Independent, not-for-profit, low carbon technology experts

DEDICATED TO

GAS

An Innovate UK Research Project to Assess the Viability of Gas Vehicles

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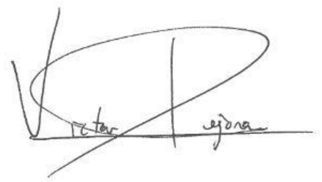

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Document Revisions

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001	Initial draft	12/09/2019
002	Second draft	27/09/2019
003	Final draft	15/10/2019
004	Final revision	31/10/2019

Contents

Table of abbreviations

BMCS	Biomethane Certification Scheme
CH_4	Methane
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DEFRA	Department for Environment, Food and Rural Affairs
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EEA	European Environment Agency
EGR	Exhaust Gas Recirculation
FTA	Freight Transport Association
GGCS	Green Gas Certification Scheme
GHG	Greenhouse Gases
GVW	Gross Vehicle Weight
HGV	Heavy Goods Vehicles
KI	Kinetic Intensity
LEFT	Low Emission Freight and Logistics Trial
LNG	Liquified Natural Gas
MJ	Mega-Joule
MPGe	Miles Per Gallon equivalent
N_2O	Nitrous oxide
NCV	Net Calorific Value
NOx	Oxides of Nitrogen
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
PN	Particulate Number
RHI	Renewable Heat Incentive
RTFO	Renewable Transport Fuel Obligation
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SR	Substitution Ratio
TCO	Total Cost of Ownership
THC	Total Hydrocarbons
TTW	Tank-to-Wheel
VECTO	Vehicle Energy Consumption calculation TOol
VTEC	Variable Temperature Emissions Chamber
WHVC	World Harmonised Vehicle Cycle
WP	Work Package
WTT	Well-to-Tank
WTW	Well-to-Wheel

1 Executive summary

Scope:

- This is the first UK study to assess in-service and tested performance of vehicles which are all **Euro VI factory-fitted OEM gas vehicles**.
- This trial builds on the foundations set by previous Innovate UK HGV projects like the 2016 Low Carbon Truck Trial, which involved mainly Euro V retrofitted vehicles.

Greenhouse Gases (GHG):

- The 20 trial gas vehicles **saved over 1,400 tonnes of well-to-wheel CO_2e** compared to diesel across 2 years on the road via fossil gas displacement schemes that require injection of biomethane in the natural gas grid network.
- GHG savings are significant even with small blends of biomethane. The gas vehicles provided the best GHG savings in long-haul and regional drive cycles at high payloads. **Methane slip was minimal** (0 to 3% of WTW CO_2e).

Air Quality:

- The gas vehicles presented **similar NOx levels** as diesel and all values were within Euro VI regulatory limits.
- Particulate emissions were similar to diesel in the LNG vehicles but higher in the CNG rigid vehicle.
- Note: spark ignition gas vehicles only use 1 aftertreatment system compared to 3 in diesel vehicles.

Total Cost of Ownership:

- Gas vehicles require a higher initial capital investment than diesel and involve higher maintenance costs, but the fuel costs are lower.
- Due to the fuel cost savings, gas vehicles can **pay back from 2 years at 160,000 km/year**.

As part of the Low Emission Freight and Logistics Trial (LEFT), the Dedicated to Gas project seeks to evaluate as accurately as possible the viability of Euro VI gas heavy goods vehicles (HGVs) as an alternative to diesel. The project deployed 20 Euro VI vehicles running on biomethane, which is a sustainable version of natural gas derived from the decomposition of organic matter, such as food waste. The project deployed a combination of compressed natural gas (CNG) and liquified natural gas (LNG) trucks using both spark ignition (SI) and compression ignition (CI) engine technologies. Cenex was responsible for trial monitoring and evaluation, and this report presents the main outcomes from this work package.

Using data provided by consortium partners, Cenex has analysed fuel economy, range, greenhouse gas (GHG) emissions, vehicle reliability, driver perceptions and emission testing results during the trial. A sensitivity analysis on different business case scenarios is also included in this report, along with policy implications and recommendations.

Fuel economy: The CNG and LNG SI vehicles have an MPGe (miles per gallon of diesel equivalent on an energy content basis) 15 to 28% worse than their diesel comparators, which is an expected result as SI engines are inherently less efficient than CI diesel engines. The LNG CI vehicles, however, only show a 3% decrease in MPGe because they use the same basic engine technology as their diesel comparators. These fuel economy results are based on the in-service operation of the vehicles in this trial, which drive at a daily average speed of 55-65 km/h and carry an overall daily average payload of 20-40% (including empty running time).

The fuel economy of all vehicles improves with average speed because HGVs are optimised for long haul operations, and the proportion of gas used in the LNG CI vehicles increases with average speed for the same reason. An increase in daily average speed from 50 to 70 km/h involves an improvement in fuel economy of 10 to 20%.

Range: The range on a full tank from the CNG vehicles is 35 to 39% lower than their diesel comparators, whereas the range from the LNG SI vehicles is 45% higher than their diesel comparators because of the higher energy per unit of volume of LNG compared to CNG. The range on the LNG CI vehicles is however 18 to 36% lower than their diesel comparators because of the space required by the LNG tanks in addition to the diesel and AdBlue tanks.

Greenhouse gas emissions: The trial vehicles travelled over 2.2 million km saving over 1,400 tonnes of well-to-wheel (WTW) GHG CO_2e. As all the trial gas vehicles are using 100% biomethane for the majority of time, they are saving 76 to 81% in WTW GHG emissions compared to the diesel vehicles. Across all 20 trial trucks, the emissions savings are the equivalent to displacing 16 diesel vehicles from the road. If the trial vehicles used standard natural gas (fossil fuel), the WTW GHG savings would range from 13 to -4%. Therefore, a bio-blend of at least 25% would be required to produce significant GHG savings, higher than 17%, compared to diesel vehicles. If the CNG SI vehicles used standard gas, they would produce WTW GHG savings ranging from -4 to 10%, while the LNG SI vehicles would produce savings of -1%. The LNG CI vehicles would produce WTW GHG savings of 13% if they used standard gas. The DEFRA emission factors for CNG, LNG and biomethane were used in the calculations. It is recommended that future versions of the emissions factors differentiate between bio-CNG and bio-LNG rather than the current single factor for biomethane.

Vehicle reliability: The gas vehicles present a similar number of annual maintenance events compared to the diesel vehicles. However, it takes longer to repair the faults in the gas vehicles due to the lower level of market maturity in the UK. 26% of the unplanned faults in the gas vehicles were related to the gas systems, while 13% of the unplanned faults in the diesel vehicles were related to the diesel systems.

Driver perceptions: Most of the gas vehicle drivers have over 10 years of driving experience and have shown their perceptions of gas vehicles in pre-, mid- and post-trial surveys. According to these, gas vehicles perform better than diesel comparators in engine noise / vibration, overall drive comfort, engine braking and environmental performance. However, in performance aspects such as handling steep inclines and acceleration from standing, SI gas vehicles were rated worse than diesel, whereas CI gas vehicles were rated as similar to diesel. While the range on a full tank in the LNG SI vehicle was regarded as better than diesel, the rest of the gas vehicles were rated as worse than diesel in this aspect.

Emission testing: Dynamometer and track tests were performed on several vehicle types within the trial, showing that GHG savings comparing gas to diesel increase when moving from urban to motorway drive cycles and from 60 to 100% payload. The results from vehicle testing show that SI gas vehicles can provide WTW GHG savings (using fossil gas) ranging from -9 to 23% depending on drive cycle, payload and vehicle. Vehicle testing also shows that CI gas vehicles can achieve GHG savings from 6 to 14% without the need of biomethane. The higher end of these ranges of GHG savings match the long haul and regional drive cycles, which represent 88% of the distance covered by UK HGV fleets (1) as well as the specific operation in this trial. The use of a 100% bio-blend in the tested vehicles and drive cycles would yield WTW GHG savings of around 80%. The tests have proven that the methane slip in the gas vehicles was minimal and made very little contribution to GHG emissions (0 to 1%). The N_2O contribution to GHG emissions from the tested diesel comparators ranges from 2 to 6%.

Vehicle testing has also shown that NOx emissions are similar in the gas vehicles, but the absolute values of these emissions are very small for both gas and diesel vehicles because all the tested vehicles comply with Euro VI standards. Particulate number (PN) emissions are similar in the LNG vehicles compared to diesel, but they are higher in the CNG Rigid vehicle. It must be noted that the SI gas vehicles only use one aftertreatment system while the diesel and CI gas vehicles use 3 (including the need for AdBlue) to achieve similar Euro VI results in terms of exhaust pollutants.

Business case: Gas vehicles require a higher initial capital investment than diesel vehicles and involve higher maintenance costs, but the fuel costs are lower. Fuel costs represent a major proportion of HGV operational costs and, therefore, the fuel savings from gas vehicles can negate their increment in other costs to produce total cost of ownership (TCO) savings compared to diesel vehicles under the right mileage and gas price conditions. Across different fuel types (CNG/LNG) and engine technologies (SI/CI), gas vehicles can pay back from 2 years at 160,000 km/year.

Policy implications: The implications from this report for UK fleets are that gas Euro VI HGVs can offer TCO savings compared to diesel Euro VI HGVs at similar levels of air quality performance. There are still some challenges regarding range on a full tank and WTW GHG emissions savings. To solve these, more refuelling stations are required and a minimum biomethane blend of 25% should be introduced to ensure that GHG savings are achieved across the gas fleet. GHG savings of up to 80% are available at higher bio-blends showing that gas vehicles fuelled by biomethane can offer a strong contribution to the UK's 2050 net zero carbon target using technology which is proven, reliable, mature and cost effective.

2 Introduction

This section describes the Dedicated to Gas project and the role of Cenex within the consortium.

The Dedicated to Gas project is part of the Low Emission Freight and Logistics Trial (LEFT, Stream 1) funded by Innovate UK. The objective of the project is to promote the uptake of biomethane in heavy goods vehicles (HGV). Dedicated gas vehicles can be a clean and economically viable alternative to diesel HGVs. The project consortium is formed by a biomethane supplier and project lead, Air Liquide; 3 transport operators, Asda, Howard Tenens and Kuehne + Nagel; and 3 technical partners, Cenex (data monitoring and evaluation), Emissions Analytics (vehicle testing) and Microlise (telematics) as shown in Figure 1.

Figure 1: Dedicated to Gas consortium

Table 1 shows the timeline of the vehicles deployed as part of the trial. Table 2 shows the 4 types of vehicles operated in the trial and the terminology used throughout the report. To preserve commercial confidentiality, no Original Equipment Manufacturers (OEMs) are mentioned in this report and the types of trial vehicles are not linked to any of the fleet operators. The performance of the vehicles is presented per vehicle type, hence keeping anonymity on vehicle usage statistics.

Table 1: Vehicle deployment timeline

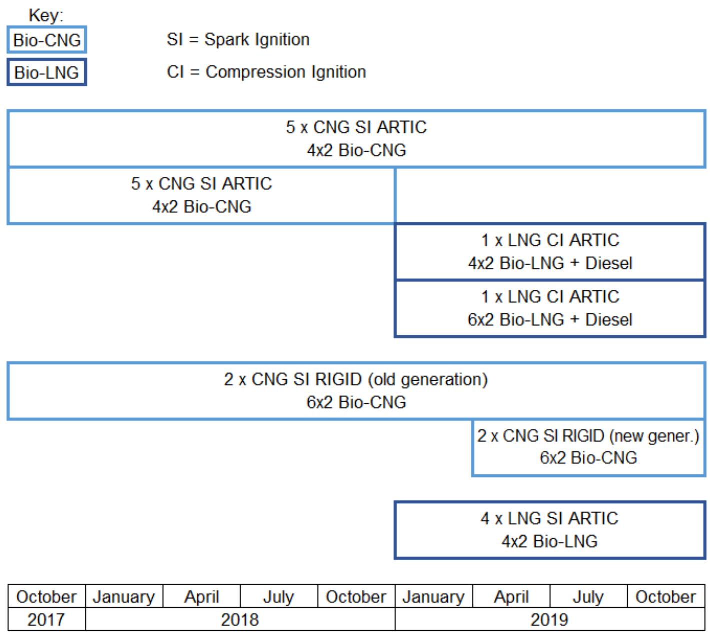

Table 2: Gas vehicles operated in the trial

ACRONYM	CNG SI RIGID	CNG SI ARTIC	LNG SI ARTIC	LNG CI ARTIC
Fuel type	Bio-Compressed Natural Gas	Bio-Compressed Natural Gas	Bio-Liquefied Natural Gas	Bio-Liquefied Natural Gas + Diesel
Engine technology	Spark Ignition (same as gasoline engines)	Spark Ignition (same as gasoline engines)	Spark Ignition (same as gasoline engines)	Compression Ignition (same as diesel engines)
Emission standard	Euro VI	Euro VI	Euro VI	Euro VI
Body type & GVW	Rigid 26t	Articulated 40t	Articulated 40t	Articulated 40-44t
Axle configuration	6x2	4x2	4x2	4x2 & 6x2
Engine horsepower / capacity (L) / torque (Nm)	340 / 9.3 / 1,600	340 – 400 / 9.3 – 8.7 / 1,600 – 1,700	400 / 8.7 / 1,700	460 / 12.8 / 2,300
Duty cycle	Urban & regional delivery	Regional delivery	Regional delivery & long haul trunking	Regional delivery

Within the project, Cenex was tasked with Work Package 6 (WP6): "Monitoring and data analysis, evaluation and reporting". The objectives of this WP are to monitor, record and evaluate the operational fuel economy, greenhouse gas (GHG) emissions, cost performance and reliability of the dedicated gas trucks and their diesel comparators during their time in service over the period of the trial. Other objectives include the interpretation and evaluation of the emissions test data recorded by Emissions Analytics and Millbrook, recording and reporting the data required by Innovate UK, and updating and relaunching the Gas Vehicle Hub website. The following sections show the main results and findings of this WP.

