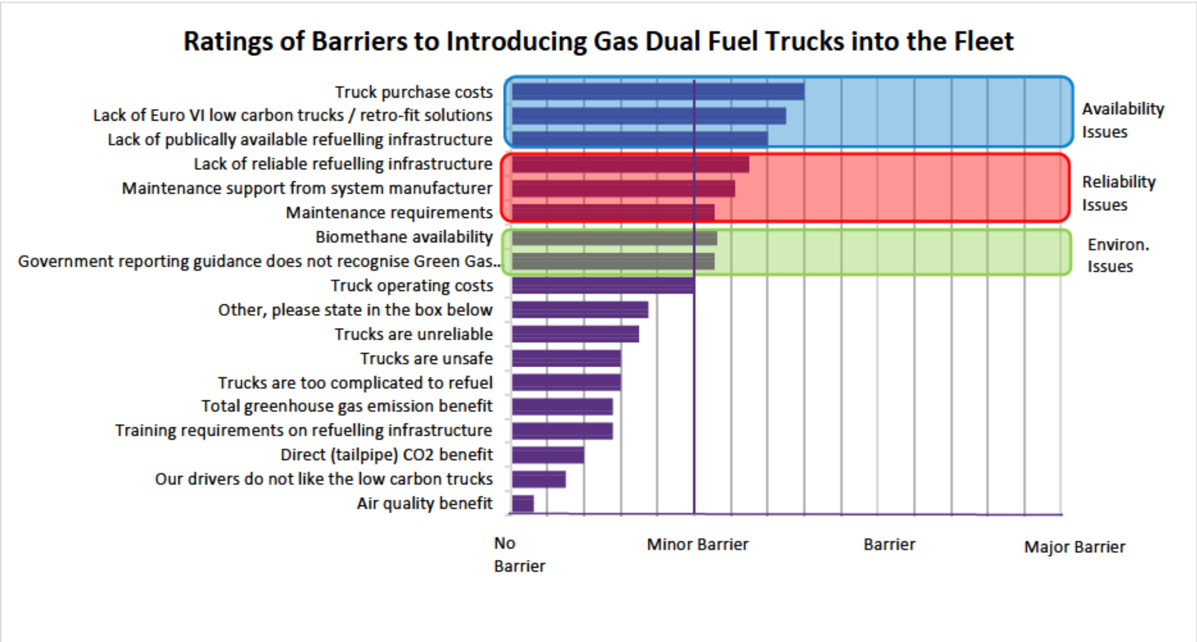
Future Plans: 33% of fleet managers stated that they had firm plans to increase the number of dual fuel diesel/gas trucks within their fleet and 22% stated they would buy dual fuel diesel/gas trucks from now on. Other fleet managers were keen to expand their fleets but only when they were certain that other factors (economic, refuelling availability, reliability) were positively aligned.

'we are in a position to move forward with further dual fuel vehicles when the efficiencies and other benefits allow'

12.1.2. Barriers to Dual Fuel Diesel/Gas Trucks

Figure 15 below shows how fleet managers rated the barriers to introducing dual fuel diesel/gas trucks within their fleets. Fleet managers were asked to rank each as a Major Barrier, Barrier, Minor Barrier or No Barrier.

Figure 15. Perceived barriers to alternatively fuelled trucks



No items were unanimously ranked as major barriers. The highest ranking barriers to dual fuel diesel/gas truck deployments can be summarised into three categories as shown in Table 28 below.

Table 28. Barriers to introducing dual fuel gas/diesel trucks

Barrier ranking	Grouping	Description
1st	Availability	Ranked as barrier: The lack of low costs systems, retro-fit solutions for Euro VI and low levels of public infrastructure were the highest ranking barriers to operating dual fuel gas trucks.
2nd	Reliability	Ranked as minor barrier: The reliability of the public gas infrastructure and the variable quality of maintenance support between the retro-fit dual fuel system providers were regarded as barriers to the purchase of dual fuel diesel/gas trucks.
3rd	Environmental	Ranked as minor barrier: The lack of biomethane and officially recognised Green Gas Certificate schemes was considered a barrier to uptake of more dual fuel diesel/gas trucks.

12.2. Fleet Manger Surveys – Dual Fuel Diesel/UCO

Just one fleet operated dual fuel diesel/UCO vehicles within the trial. The UCO vehicles were reported to perform comparably to diesel vehicles in all aspects with the exception of emissions, where the fleet manager viewed these as much better than a diesel. The operator of the UCO vehicles stated that since trial commencement further systems have been purchased without grant funding and there are firm plans to increase the number of dual fuel diesel/UCO trucks within the fleet.