3 Trial monitoring

This section shows the results of the trial monitoring in terms of vehicle performance, greenhouse gas emissions, vehicle reliability and driver perceptions.

In order to timely collect all the relevant data from the trial, Cenex developed a monitoring plan and spreadsheet templates for the consortium partners to fill. On a monthly basis, vehicle operators send to Cenex a data log containing specifications of vehicles deployed, refuelling records, and a description of the maintenance events that took place in both the gas and diesel comparator vehicles. Microlise provide a detailed monthly log including distance, average speed, payload and fuel consumption amongst other data items that are collected on a daily basis for each vehicle in the trial. Cenex collates all this information, sense-check it and submit it to TRL, who are responsible for collecting all the data from the LEFT projects on behalf of Innovate UK. Cenex also analyses the data and provide the results to the consortium at the quarterly project meetings. The following sub-sections show the results from this analysis exercise for the different aspects of the trial data monitoring until 31st July 2019. The traffic light colour coding in Table 3 is used throughout the report to present the differences between diesel and gas vehicles.

Table 3: Colour coding for comparison between gas and diesel vehicles

Colour coding	
(green)	Parameter > 10% better in gas vehicle compared to diesel.
(orange)	Parameter in gas vehicle within +/-10% difference compared to diesel.
(red)	Parameter > 10% worse in gas vehicle compared to diesel

3.1 Fuel economy and range

Most dedicated gas vehicles are inherently less efficient than diesel vehicles because they use spark ignition (SI) engines, which are also used in gasoline vehicles. The compression ignition (CI) engines used in diesel vehicles are typically 15 to 30% more efficient than SI engines because their compression ratio is higher and hence, they extract more power from the fuel during expansion of the hot exhaust. The exceptions to this rule are the LNG CI Artic vehicles in the trial, which use the CI technology but require the use of some diesel to ignite the fuel mixture inside the engine cylinders.

Table 4 shows the fuel economy and range for the gas and diesel vehicles in miles per gallon of diesel equivalent (MPGe), which is a variable required to make the performance of gas and diesel vehicles comparable on an energy basis (formula in Appendix 1: Formulae). Based on Net Calorific Value (NCV), 1 kg of gas is equivalent to 1.25 litres of diesel. The diesel comparator vehicles were chosen by each fleet operator fulfilling the following criteria: similar operation and route, same Gross Vehicle Weight (GVW) and axle configuration, same Euro standard (all gas and diesel vehicles are Euro VI), and similar power rating.

The average payload percentage (defined as the ratio between the carried load and the total load capacity) and average speeds of the different types of vehicles are also shown. The substitution ratio (SR) parameter is only applicable to the LNG CI Artic vehicles and is defined as the proportion of the total amount of energy supplied by both fuels that is provided exclusively by the LNG (formula in Appendix 1: Formulae). Table 4 also shows the range that each vehicle can cover on a full tank in km. It is calculated using the average fuel consumption recorded during the trial and the tank capacity as quoted by the vehicle manufacturers.

The data for Table 4 comes from refuelling records for all vehicles except LNG CI Artics, for which these records were unavailable for the whole trial and telematics data was used instead. Refuelling records were preferred for the calculation of total trial results because a discrepancy was observed between refuelling logs and telematics data, with the telematics usually reporting less fuel usage than refuelling records. The telematics data is however still very valuable to investigate the more granular day-to-day performance of the vehicles.

Table 4: Fuel economy and range from trial vehicle in-service data: refuelling logs (SI) and telemetry data (CI)

Technology (gas vehicles and their diesel comparators)	Average speed (km/h)	Payload (% of max)	MPGe	% diff. MPGe gas vs diesel	Range (km)	% diff. range gas vs diesel	Substitution ratio (SR)
CNG SI Artic	53	26%	7.9	-28%	700	-39%	N/A
Diesel (CNG SI Artic)	62	19%	10.9		1150		
CNG SI Rigid	59	20%	10.4	-15%	850	-35%	
Diesel (CNG SI Rigid)	59	25%	12.2		1300		
LNG SI Artic	64	34%	9.2	-16%	1600	45%	
Diesel (LNG SI Artic)	64	25%	10.9		1100		
LNG CI Artic	58	41%	8.9	-3%	700-900	-36 to -18%	90%
Diesel (LNG CI Artic)	56	40%	9.2		1100		N/A

The average speed and payload values are similar between the gas vehicles and their diesel comparators, which allows a reasonable comparison between the performance of gas and diesel trucks. It must be highlighted that, even though the payload values may seem low, they are averaged for the whole trial period and include trips when the vehicles were operating empty (e.g. coming back to depot from a delivery). **The SI gas vehicles present an MPGe 15 to 28% lower than their diesel comparators, whereas for the CI gas vehicles this difference was only 3%** because they use the same engine technology as the diesel comparator. It must be noted that the difference in performance between CNG SI Artic and Rigid vehicles is not necessarily linked to the difference in body configurations, but to the difference in duty cycles and operational patterns across the trial period.

The range from the CNG vehicles is 35 to 39% lower than their diesel comparators, whereas the range from the LNG SI vehicles is 45% higher than their diesel comparators. LNG vehicles have a larger range than comparable CNG vehicles with the same axle configuration and GVW because LNG is liquified and hence carries more energy per unit of volume. Therefore, for the same volume of a fuel tank, the vehicle is able to take a higher mass of LNG than CNG.

The range from the LNG CI vehicles is however lower than their diesel comparators (even though it is LNG and not CNG) because of the space required by the LNG tanks in addition to the diesel and AdBlue tanks, which are not required in an LNG SI vehicle. The range from the 4x2 LNG CI vehicle is 18% lower than its diesel comparator, while the 6x2 LNG CI vehicle has a range 36% lower than the diesel vehicle. The range from the 6x2 truck is smaller than from the 4x2 one because, due to the additional axle in the 6x2 truck, there is less space left for the gas tank.

The daily performance of the gas vehicles and their comparators from the vehicle telematics was analysed to find correlations between speed, payload, fuel economy and SR. This analysis shows that:

- MPGe increases with average speed: the best fuel economy is achieved on high-speed long-haul trips, for which HGVs are optimised to perform at their best as opposed to inner-city trips. **An increase in daily average speed from 50 to 70 km/h involves an improvement in fuel economy of 10 to 20%.**
- The SR in the LNG CI Artics increases with average speed because the vehicles are optimised for long haul operations at high constant speeds. **An increase of daily average speed from 40 to 70 km/h produces an increase in SR of around 4%.** The higher the SR is, the more LNG is being used as opposed to diesel and, therefore, the larger the emissions and cost savings are.
- Higher payloads produce a lower MPGe because the gradient, rolling resistance and inertia forces required to move the vehicle forward are directly proportional to the mass of the vehicle. **An increase in daily average payload of 20% involves a reduction in MPGe of**

around 15%. It must be noted however that increasing the delivery payload is the most efficient way of improving the emissions and energy usage per tonne of product delivered. A more detailed analysis comparing the vehicle testing results at 60 and 100% payload can be found in Appendix 3: Test results per vehicle.

Although the trial data gives a good picture of how operating conditions affect fuel economy, it needs to be complemented with vehicle testing to understand the effects of different drive cycles and payloads. The in-service operation of the vehicles during the trial has shown that, including the time when the vehicles are running empty, they achieve a daily average payload of 20-40% and drive at a daily average speed of 55-65 km/h (rural and motorway driving). The vehicle tests were however performed at a range of different operational conditions: payloads of 50, 60 and 100% and urban, rural and motorway drive cycles. The testing methodology and results are discussed in section 4.

3.2 Greenhouse gas emissions

Gas and diesel vehicles emit several greenhouse gases (GHG) that cause global warming because they trap solar radiation within the atmosphere. The method used to calculate GHG emissions is to apply the emission factors provided by the UK government's Department for Environment, Food and Rural Affairs or DEFRA (2), which give an amount of Tank-to-Wheel (TTW) and Well-to-Tank (WTT) CO_2 equivalent emissions (CO_2e) per unit of fuel consumed. The sum of TTW and WTT emissions are the Well-to-Wheel (WTW) or total fuel life cycle emissions. For an explanation on the concepts of WTT, TTW and WTW, see Figure 2.

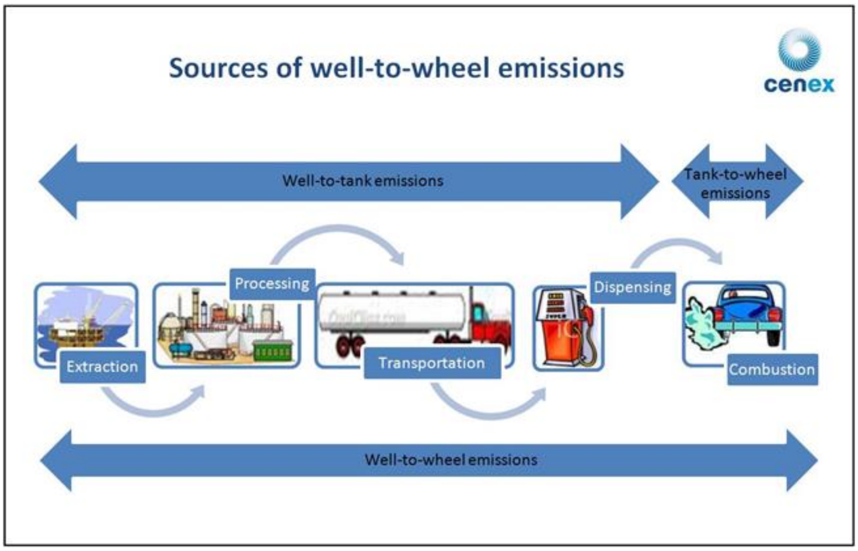

Figure 2: Sources of Well-to-Wheel emissions

Innovate UK recommended the use of this emission factors to standardise GHG reporting due to the variety of fuel sources in this trial (and the variety that any fleet would experience in the future). The DEFRA guidelines only provide emission factors for 'biomethane', the ones used in this report, and do not differentiate between bio-CNG and bio-LNG. **It is therefore recommended that future DEFRA GHG reporting guidelines provide separate emission factors for bio-CNG and bio-LNG**. However, it must be noted that the biomethane emission factor from DEFRA is quite close to that calculated by Air Liquide's Renewable Transport Fuels Obligation (RTFO) auditing process.

The GHG emission results per vehicle type are shown in Figure 3, where the percentage values above the bars represent the % change of gas and biomethane vehicles compared to diesel vehicles using the colour coding described previously. The results using 3 types of fuel are presented: "standard gas" for standard fossil natural gas, "biomethane" for 100% biomethane blend and "diesel" for the comparator vehicles.

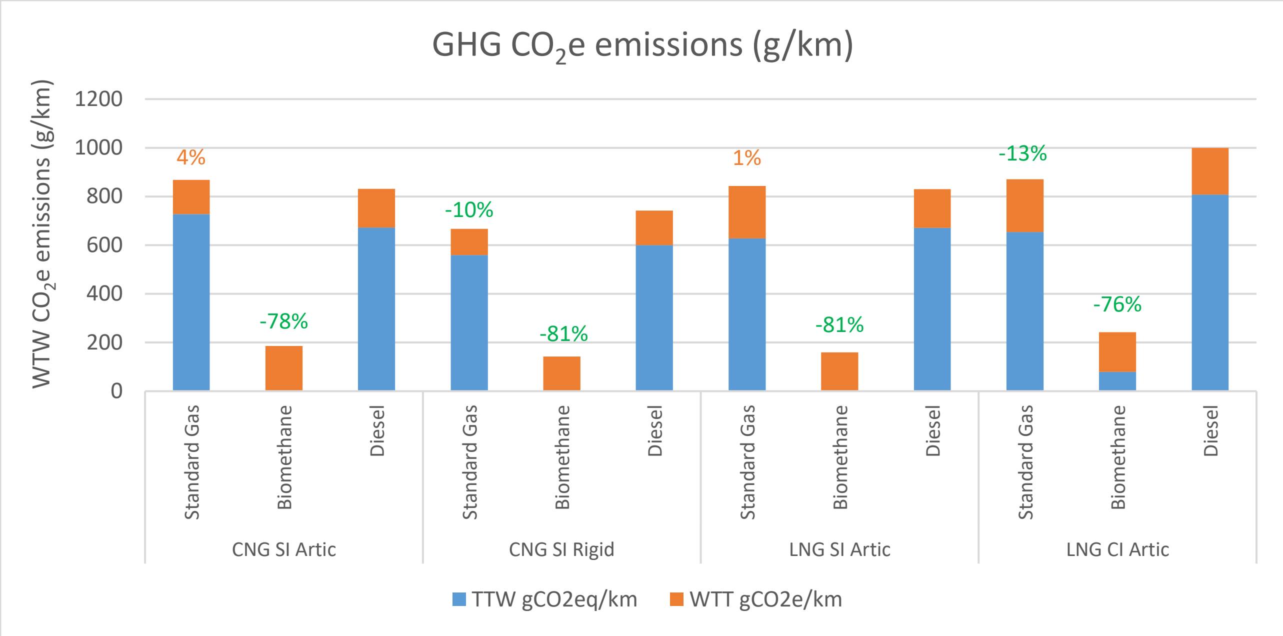

Figure 3: Trial GHG emissions from refuelling logs (SI) and telemetry data (CI)

All gas vehicles in the trial have used 100% biomethane for the majority of the time, so the GHG emission savings are significant (around 80% compared to diesel) across all vehicle types. The CNG and LNG stations used in the trial dispense standard fossil natural gas. However, in the GHG calculations this is accounted as bio-CNG or bio-LNG, which is either certified through the RTFO scheme, or by using Green Gas Certificates (GGC). These schemes work on the basis that each unit of biomethane injected into the grid displaces a unit of fossil-derived natural gas.