'The trial provided funding and structure to prove independently benefits and effects of operating 44 tonne trucks on waste oils. Our project has received great interest and recognition in the UK and abroad and our success has been shared in forums with our customers'

In agreement with the gas dual fuel projects, the current low cost of diesel affected the economics of truck operations during the trial period.

'Initially we saw cost savings, however the fall in world crude prices have squeezed this benefit'

The main (and only major) barrier to implementing dual fuel diesel/UCO vehicles was stated to be the fuel cost, where it is felt that the low carbon benefit of using a renewable fuel is not fairly represented in taxation mechanisms.

'The government removed the duty break for bio-fuels and replaced it with a system with a much lower monetary incentive. I think the government should revert to a duty break but restrict this to bio-fuel from proven waste oils i.e. not virgin oils'

No negative aspects were reported regarding the use of UCO in trucks. However, some teething issues (such as station metering system and a nozzle design causing drips) with the UCO dispensing station were noted.

13. Driver Attitudes and Experiences

Key Points

Dual fuel diesel/gas trucks

- 324 drivers completed questionnaires about their experiences with the dual fuel diesel/gas trucks.
- On average the dual fuel trucks were rated as having similar performance to a standard diesel truck.
- 75% of the drivers felt positively or neutrally towards the trial trucks. 61% of the drivers felt positively or neutrally towards the gas refuelling stations.
- Positive comments received from the drivers were mostly about the environmental performance of the trucks. Drivers rated the trial trucks and refuelling stations positively/neutrally when they operated on set routes, had reliable/repeatable access to infrastructure, and experienced few system faults with the trucks.
- Drivers who rated the dual fuel diesel/gas trucks and refuelling stations negatively commented on the lack of stations, leading to additional mileage required to refuel, reliability issues with vehicles whilst driving, poor range, difficulties in refuelling and lack of training.
- Throughout the trial period, drivers' perception of station reliability, truck reliability, environmental performance and safety performance of the vehicles improved.

Dedicated gas trucks

- Seventeen questionnaires were returned for dedicated gas vehicles from just one fleet.
- A predominantly positive perception was observed with 93% of drivers feeling positivity or neutrally towards the trucks and 83% feeling positive or neutrally towards the refuelling stations.

Used cooking oil trucks

- Six questionnaires were returned for the dual fuel diesel/used cooking oil trucks from just one fleet.
- There were no negative ratings of the UCO trucks and stations. 100% of drivers felt positive or neutrally about the vehicles and refuelling station.

13.1. Dual Fuel Diesel/Gas Driver Surveys

Questionnaires were completed by truck drivers throughout the trial to capture their feedback and to understand perceptions and attitudes toward the trucks and refuelling infrastructure. 324 drivers completed trial questionnaires. The majority (76%) of all truck drivers who responded to the surveys were over the age of 40 and had above 10 years of experience driving trucks (74%).

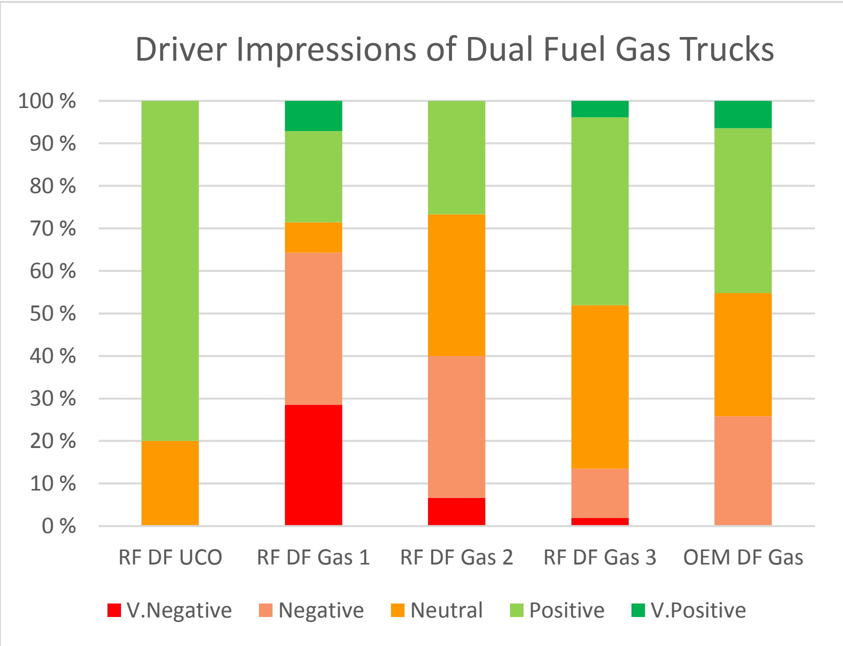
13.1.1. Dual Fuel Diesel/Gas Trucks

On average 75% of the drivers felt positively or neutrally towards the trial trucks and rated them as having similar performance to a standard diesel truck. Perception ratings varied depending on the system used. Throughout the trial period, drivers' perceptions of truck reliability, environmental performance and safety performance of the vehicles improved. 47% of drivers wished to know more about the environmental performance of the trucks they drive. Positive comments received from drivers referred to the perceived environmental performance of the trucks and the positive image this reflected on the company. All RF DF systems were rated poorly in acceleration from a standing start. A summary of driver experiences is given in *Section 13.1.3.*

'Gives good image for company that they are doing their bit for the environment'

Figure 16 below shows the large variation in opinions toward the different systems. This is demonstrated, for example, when comparing the percentage of drivers which felt negatively about RF DF Gas 3 (13%) and RF DF Gas 1 (64%).

Figure 16. Drivers' views of dual fuel trucks by conversion system



13.1.2. Refuelling Stations

61% of the drivers felt positively or neutrally towards the gas refuelling stations. The overall refuelling experience of drivers was assessed relative to their refuelling infrastructure. The analysis showed that drivers with access to multiple types of infrastructure (own depot, public infrastructure and other fleets' depots) had a more positive refuelling experience (66% positive/neutral) relative to fleet owned depots (51% positive/neutral). This aligns with the driver comments, where many reliability complaints were made about fleet depot stations.

"Gas pumps were unreliable and frequently broke down."

13.1.3. Summary of Driver Experiences

The general opinions of the drivers were cross referenced against their operational scenarios and questionnaire comments. Analysis of the factors which led to drivers having an overall positive or negative experience are summarised in the table below.

Table 29. Summary of driver experiences

Positive comments
Positive comments received from drivers were mostly about the environmental performance of the trucks. Drivers rated the trial trucks and refuelling stations positively/neutrally under the following circumstances. • They operated on set routes. • They had reliable/repeatable access to infrastructure. • They experienced few system faults with the trucks.
Negative comments
Drivers who rated the dual fuel diesel/gas trucks and refuelling stations negatively commented on the following. • Lack of stations, additional mileage. • Issues with vehicles whilst driving. • Poor range. • Difficulties in refuelling. • Lack of training.

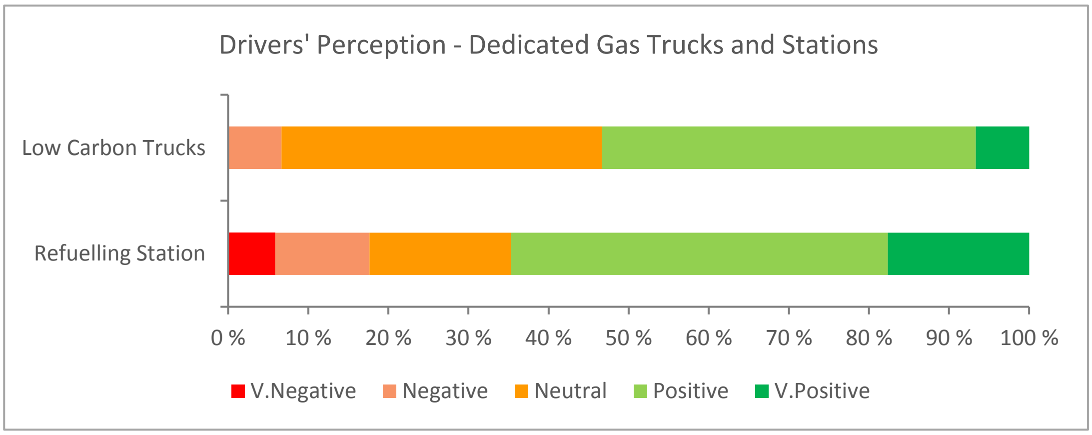
Finally, drivers understood that the trucks were part of a trial as summarised in the comment below.

"…once the issues are ironed out I believe there will be benefits across the board … but there have been many teething problems".