- The RTFO supports the government's policy on reducing greenhouse gas emissions from vehicles by encouraging the production of biofuels that don't damage the environment. Under the RTFO scheme, suppliers of transport fuel in the UK must be able to show that a percentage of the fuel they supply comes from renewable and sustainable sources. With the reduction of the Renewable Heat Incentive (RHI) for biomethane in the recent years, this scheme could act as a major driver of future development in the production of biomethane from waste in the UK. The CNG SI Artic, LNG SI Artic and LNG CI Artic vehicles run on biomethane under the RTFO scheme.
- The Green Gas Certification Scheme (GGCS) and Biomethane Certification Scheme (BMCS) also enable biomethane ('green gas') to be tracked through the supply chain, ensuring certainty for those that buy it. The CNG SI Rigid vehicles use this scheme.

In terms of its chemical composition, biomethane is very similar to natural gas. The main difference between both gases lies on the process of obtaining the fuel. While standard natural gas is a fossil fuel extracted from marine or terrestrial reserves, biomethane is produced via anaerobic digestion of organic matter (e.g. food waste or landfill gas). These processes produce gas that, when combusted, only produces biogenic CO_2, which does not contribute to the greenhouse effect because this CO_2 is absorbed by the source of the fuel when the original biological material was growing (3). Hence, the TTW emissions from biomethane are zero while the WTT emissions account for the electricity used in the biogas purification, feedstock transport and methane slip in the biogas and biomethane production.

The use of standard fossil natural gas would yield GHG emission savings ranging from 13% to increases of 4% compared to diesel depending on the vehicle type. Therefore, once the trial is finished, the gas vehicles need to run on a blend of biomethane in order to make significant GHG emissions savings. A sensitivity analysis is shown in Table 5 with the % difference in GHG WTW CO_2e emissions across different vehicle types and biomethane blends (e.g. B25 means a fuel mix of 25% biomethane and 75% standard fossil natural gas).

Table 5: Sensitivity on GHG emission savings depending on bio-blend

% WTW Greenhouse difference: gas vs diesel vehicles				
Biomethane blend	**CNG SI Artic**	**CNG SI Rigid**	**LNG SI Artic**	**LNG CI Artic**
B0 (Fossil natural gas)	4%	-10%	1%	-13%
B25	-17%	-28%	-19%	-29%
B50	-37%	-45%	-40%	-45%
B75	-58%	-63%	-60%	-60%
B100 (100% biomethane)	-78%	-81%	-81%	-76%

All vehicles would make at least 17% GHG emission savings with a B25 blend, but a B100 blend yields savings of at least 76%. The reason why the savings are the least for the LNG CI vehicle is that this vehicle uses diesel too, which was assumed to be standard forecourt diesel (not biodiesel). Table 6 shows the total distance covered by the gas vehicles in the trial and the total amount of GHG emissions per vehicle type. The emissions for the diesel vehicles have been calculated assuming they drove the same distance as the gas vehicles in order to calculate the total amount of GHG savings made by the gas vehicles in tonnes of CO_2e.

Table 6: Total trial distance and GHG emissions from refuelling logs (SI) and telemetry data (CI)

Technology		Total km by gas vehicles	Tonnes TTW CO_2e	TTW Savings vs diesel (tonnes CO_2e)	Tonnes WTW CO_2e	WTW Savings vs diesel (tonnes CO_2e)
CNG SI Artic	Standard Gas	1,019,003	742	-57	884	-37
	Biomethane	1,019,003	1	683	189	658
	Diesel	1,019,003	685		848	
CNG SI Rigid	Standard Gas	689,018	386	27	460	52
	Biomethane	689,018	1	412	98	413
	Diesel	689,018	413		511	-
LNG SI Artic	Standard Gas	398,851	250	18	336	-5
	Biomethane	398,851	1	267	64	268
	Diesel	398,851	268		331	
LNG CI Artic	Standard Gas	121,153	79	19	105	16
	Biomethane	121,153	10	88	29	92
	Diesel	121,153	98		121	
TOTAL (STANDARD GAS)		**2,228,025**		**7**		**26**
TOTAL (BIOMETHANE)		**2,228,025**		**1451**		**1431**

The trial vehicles travelled over 2.2 million km saving over 1,400 tonnes of WTW CO_2e. In order to put these large figures into context, **all the biomethane trial vehicles have driven 5.8 times the distance between the Earth and the Moon**, which is equivalent to 56 times around the globe. As the trial trucks used a 100% bio-blend for the majority of the time, **they have displaced the WTW GHG emissions from 16 diesel vehicles**. This equates to the CO_2 absorbed by the lifetime of around 3,150 trees, which would occupy a forest equivalent to the area of 18 football pitches.

3.3 Vehicle reliability

Several maintenance and reliability data items were provided by the fleet operators: event type (planned/unplanned), event description, fault duration, gas related fault (yes/no). Using this data for each vehicle in the trial, we were able to compare the maintenance requirements and reliability of gas vehicles against diesel vehicles. Figure 4 indicates the annual number of maintenance events per vehicle split into planned and unplanned, including a further separation for unplanned events to highlight those related to gas systems. Note that the unplanned faults exclude body damage due to road accidents for both gas and diesel vehicles as they are irrelevant to this analysis. The percentage figures over the bars represent the % difference in total number of events compared to diesel.

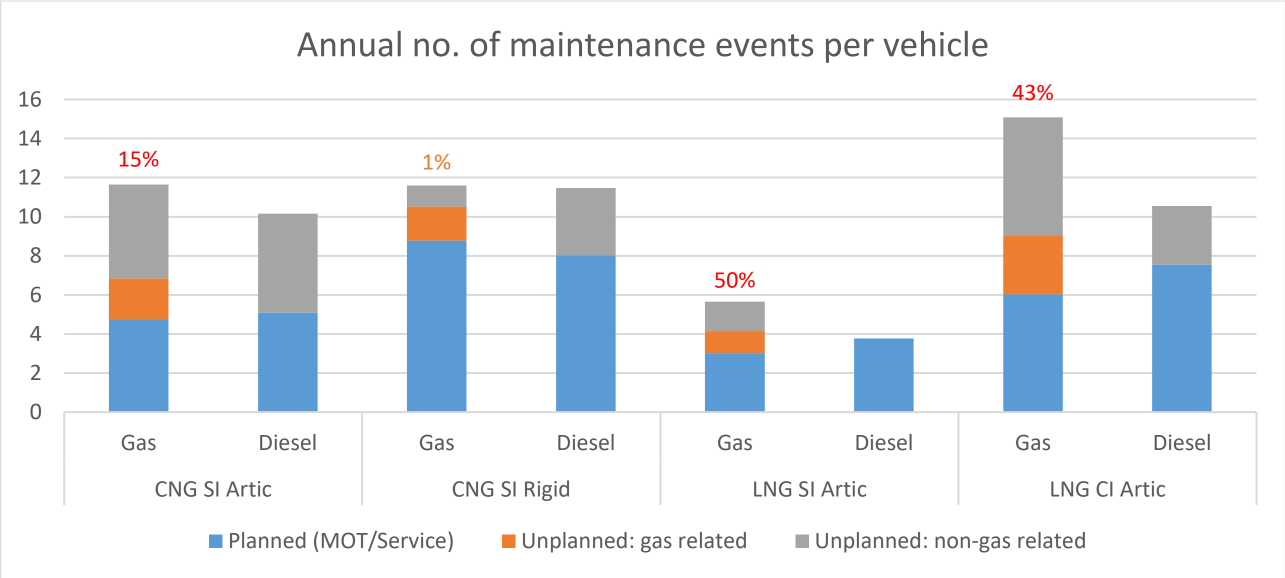

Figure 4: Number of maintenance events per vehicle and year

The number of annual maintenance events is similar or higher in gas vehicles compared to diesel vehicles, with a roughly equal split between planned and unplanned events. In the gas vehicles, **26% of the total number of unplanned faults were related to the gas systems:** generic gas faults, gauge/valve faults, faulty leakage sensors and emission faults. This figure **compares to the 13% of the total number of unplanned faults that were related to the diesel systems in the comparator vehicles**. This small difference between gas and diesel vehicles could be related to the lower market maturity of the gas vehicles. Figure 5 shows the fault duration in days per year and vehicle, where the percentage over the bars is the difference of gas against diesel vehicles.

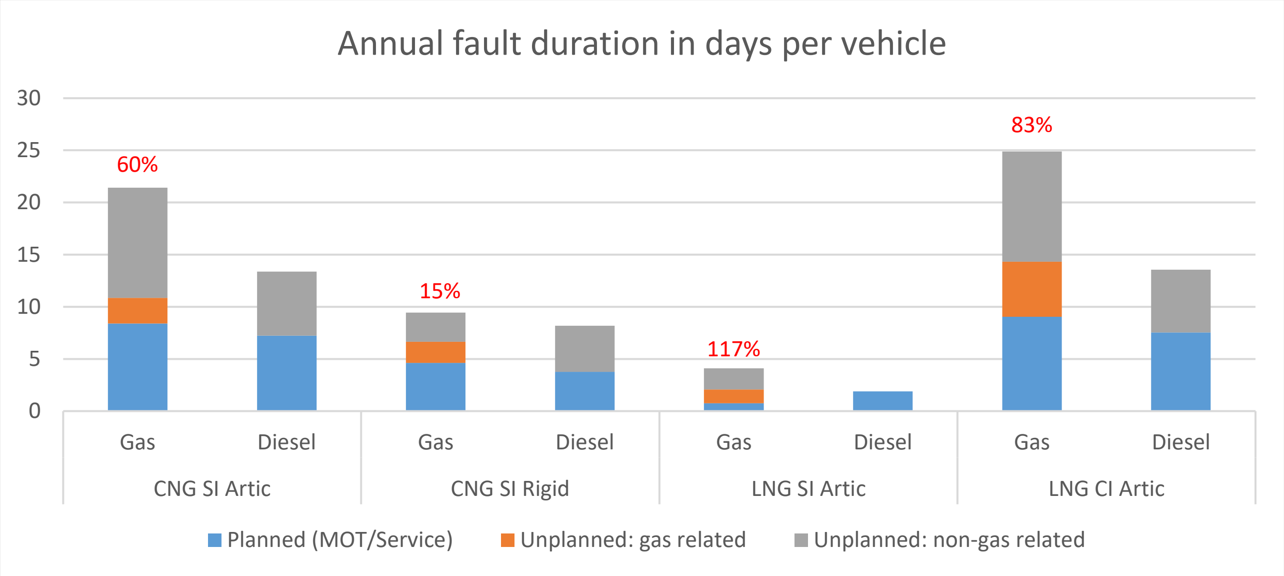

Figure 5: Fault duration per vehicle and year

The general trend is that **it takes longer to repair and service the gas vehicles against the diesel vehicles mainly due to the lower level of market maturity in the UK**. As gas vehicles become more common the availability of parts and time taken to repair faults should improve. The planned maintenance events are MOT and regular servicing, while the reasons for the unplanned faults are various and their annual frequency per gas vehicle is shown in Figure 6.