13.2. Dedicated Gas Driver Surveys

Seventeen questionnaires were returned from drivers of one fleet of dedicated gas vehicles. Figure 17 shows the drivers' overall ratings of the dedicated vehicles and stations.

Figure 17. Drivers' perceptions on dedicated gas trucks and stations



There was mixed feedback on the performance of the dedicated gas trucks and their refuelling stations. However, a predominantly positive perception was observed with 93% of drivers feeling positivity or neutrally towards the trucks and 83% feeling positively or neutrally towards the refuelling stations used. The dominant criticisms were about the accuracy of the vehicle fuel gauge and the reliability of the refuelling station.

"Fuel gauge readings poor"

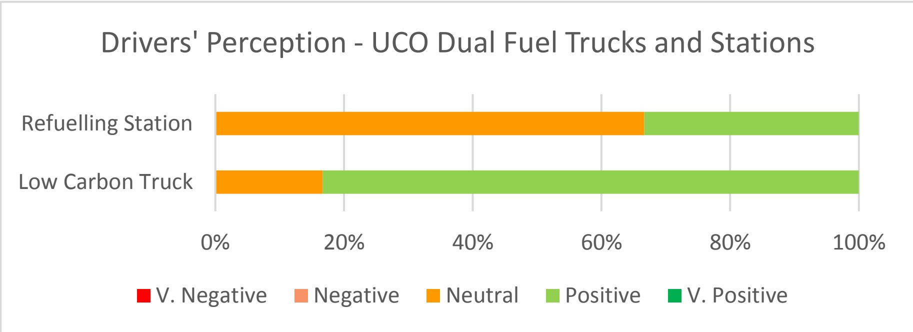
"Pump out of action - vehicles at stand still"

Overall drivers rated the performance of the dedicated gas truck similar to that of a regular diesel truck. They considered the gas truck to be superior to a diesel in environmental performance, engine noise and truck reliability. However, the drivers perceived the gear change performance of the dedicated gas truck to be inferior to a diesel truck. This could show the drivers' preference for an automated manual gear box (used in the diesel comparator vehicles) to a fully automatic gearbox (used in the gas vehicle).

13.3. UCO Driver Surveys

Six questionnaires were returned from drivers of the dual fuel diesel/UCO trucks from one fleet. Figure 18 shows the drivers' ratings of the UCO trucks and refuelling station.

Figure 18. Drivers' perception of UCO trucks and refuelling station



There were no negative ratings given by drivers of the dual fuel diesel/UCO trucks. 83% of drivers felt positive about the UCO trucks, with the remainder being neutral. 33% of drivers felt positive about the UCO refuelling station, with the remainder being neutral.

The sole negative comment received from the UCO drivers was about the refuelling station where five out of six drivers noted that there had been UCO spillages from the nozzle.

"Oil left in the nozzle always causes spillages and unnecessary mess."

14. Summary of Barriers

The table below presents the main barriers to the uptake of the trial trucks and potential solutions identified by the trial participants and industry representatives during the LCTT, including through workshops and interviews. The table also presents some solutions to address these barriers which have been suggested by the trial participants and industry representatives during LCTT workshops and interviews.

Economic Barriers	
Barriers	**Potential solutions**
• Economic performance is sensitive to diesel cost fluctuations. • Short term support offers limited opportunities for long term change. • High capital cost of stations.	• Create more attractive economic environment through long term subsidised operation (e.g. incentives for lower carbon fuels, and/or grants for low carbon systems). • Offer low interest loans for alternative fuel refuelling stations.
Environmental Barriers	
Barriers	**Potential solutions**

• Variability in CO_2 emission savings across different technologies and retro-fit systems.
• Limited CO_2 savings from some systems.
• Air quality performance uncertainty.
• 'Methane Slip' causing potential overall increase in GHG emissions from some dual fuel (diesel / gas) vehicles.
• Confusion over legitimacy of Green Gas Certificates.
• Lack of biomethane availability.
• Uncontrolled methane venting from some vehicles and stations.
• WTW CO_2 emission factor uncertainty. Conflicting information exists on the carbon intensity of natural gas depending on supply pathway.
	• Facilitate the roll-out and uptake of independent and trusted accreditation scheme developed by Low Carbon Vehicle Partnership for testing lower carbon truck options, which could:
	  ○ Limit any future operating grants or subsidies to approved low carbon truck systems and technologies.
	  ○ Set environmental thresholds (CO_2, GHG, Air Quality) for approved systems.
	  ○ Factor operators' payment/grant level by CO_2 saving potential.
	• Fund R&D programs for technical development (e.g. high efficiency dual fuel and dedicated gas systems, more effective methane catalysts). Amend guidance on greenhouse gas reporting to allow fleets to claim the environmental benefits of Green Gas Certificates in transport.
	• Consider incentivising the production of biomethane for use as a road transport fuel above other uses.
	• Legislate the provision of methane vent capture equipment on vehicles and stations.
	• Review WTW performance of the range of pathways for natural gas and biomethane. A recent study[18] suggests current emission report factors may underestimate the WTW impact of natural gas supply.