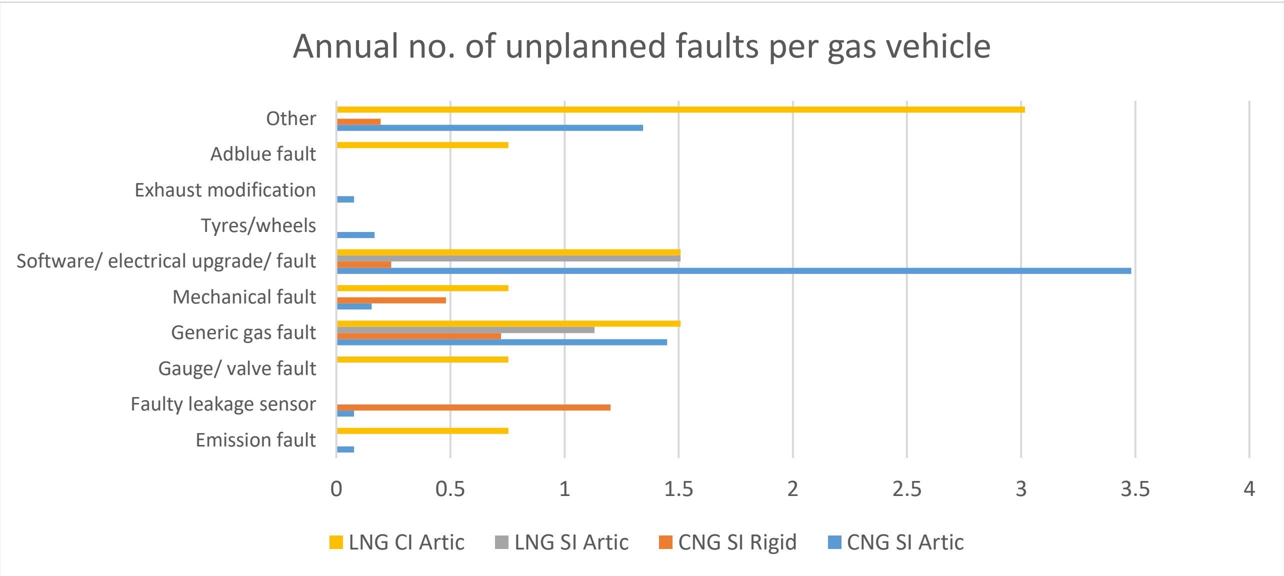

Figure 6: Number of unplanned faults per gas vehicle and year

The most frequent types of unplanned faults in gas vehicles are software and electrical faults (such as various malfunctioning lights or broken airlines) and generic gas faults.

3.4 Driver perceptions

The gas vehicle drivers filled in pre-trial surveys to indicate their expectations of gas vehicles, plus mid-trial and post-trial surveys to show the progression of their experience with the gas vehicles. In these surveys they also expressed their attitudes and opinions towards gas vehicles and the environment. Figure 7 and Figure 8 show the demographic distribution of the drivers that have completed the questionnaires.

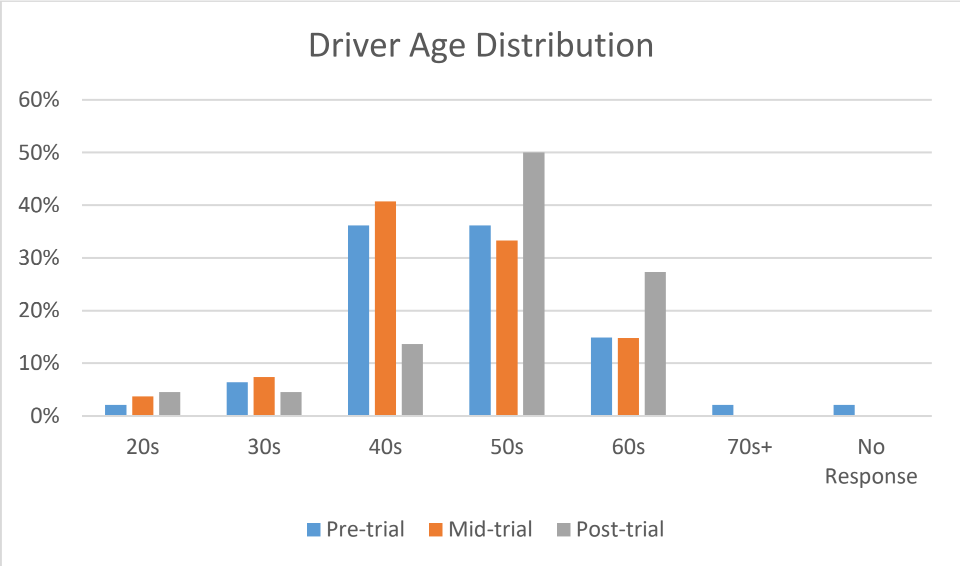

Figure 7: Driver age demographics

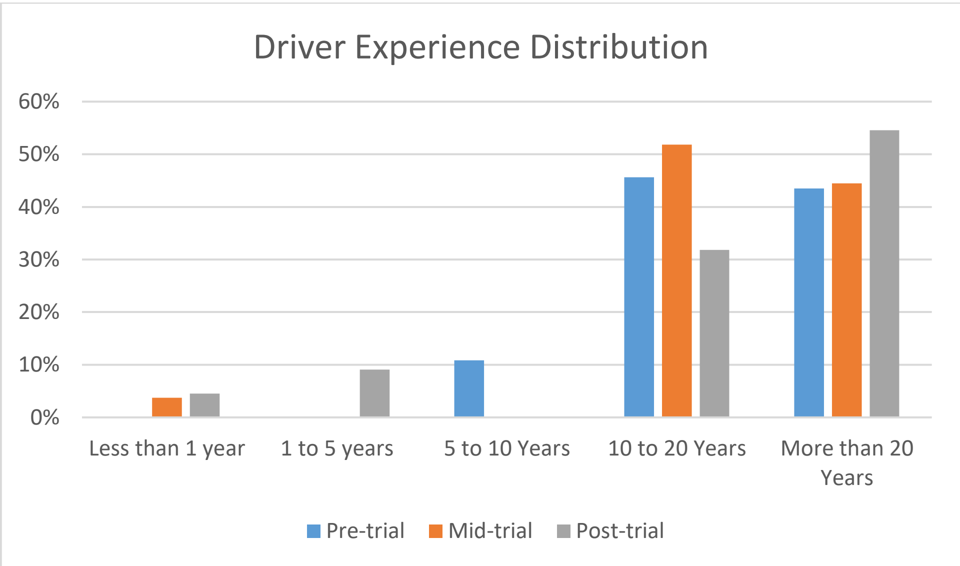

Figure 8: Driver experience demographics

Most of the gas vehicle drivers are over 40 and have driven trucks for at least 10 years. A total of 47 drivers filled in the pre-trial questionnaires, while 27 drivers filled in the mid-trial ones and 22 the post-trial ones. The difference in participation between pre-trial and the other 2 questionnaires happened because some drivers did not know whether they would be driving the gas vehicles regularly and filled the surveys to be on the safe side. The following sub-sections show the analysis of these surveys broken down by vehicle type and focusing on the performance aspects of the vehicles. For the results on the drivers' attitudes and opinions towards gas vehicles and the environment please refer to Appendix 2: Driver attitudes towards gas vehicles and the environment.

3.4.1 CNG SI Artic

The following spiderweb graph in Figure 9 represents how the drivers rated the gas vehicles compared to the diesel ones in different aspects of their performance. Because the mid-trial results were very similar to the post-trial ones, they were omitted from this graph.

Key	
5	Much Better
4	Better
3	Same as diesel
2	Worse
1	Much Worse

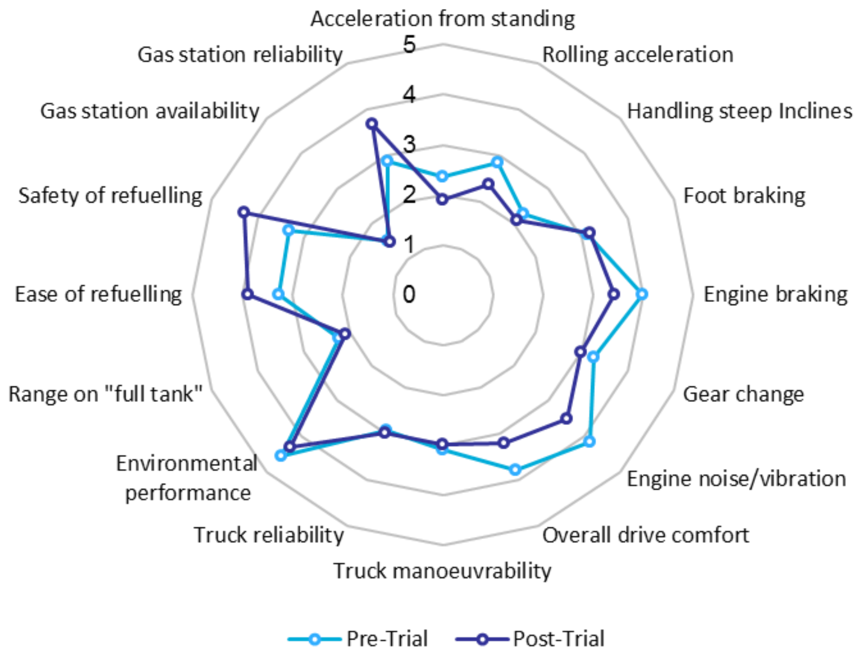

Figure 9: Driver ratings for CNG SI Artic

The poorest ratings for the gas vehicles both pre and post-trial were for range on a full tank (CNG vehicles currently have a smaller range than LNG vehicles) and number of gas stations available. Most of the vehicle-related category ratings decreased slightly from pre to post-trial. However, the drivers' perception of safety, ease and reliability of refuelling improved considerably along the trial. The categories where gas vehicle and stations were regarded as better than their diesel comparators were safety and ease of refuelling, environmental performance, engine noise / vibration and engine braking. Table 7 below shows the level of vehicle performance and range anxiety as per the indicated key.

Table 7: Level of range and vehicle performance anxiety from CNG SI Artic

Key	
5	Very High
4	High
3	Medium
2	Low
1	None

	Pre → Mid → Post
Average Level of Vehicle Performance Anxiety (i.e. fear of the vehicle not being able to perform the job)	**2.9 → 2.7 → 2.3**
Average Level of range Anxiety (i.e. fear of not making the destination due to restricted vehicle range)	**3.2 → 3.3 → 3.0**

The level of vehicle performance anxiety has consistently decreased along the trial from medium to low, while the level of range anxiety has stayed at medium levels along the trial.

3.4.2 CNG SI Rigid

Figure 10 below shows the driver ratings for the CNG SI Rigid; in this case the mid-trial results were not omitted due to the variance of results along the trial.

Key	
5	Much Better
4	Better
3	Same as diesel
2	Worse
1	Much Worse

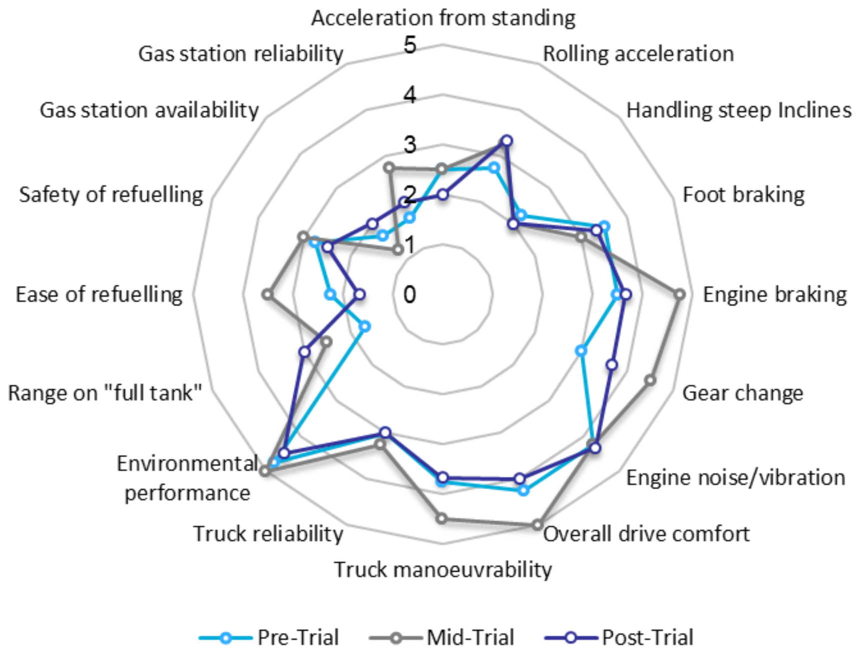

Figure 10: Driver ratings for CNG SI Rigid

Engine braking and noise, gear change, manoeuvrability and environmental performance were regarded as better than diesel. However, the power performance (steep inclines and acceleration from standing) and the refuelling aspects were rated as worse than the diesel equivalents. The ratings improved significantly from pre to mid-trial and then decreased in the post-trial surveys, probably because drivers were more used to driving the gas vehicles at the end of the trial than at the mid-trial point. Table 8 below shows the level of vehicle performance and range anxiety as per the indicated key.

Table 8: Level of range and vehicle performance anxiety from CNG SI Rigid

Key	
5	Very High
4	High
3	Medium
2	Low
1	None

	Pre → Mid → Post
Average Level of Vehicle Performance Anxiety (i.e. fear of the vehicle not being able to perform the job)	**3.0 → 3.3 → 2.5**
Average Level of range Anxiety (i.e. fear of not making the destination due to restricted vehicle range)	**3.3 → 2.7 → 2.5**

The levels of vehicle performance and range anxiety have decreased from medium to low/medium along the trial.

3.4.3 LNG SI Artic

The graph in Figure 11 represents how the drivers rated the gas vehicles compared to the diesel ones in different aspects of their performance. Because the mid-trial results were very similar to the post-trial ones, they were omitted from this graph.

Key	
5	Much Better
4	Better
3	Same as diesel
2	Worse
1	Much Worse

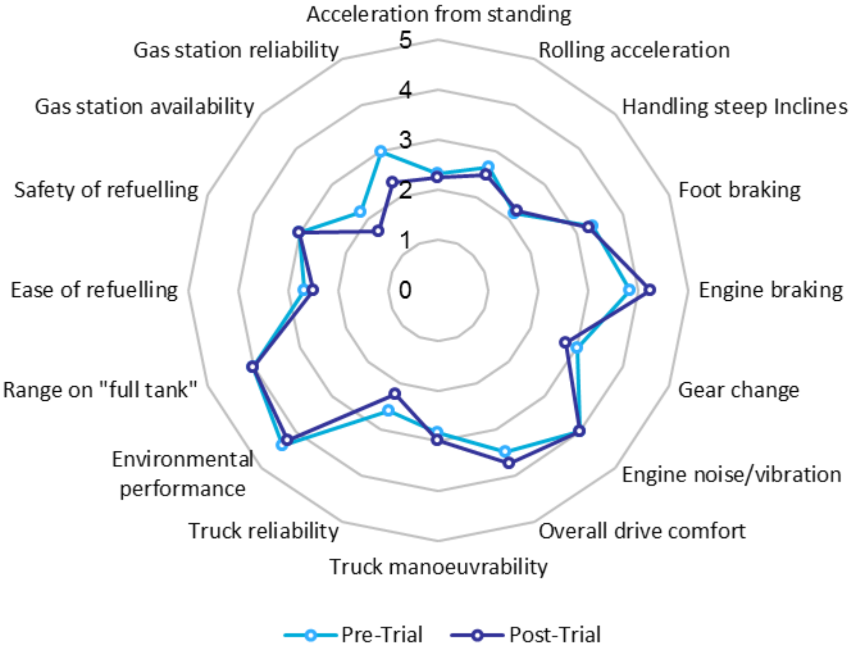

Figure 11: Driver ratings for LNG SI Artic

The driver ratings remained the same from pre to post-trial in most categories. There are several aspects of gas vehicles that were rated better than the diesel vehicles: range on a full tank (LNG trucks currently have a longer range compared to CNG and diesel trucks), environmental performance, engine noise / vibration, engine braking and overall driving comfort. The LNG vehicles performed worse than diesel in handling steep inclines, acceleration from standing and availability of gas stations. Table 9 below shows the levels of performance and range anxiety.

Table 9: Level of range and vehicle performance anxiety from LNG SI Artic

Key	
5	Very High
4	High
3	Medium
2	Low
1	None

	Pre → Mid → Post
Average Level of Vehicle Performance Anxiety (i.e. fear of the vehicle not being able to perform the job)	**1.5 → 2.5 → 3.0**
Average Level of range Anxiety (i.e. fear of not making the destination due to restricted vehicle range)	**1.5 → 1.8 → 1.8**

The levels of vehicle range and performance anxiety were at low / very low levels pre-trial, but the fear of the vehicle not being able to perform the job increased to medium levels due to isolated unplanned faults during the trial. The level of range anxiety (not being able to reach destination) only increased slightly and remained between low and very low along the trial.

3.4.4 LNG CI Artic

The spiderweb graph in Figure 12 represents the performance ratings of the gas vehicles compared to the diesel ones. Only the mid and post-trial survey results are included because these vehicles were introduced to the trial when they were already operational in the fleet.

Key	
5	Much Better
4	Better
3	Same as diesel
2	Worse
1	Much Worse

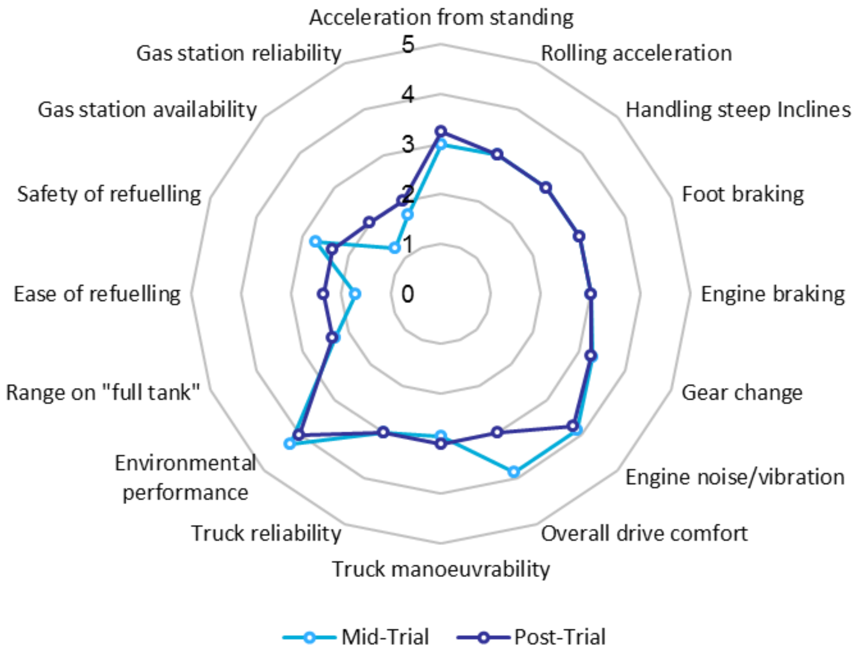

Figure 12: Driver ratings for LNG CI Artic

Most of the vehicle-related categories have been rated as same as diesel (which makes sense as both diesel and LNG vehicles share the same engine technology), with little change between mid and post-trial. Engine noise and environmental performance were regarded as better than diesel, whilst the LNG refuelling-related aspects were viewed as worse than diesel refuelling. Table 10 below shows the level of vehicle performance and range anxiety as per the indicated key.

Table 10: Level of range and vehicle performance anxiety from LNG CI Artic

Key	
5	Very High
4	High
3	Medium
2	Low
1	None

	Mid → Post
Average Level of Vehicle Performance Anxiety (i.e. fear of the vehicle not being able to perform the job)	**2.7 → 2.2**
Average Level of range Anxiety (i.e. fear of not making the destination due to restricted vehicle range)	**3.1 → 2.2**

Both levels of anxiety were at medium values in the mid-trial point but have decreased to low values thanks to the familiarisation of the drivers with the vehicles.

3.4.5 Summary of driver perceptions

As a general trend across all surveys, gas vehicles perform better than diesel comparators in the following categories: engine noise / vibration, overall driving comfort, engine braking and environmental performance. However, SI gas vehicles were rated worse than diesel in these categories: handling steep inclines, acceleration from standing and number of gas stations available. CI gas vehicles were rated as similar to diesel in the power aspects (inclines and acceleration) but worse than diesel in number of stations available. Regarding the range on a full tank, the ratings were different depending on the vehicle type: while LNG SI Artic was regarded as better than diesel, the rest of the gas vehicles were rated as worse than diesel in this aspect. Figure 13 and Figure 14 below show where the average post-trial performance of SI and CI gas vehicles sit in the rating scale when compared to diesel vehicles.

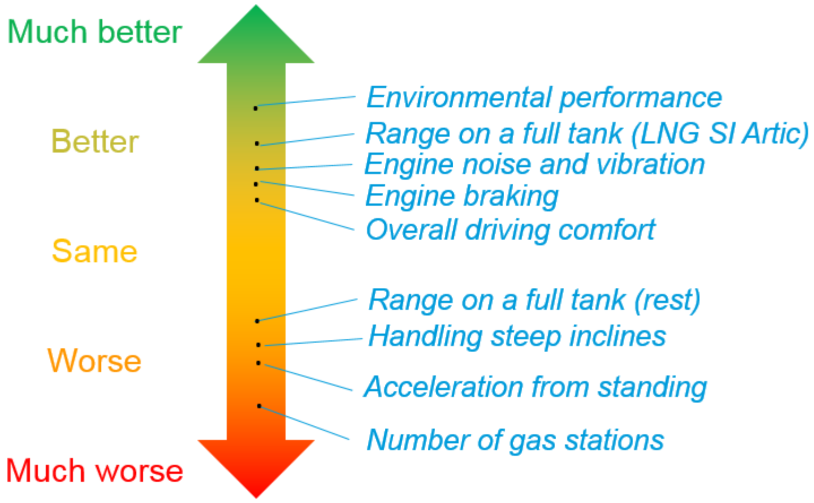

Figure 13: Summary of performance ratings in SI gas vehicles compared to diesel

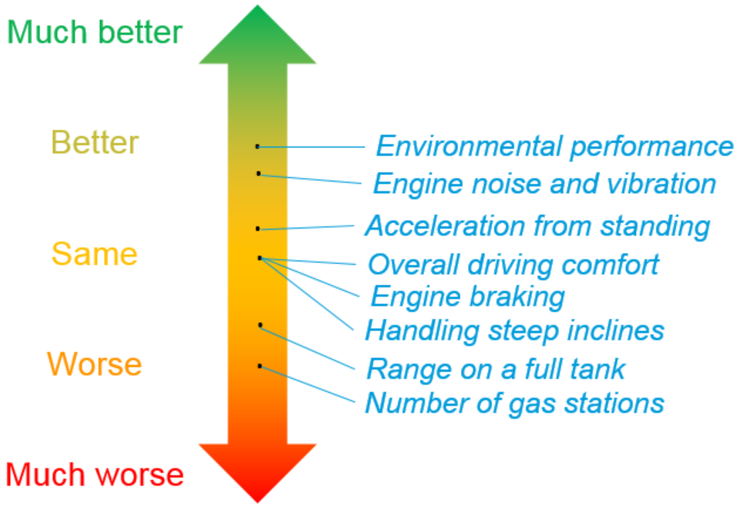

Figure 14: Summary of performance ratings in CI gas vehicles compared to diesel

4 Vehicle testing

This section shows the methodology and results of the vehicle tests performed as part of the project.

4.1 Testing procedure

In-service driving of the vehicles on the road involves a wide range of operational conditions such as payload, driving style, weather and road surface. Although the operational performance of the vehicles in the trial is important and needs to be monitored, there is also a need to measure the emissions and fuel consumption of the vehicles in a controlled environment. For the most accurate comparison between technologies to take place, both diesel and gas vehicles must perform the same drive cycle in the same testing facility and under similar weather conditions. To that end, 2 different sets of tests are taking place as part of the project:

1. Tests performed by Emissions Analytics at the HORIBA MIRA tracks using Portable Emissions Measuring Systems (PEMS). These tests were performed at both 60 and 100% payloads to investigate emissions at a range of operating conditions.
2. Tests performed at Millbrook and commissioned by Cenex on a chassis dynamometer at 50% payload. These tests were included to measure N_2O and mass of particulate matter (PM) as these measurements were unavailable in the PEMS tests. N_2O cannot practically be measured with the current PEMS technology and particulate number (PN) was prioritised over PM as both were unavailable for simultaneous PEMS measurement.

Other tests external to this project consortium were commissioned by TRL on behalf of Innovate UK as part of LEFT and they were performed at Millbrook both on a chassis dynamometer and on the track using PEMS. The vehicle technologies used in these tests were also deployed in the Dedicated to Gas trial, but the results from the tests are not shown in this report because they will be published in the LEFT end-of-project report in 2020.

Table 11 indicates the testing schedule and the specifications of the gas vehicles and the comparators used in the tests. An old and a new generation version of the CNG SI Rigid vehicle were tested, but the new generation version of their diesel comparator was unavailable. Therefore, the old generation diesel vehicle was used as it was the only available baseline. It was however considered a valid comparator vehicle because the old and new generation diesel vehicles were manufactured only 2 years apart and they still share the same Euro VI standard and technical specifications. The 4x2 version of the LNG SI Artic was used because the 6x2 version was unavailable, but the comparison between gas and diesel remains valid as it was ensured that both vehicles had the same GVW during tests.

Table 11: Vehicle testing schedule

Technology (gas vehicles and their diesel comparators)	GVW (tonnes)	Axle configuration	Engine power (bhp)	Emission standard	1. Emissions Analytics - PEMS	2. Millbrook - Dynamometer
CNG SI Rigid (old gen)	26	6x2	340	Euro VI		Jan-18
Diesel (CNG SI Rigid, old gen)	26	6x2	360	Euro VI	Aug-19	Jan-18
CNG SI Rigid (new gen)	26	6x2	340	Euro VI	Aug-19	Aug-19
Diesel (CNG SI Rigid, new gen)	Vehicle unavailable. Old generation diesel vehicle used as comparator.					
LNG SI Artic	40	4x2	460	Euro VI	Oct-18	
Diesel (LNG SI Artic)	44	6x2	460	Euro VI	Oct-18	
LNG CI Artic	44	6x2	460	Euro VI	Jun-19	
Diesel (LNG CI Artic)	44	6x2	460	Euro VI	Jun-19	

4.1.1 Dynamometer tests

The chassis dynamometer tests were performed in Millbrook's Variable Temperature Emissions Chamber (VTEC), which allows to test all vehicles at 23 degrees C. The tested drive cycle was the World Harmonised Vehicle Cycle (WHVC, Figure 15), which was driven on a single axle dynamometer at 50% payload. In these tests, the analysed exhaust gases are total hydrocarbons (THC), CO, NO_x, CO_2, PM, particulate number (PN), N_2O and CH_4 (methane slip).