Operational Barriers (Vehicles)	
Barriers	**Potential solutions**
• Variable performance across retro-fit systems. • Lack of performance knowledge of different fuels and systems. • Limited system availability in Euro VI.	• Low carbon truck system accreditation scheme (see previous comments in environmental section). • Facilitate independent environmental case studies and industry dissemination events on available systems, channel information through trade associations. • Identify opportunities to provide further funding for the development of Euro VI systems meeting defined quality criteria (emission performance).
Operational Barriers (Stations)	
Barriers	**Potential solutions**
• Delays obtaining planning permissions and uncertainty over HSE requirements. • Delays establishing gas network information and requirements. • Lack of refuelling stations.	• Produce standardised guidance for planning authorities, and locate specialised support team within central Government. • Encourage gas network operators to allow station developers better access to network technical information. • Continue funding the deployment of refuelling stations.
Other Considerations	
Barriers	**Potential solutions**
• A limited range of technologies was evaluated within the LCTT.	• Future policy should consider and include technologies which have not been considered in the LCTT. • Future demonstration trial funding requirements should be designed to allow a broader technology spread.

[18] The role of natural gas and biomethane in the transport sector, Riccardo Energy & Environment, 2016 (Issue No 1)

15. Conclusions

The LCTT has met its original key objectives to facilitate alternatively fuelled truck learning, product development and the initiation of a publicly accessible UK gas refuelling infrastructure. It has provided a rich and valuable data source to assist policy makers in evaluating the technologies within the trial and provided feedback to the fleet community to give them the knowledge to make informed choices within their fleets. The trial findings are summarised by the following key conclusions by the study team:

Technology Selection

- Technology selection was challenging for fleet operators. When looking to make technology purchases (vehicles or stations) fleets reported a lack of independent information on the performance of lower carbon technologies and a lack of available guidance to assist them in making the right decisions.

Technology Deployment and Learning

- **Vehicles** - Teething issues associated with deploying new technologies (e.g. system faults, emission warning lights etc.) reduced throughout the trial period as the technology providers gained more experience in system deployments. Fleets generally found any teething issues with new technologies acceptable, but reported concerns over the variable quality of support across the retro-fit system suppliers. Driver training and engagement was reported to be a key success factor in operating and refuelling gas vehicles. During the trial, some fleets redeployed trucks on to the most economic drive cycles (e.g. high fuel consumption, high mileage, near low cost gas stations).
- **Stations** - Significant programme delays were experienced with the deployment of stations due to factors such as station design optimisation (especially for new and innovative station designs), assessing the ideal station site locations (to maximise customer throughput) and delays in gaining planning permission, land use agreements, and technical information from the local gas grid operator. Station providers called for standardised guidance for planning authorities, and a specialised support team within central Government.

Environmental

- **CO_2 Performance** - CO_2 performance was variable across the trialled technologies. The best performing dual fuel diesel/gas systems offered CO_2 savings of up 9% TTW and 6% WTW. The biofuel blend of the alternative fuel used by fleets had a significant effect on trial emissions performance. When operating using only natural gas, the dedicated gas vehicle and some of the dual fuel systems showed an increase in CO_2 emissions against their real-world diesel comparator vehicles. Biofuel use was a key factor in enabling a step change improvement in CO_2 emissions savings. For example, the dual fuel diesel/UCO vehicles provided an 86% TTW and 84% WTW emission saving, and the dedicated gas truck produced real-world emission savings of 11% TTW and 10% WTW when operating on a 15% biomethane blend.
- **Methane Slip** - Emission testing undertaken by consortia highlighted that relatively large amounts of methane were present in the exhaust gas stream of dual fuel diesel/gas vehicles, which resulted in some of these trucks increasing overall GHG emissions. This highlights the need for a better understanding and evaluation of the total GHG and air quality effect of different technologies under real-world driving conditions before policy is set in favour of certain technologies. Policies should also take into account how the environmental impact of retro-fit technologies (which are sold without evidence of Euro emissions compliance) are managed and enforced.
- **Air Quality Performance** – Two consortia provided results of independent air quality emissions testing showing air quality performance was generally improved from dual fuel diesel/gas systems. One system showed reductions in all air quality pollutants (CO, NO, NO_2, PM, NOx) and another system showed an emissions reduction in some air quality pollutants, with increases in CO and variable PM performance.