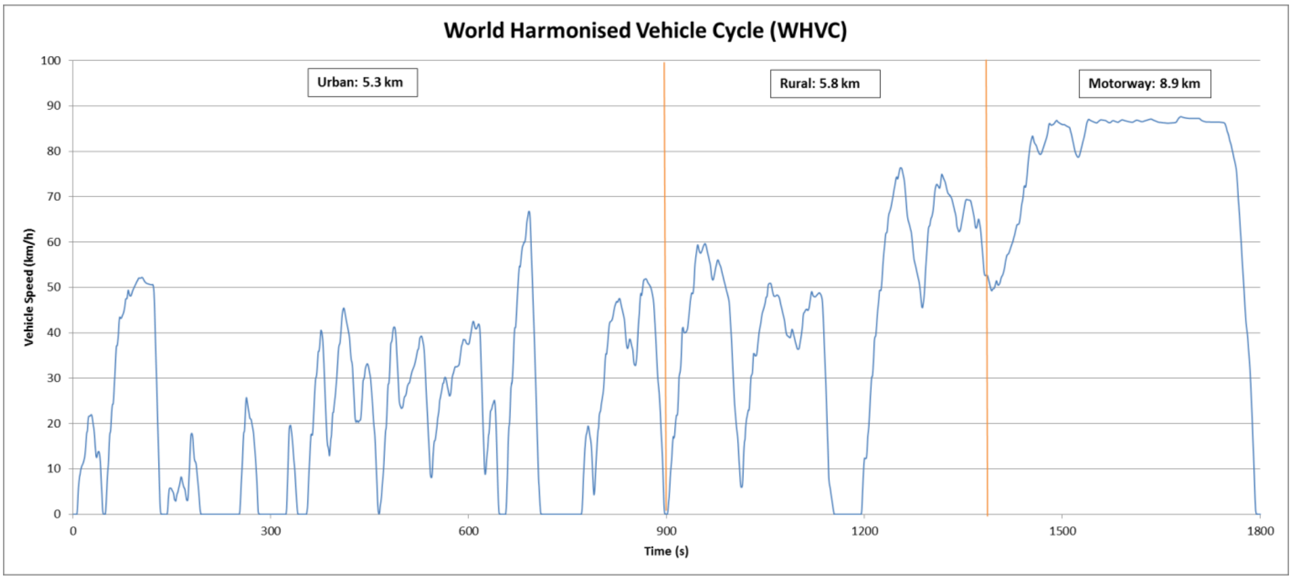

Figure 15: World Harmonised Vehicle Cycle (WHVC)

4.1.2 PEMS tests

The PEMS tests were performed by Emissions Analytics at the HORIBA MIRA tracks at 60% payload (as recognised by the industry to be the average UK payload) and at 100% payload. As shown in Figure 16, in this type of tests the equipment is attached to the vehicle tailpipe to measure the same exhaust gases as in the dynamometer tests except for N_2O and PM for the reasons explained above.

Figure 16: Fitting of PEMS equipment

The PEMS test drive cycles performed as part of the LEFT projects are determined according to the LowCVP HGV Accreditation Scheme. As per the procedure detailed in (4) and (5), the vehicles have to follow a standard procedure and 4 drive cycles: Long Haul, Regional Delivery, Urban Delivery and

City Centre Delivery. The City Centre Delivery cycle is only recommended for rigid trucks, but it was not tested for the CNG SI Rigids because these vehicles did not perform this type of operation during the in-service trial. Each of these drive cycles must have a kinetic intensity (KI) within certain boundaries, which match the KI of the European Commission's Vehicle Energy Consumption Calculation TOol (VECTO). As defined in (6), KI is a non-dimensional factor that characterises the changes in speed and elevation over time for any given duty cycle. The KI of the drive cycles will slightly vary depending on the testing location, as well as other drive cycles statistics that must be within certain limits as per Table 12. The specific drive cycles tested by Emissions Analytics at the HORIBA MIRA tracks are shown in Figure 17, Figure 18 and Figure 19.

Table 12: LowCVP PEMS drive cycle requirements

	Long Haul	Regional Delivery	Urban Delivery	City Centre Delivery
Distance (km)	> 20	> 7.5	> 7.5	> 4.0
Average speed (km/h)	> 65	50 – 60	30 – 45	15 – 25
Stops/km	< 0.2	0.2 – 0.7	0.8 – 1.2	> 1.2
Aerodynamic speed (km/h)	75 – 85	65 - 75	50 – 60	20 – 30
Characteristic acceleration (m/s^2)	0.07 – 0.09	0.09 – 0.13	0.12 – 0.25	0.12 – 0.25
Kinetic Intensity (per km)	0.14 – 0.18	0.20 – 0.36	0.70 – 1.10	2.50 – 3.10

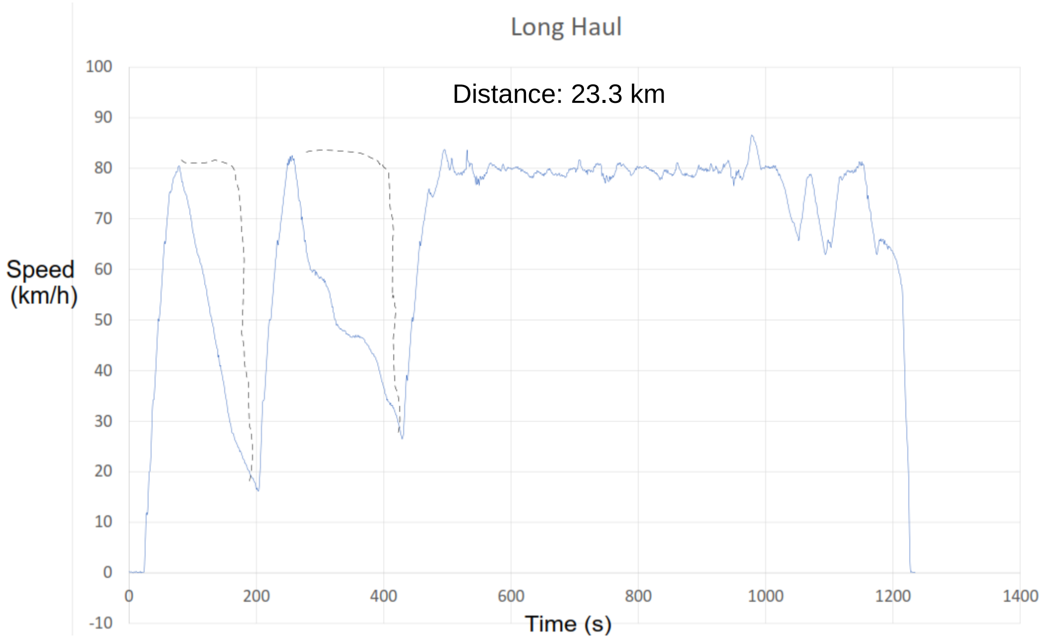

Figure 17: LowCVP MIRA Long Haul drive cycle (blue line)

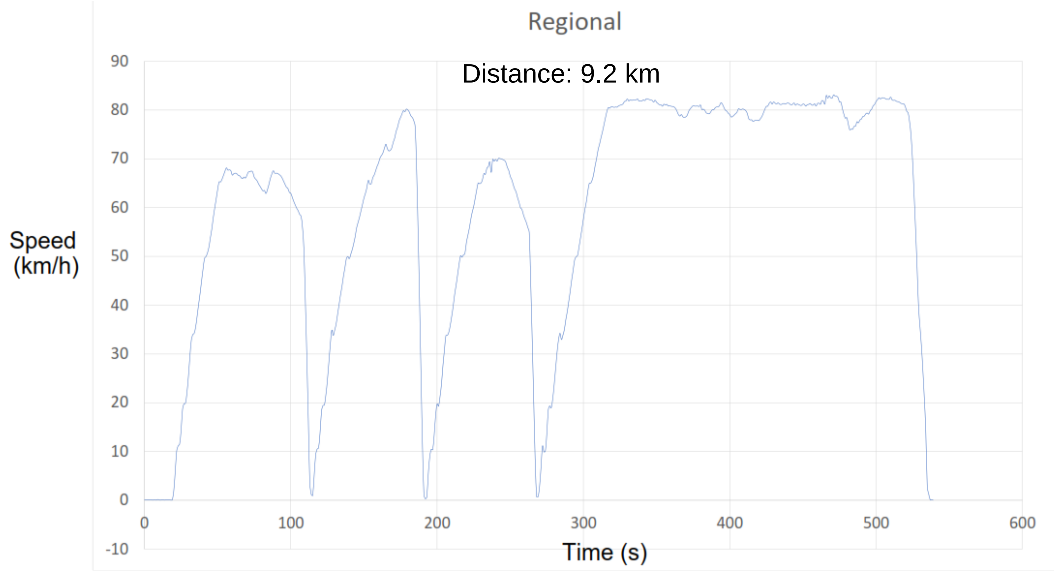

Figure 18: LowCVP MIRA Regional drive cycle

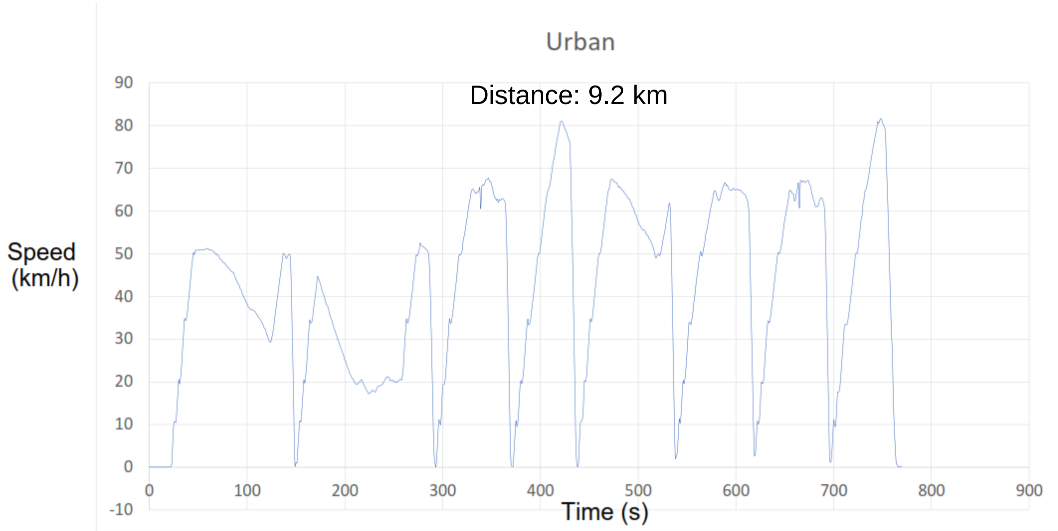

Figure 19: LowCVP MIRA Urban drive cycle

The following 2 assumptions were made during the PEMS data analysis:

- The diesel comparator of the LNG SI Artic was not provided with an aero package while the gas vehicle and all the rest of the tested vehicles had one. Therefore, the fuel economy and GHG emission results for the diesel comparator of the LNG SI Artic were corrected using the coast-down data provided by TRL from the other LEFT tests on this diesel vehicle.
- The diesel consumption in the LNG CI Artic was not measured, so we assumed the same SR as in the data provided by TRL from the other LEFT tests on the same vehicle (these tests were performed at 60% payload on equivalent drive cycles).

4.2 Summary of test results

The following graphs show a summary of the results for all the types of tests and vehicles. For the individual test results from each vehicle, please refer to Appendix 3: Test results per vehicle.

4.2.1 Fuel economy

Figure 20 shows the difference in MPGe between gas and diesel vehicles, where the positive values (green arrow above the x axis) indicate a better MPGe for gas compared to diesel. Note that when the difference is 0%, the bar is not shown on the graph. The amount of fuel consumed was obtained via the carbon balance method from the tested emissions. The data collected from the in-service trial (as per section 3.1) has been added to this graph via the red diamonds to compare the results from tests in controlled conditions to those of the variable nature of day-to-day operation of the vehicles.

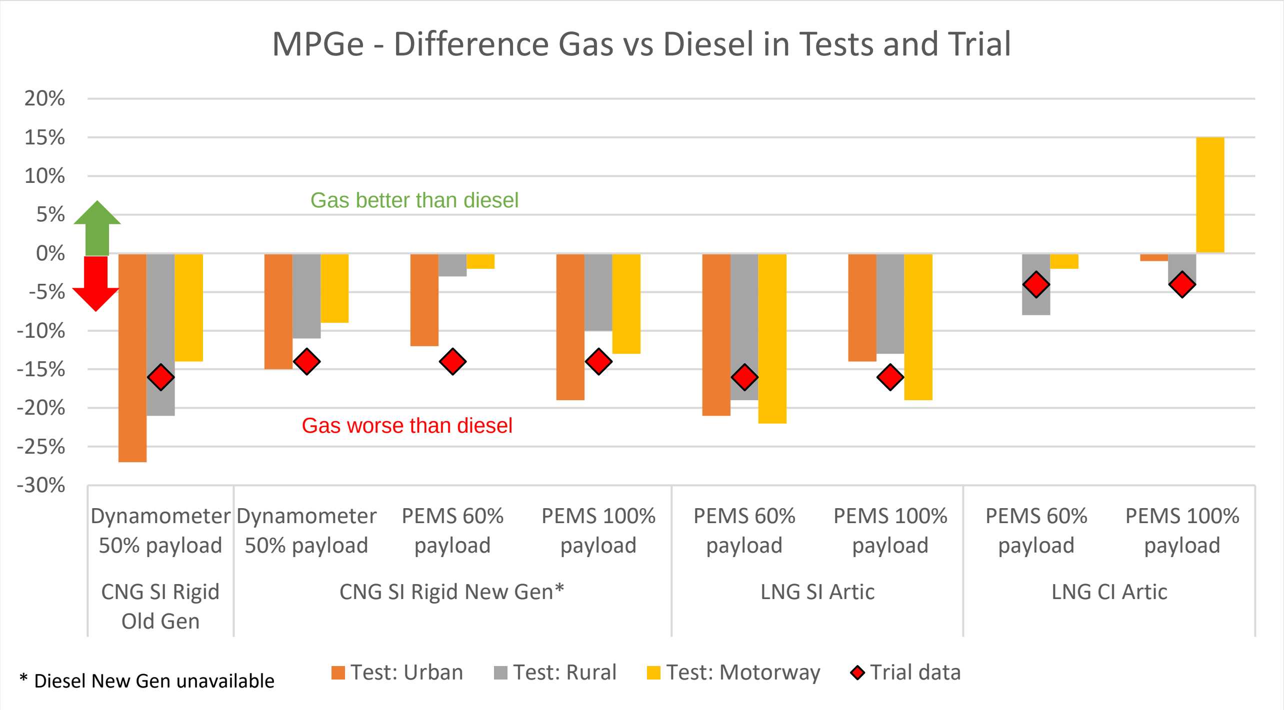

Figure 20: Summary of tested MPGe results

It must be noted that the CNG SI Rigid New Gen vehicle is compared in this graph against the old generation version of the diesel vehicle. Although it is a valid comparator vehicle, this can explain the small efficiency drop in the PEMS 60% payload tests conducted in this vehicle. However, the positive conclusion that can be extracted from these results is the **significant performance improvement in the CNG SI Rigid New Gen vehicle compared to the Old Gen** version of the same vehicle.

As a general trend, the trial data is consistent with the test data, with the trial data values located around the tested rural and motorway values, which matches well the duty cycles performed by the trucks in the on-road trial. Generally, **the % difference in MPGe gets reduced as the payload increases** (except for the CNG SI Rigid vehicle at 100% payload). To support this conclusion, a more in-depth comparison between the 60 and 100% payload test results is shown in Appendix 3: Test results per vehicle. **The % MPGe difference also tends to decrease when moving from urban to motorway cycles,** which is a positive outcome as rural and motorway drive cycles represent 88% of the distance covered by UK HGV fleets (1) as well as the specific operation in this trial. The LNG CI Artic presents a small % difference in fuel economy both in the test data and the trial data because it uses the same engine technology as the diesel comparator vehicle. However, the 15% improvement in fuel economy in the motorway cycle at 100% payload is not in line with the in-service trial data and the other LEFT tests and should not be considered as conclusive. This vehicle was tested in this other round of tests and the test results will be published in 2020.

4.2.2 Greenhouse gas emissions

Figure 21 below shows the % difference in WTW GHG CO_2e emissions between standard fossil gas (0% bio-blend) and diesel from both tests and in-service trial (as per section 3.2), where the negative values (green arrow below the x axis) indicate better GHG emissions for gas compared to diesel. Note that when the difference is 0%, the bar is not shown on the graph. In the dynamometer tests, the GHG TTW CO_2e emissions were calculated using the amount of CO_2, N_2O and CH_4 measured at the tailpipe as these are the 3 greenhouse gases emitted by gas and diesel vehicles. The WTW value was then obtained by adding the TTW emissions to the WTT UK government factors (2) applied to the fuel consumed. CO_2e emissions consider the fact that N_2O and CH_4 have 265 and 28 times the global warming potential of CO_2 respectively for a 100-year time horizon (7). In the PEMS tests, because N_2O measurements were unavailable, both the TTW and WTW UK government factors were directly applied to the fuel consumed. The biomethane results have been omitted from this graph as the savings would be of around 80% without a big difference between drive cycles and vehicles.

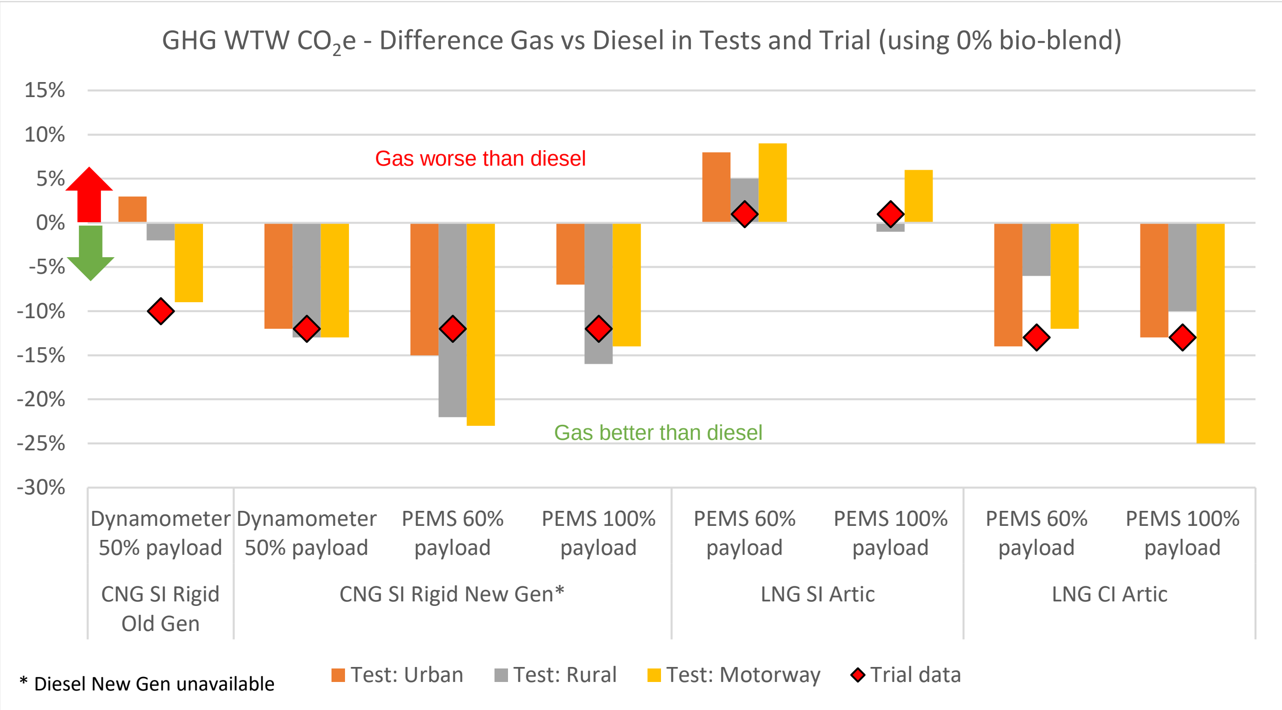

Figure 21: Summary of tested GHG emissions

The trial data sits in well again within the range of tested GHG values. CNG SI Rigid Old Gen and LNG SI Artic present GHG savings ranging from 9 to -9% depending on drive cycle and payload. CNG SI Rigid New Gen presents GHG savings ranging from 7 to 23% with the caveat that it is being compared against the old generation version of the diesel vehicle. LNG CI Artic shows large improvements in GHG emissions compared to diesel (6 to 14%) due to the low efficiency losses from the CI engine technology. However, the 25% improvement in GHG emissions in the motorway cycle at 100% payload is not in line with the in-service trial data and the other LEFT tests and should not be considered as definitive. This vehicle was tested in this other round of tests and the test results will be published in 2020. The higher end of these ranges of GHG savings match the long haul and regional drive cycles, which represent 88% of the distance covered by UK HGV fleets (1) as well as the particular operation in this trial.

N_2O emissions could only be measured on the dynamometer, so they were measured only for the rigid vehicles. **The N_2O contribution to WTW GHG emissions was 5, 3 and 1% for urban, rural and motorway phases in the diesel vehicle and 0% for the CNG vehicles.** CH4 (methane slip) was measured for both PEMS and dynamometer tests, showing that **the WTW GHG contribution from methane slip was 0 to 1% in the gas vehicles and 0% in the diesel vehicles**.

4.2.3 Air quality emissions

Figure 22 and Figure 23 below show the tested NOx emissions for all gas and diesel vehicles including a comparison against the Euro VI diesel values obtained from the COPERT tool. This simulation tool is developed by Emisia and funded by the European Environment Agency (EEA), and it calculates NOx and PM emission factors in g/km based on vehicle type (body and Euro Standard), average speed, payload and road gradient. The tested NOx results were not compared against the regulatory Euro standard limits as these are obtained from engine test beds in emissions per kWh rather than whole vehicle tests, hence a direct comparison cannot be made. Please note that the same size is used in the Y axis of both graphs to enable a better comparison across all vehicles.