Economics

- Dual fuel diesel/gas vehicle economic performance varied widely by each fleet's operating scenario with 21% of fleets expected to achieve financial payback within 6 years (average truck ownership period in trial consortiums). The main contributors to these results were the reducing cost of diesel throughout the trial period and the large engine efficiency loss apparent in some dual fuel systems. The price that different fleets paid for gas varied by as much as 30p/kg. The lowest cost gas was available from large capacity grid connected CNG stations. A gas fuel price difference of around 20p below the diesel price was shown to allow the average gas (dedicated or dual fuel) truck to achieve a payback period of within 3 – 4 years. Achieving and maintaining this fuel cost difference between diesel and gas is key to the success of the gas vehicle industry (assuming there is no reduction in system purchase price) as the current lack of a clear business case was highlighted as a major implementation barrier by fleets, vehicle/system suppliers and station suppliers.

Reliability

- **Vehicles** - The trial systems increased the unplanned downtime of the trucks by 19%. However, this was variable by technology type. Trial truck reliability was rated as a minor barrier by fleet managers, who accepted that the implementation of new technology has a learning curve for both the fleet operators and system suppliers.
- **Stations** - New stations funded under the LCTT programme proved to be very reliable achieving an average 99.4% availability. This was in contrast to some legacy gas stations in the UK (which predated the LCTT). Although legacy station performance was not monitored by the trial study team, fleet managers and drivers stated concerns about their reliability. However, anecdotally the reliability of the network stations generally improved as station utilisation and gas demand increased through the trial.

Station Providers Views

- Station providers were interviewed. They indicated that the LCTT had made a significant contribution to the increase in demand for methane and the increased number of UK gas stations. The trial volumes were not considered high enough to impact the cost of methane or the availability of biomethane. Station providers commented that demand for methane was likely to reduce in the short term due to the lack of available Euro VI gas vehicles, however Euro VI vehicle supply is improving.

Vehicle System Manufacturers' Views

- Retro-fit system suppliers generally reported increases in sales volumes (up to 100%) due to the LCTT enabling product development and increased workforce, whilst OEM providers stated the LCTT has had little effect on overall sales volumes. Retro-fit system suppliers that reported sales increases of over 50% also reported cost reductions (of up to 20%) over the trial period in their products due to the increased sales volumes.

Fleet Manager Views

- Fleet managers were generally glad they took place in the LCTT. Fleet managers rated the performance of the trial trucks similar to that of a diesel truck. Two thirds of the fleet managers were pleased with the performance of the trial trucks, whilst the remaining third cited either refuelling station closures, poor reliability, poor economic performance or concerns over the total greenhouse gas impact of the vehicles due to methane slip as reasons for feeling negatively about the trucks.
- The main barriers stated for wider use of the trial trucks reported by fleet managers can be summarised into three categories:
  - Availability - lack of low cost systems, lack of Euro VI systems, lack of infrastructure.
  - Reliability - reliability of the gas infrastructure and the variable quality of maintenance support of retro-fit dual fuel system providers were cited as a barrier to the purchase of dual fuel diesel/gas trucks.
  - Environmental - limited supply of biomethane, and lack of officially endorsed Green Gas Certificate schemes were regarded as barriers to the uptake of more gas vehicles.

Future Developments

- At the time of undertaking stakeholder interviews (February 2016) the gas truck industry was experiencing very limited growth, awaiting increases in Euro VI vehicle availability and the recovery of the diesel and gas price differential. The industry and fleets generally felt that alternatively-fuelled truck numbers were set to decline if further financial support was not provided to help bridge the gap to larger scale commercialisation. OEMs and retro-fit technology providers stated they were actively progressing the supply of more Euro VI products. For example, OEMs are improving the efficiency of dedicated gas vehicles and increasing their product range available in the UK, with 400 hp trucks now available and 450 hp trucks in 2017. New gas stations are also continuing to come online. For example, a large capacity CNG refuelling station was opened in Leyland in early 2016, which has provided a step change reduction in gas price.

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