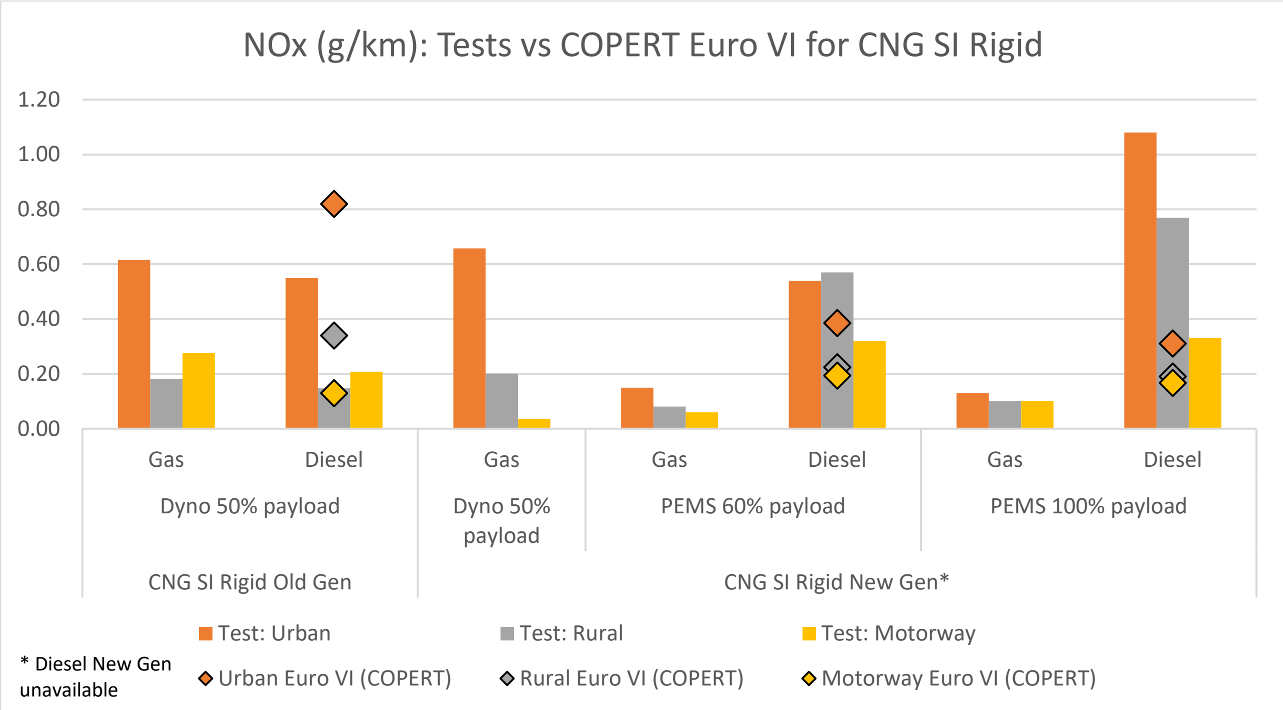

Figure 22: Summary of tested NOx emissions for CNG SI Rigid vs Euro VI

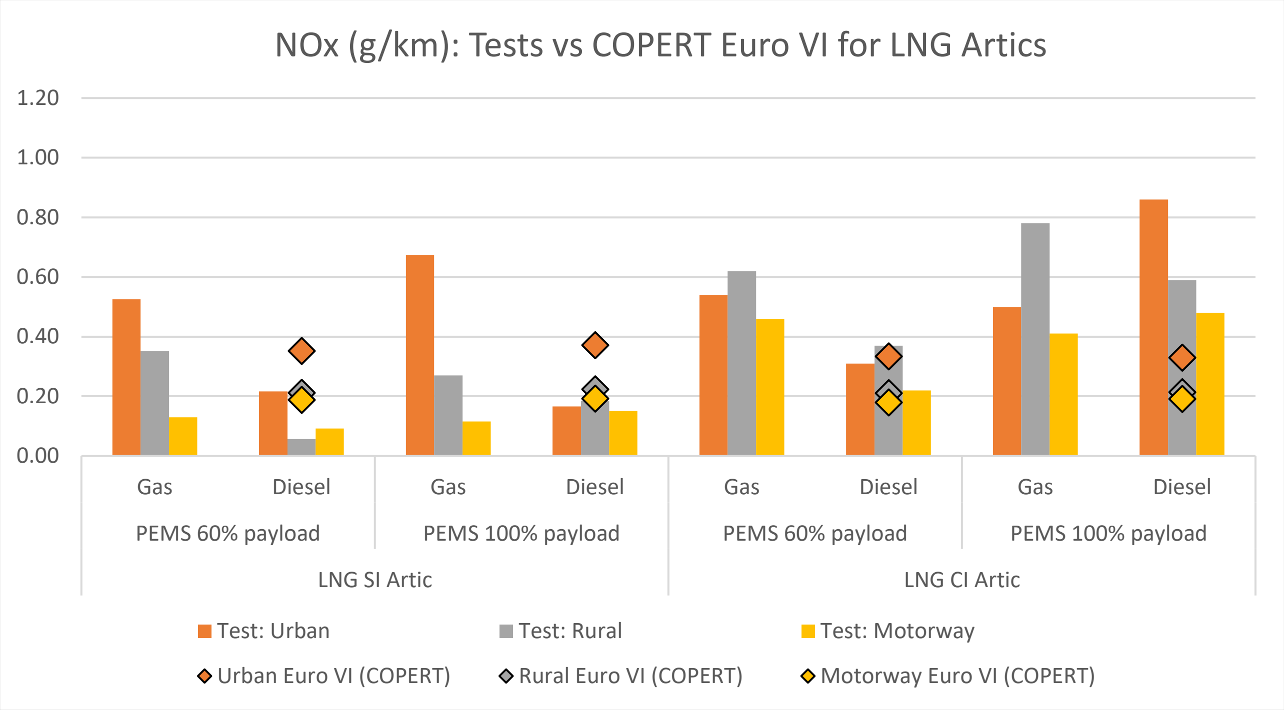

Figure 23: Summary of tested NOx emissions for LNG Artics vs Euro VI

In general, **NOx emissions from the gas vehicles are similar to diesel**. The CNG SI Rigid New Gen vehicle shows a significant improvement in NOx, however this is a comparison against the old generation of the diesel vehicle. The NOx emission levels are generally higher in the urban cycles compared to rural and motorway because NOx is typically linked to accelerations and throttle use. **The tested values in both gas and diesel vehicles fit well with the Euro VI COPERT values**, **which validates the Euro standard status of these vehicles**. A comparison against the Euro V COPERT values is included in Appendix 4: NOx comparison against Euro V to show the significant reduction in NOx emissions against a previous Euro standard.

Figure 24 and Figure 25 show the tested number of particulates (PN) for all gas and diesel vehicles. As mass of particulates (PM) could not be measured in PEMS tests, PN was the chosen variable for these graphs. The PM values for the dynamometer tests are shown in Figure 26 along with the COPERT Euro VI values. Because COPERT does not produce PN values, the Euro 6 PN values for cars and vans were included instead in the PN graphs to put the tested values into some context (the Euro VI PN emission standards are obtained from engine test beds in number per kWh of energy used, hence not comparable). Please note that the same size is used in the Y axis of both PN graphs to enable a better comparison across all vehicles.

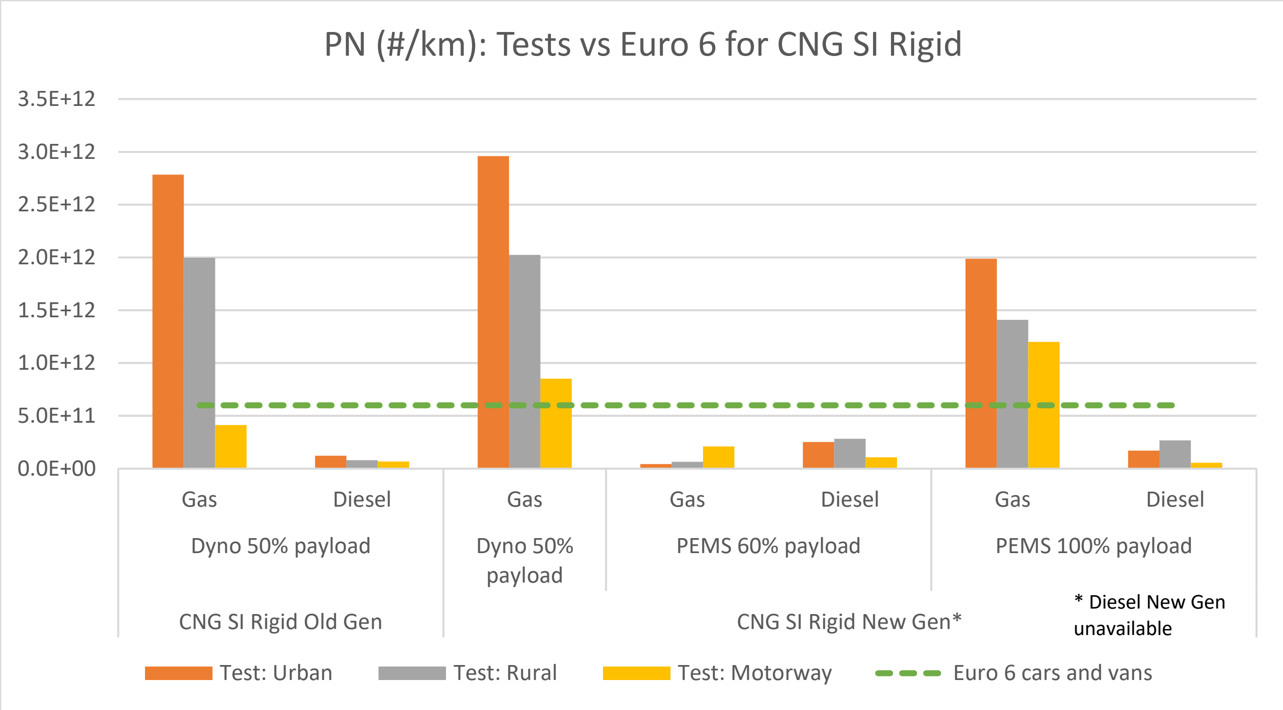

Figure 24: Summary of tested PN emissions for CNG SI Rigid

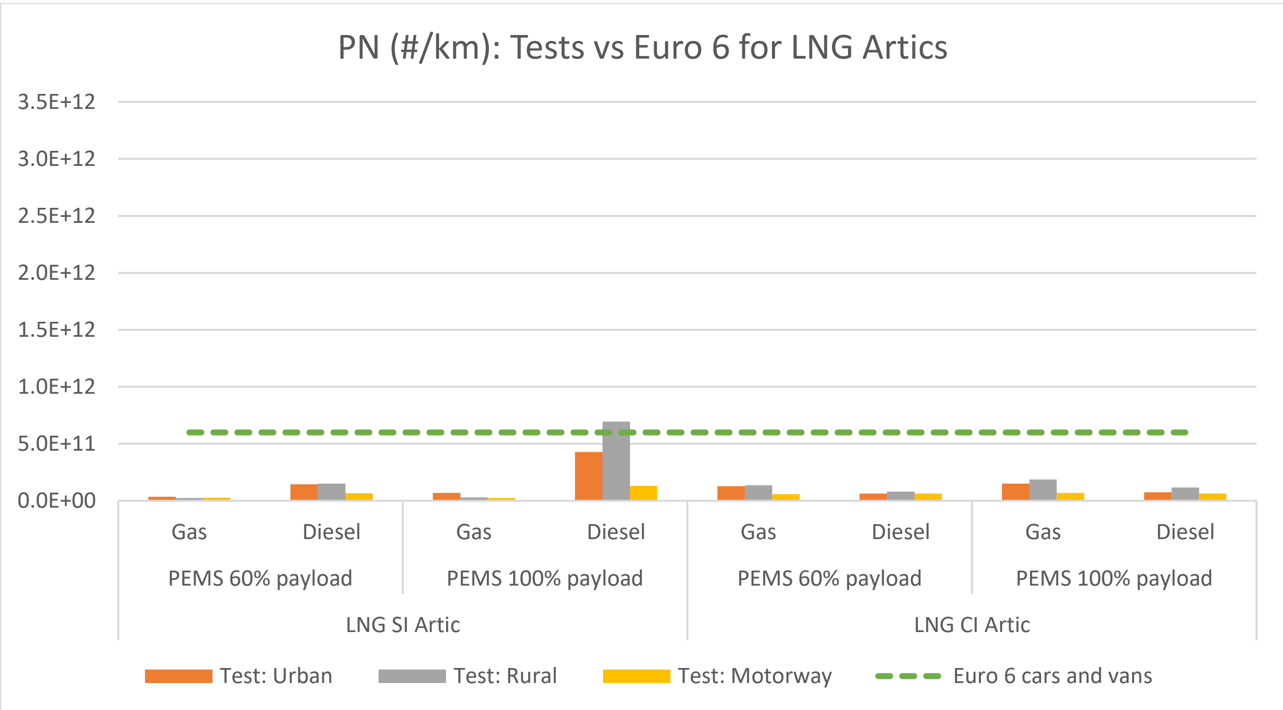

Figure 25: Summary of tested PN emissions for LNG Artics

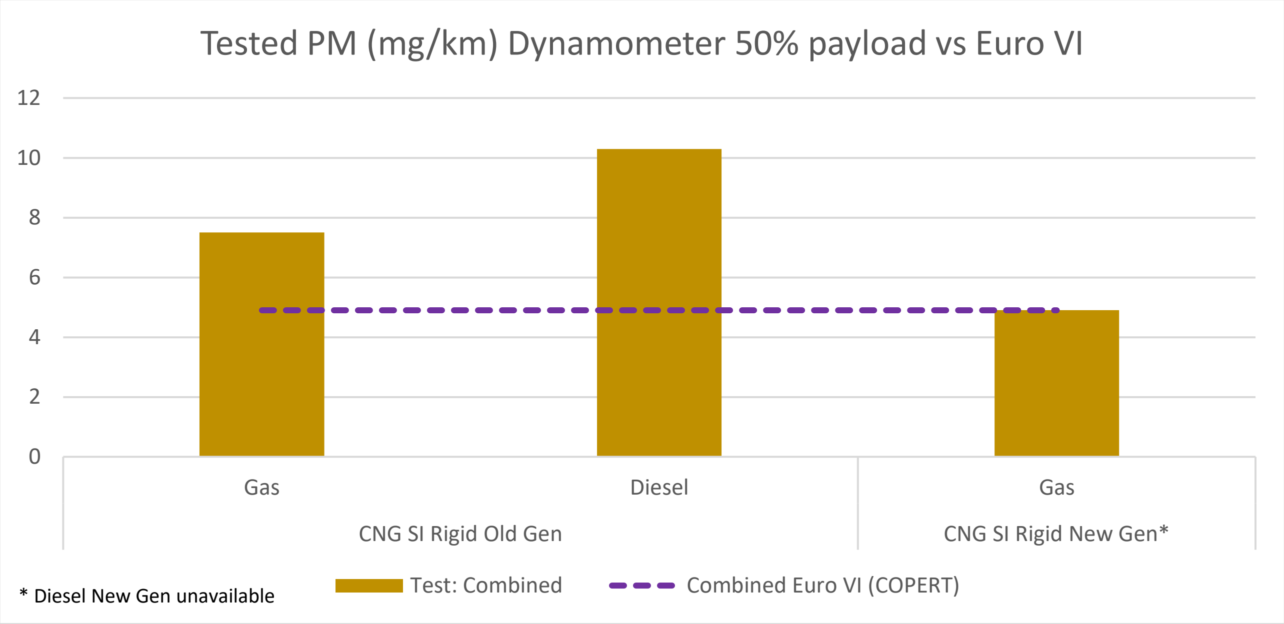

Figure 26: PM emissions from dyno tests at 50% payload on CNG SI Rigid

The CNG SI Rigid Old Gen and New Gen vehicles showed a significantly higher PN value than their diesel comparator. The PM values in g/km are however smaller in the gas vehicles and within COPERT Euro VI values as shown in Figure 26. The smaller the size of particles, the more harmful they can be for human health because they can penetrate deeper into the respiratory system and even into the bloodstream (8). Even though the emitted particle mass is low from the CNG SI Rigid vehicles according to Euro VI standards, the emitted particle number is much higher than other gas and diesel vehicles, hence the particle size is much smaller from these vehicles compared to others. Therefore, these results must be taken into further consideration in the future.

The **LNG vehicles emitted a similar or smaller number of particulates (PN) than their diesel comparators** and these values were far smaller than the Euro 6 limits for cars and vans, proving how small their PN emissions were.

It must be noted that, regarding exhaust aftertreatment systems, the SI gas vehicles tested use either Exhaust Gas Recirculation (EGR) or a three-way catalyst. However, their diesel comparators use 3 combined aftertreatment technologies: Diesel Oxidation Catalyst or DOC, Diesel Particulate Filter or DPF and Selective Catalytic Reduction or SCR, which requires the additional use of urea or AdBlue. Therefore, **the SI gas vehicles only use 1 aftertreatment system while the diesel and CI gas vehicles use 3 (including the need for AdBlue) to achieve similar Euro VI results in terms of exhaust pollutants.**

5 Business case for gas vehicles

This section explores the conditions under which it makes sense economically to operate dedicated gas vehicles as opposed to diesel.

We have seen how gas vehicles can offer significant GHG savings at certain biomethane blends along with similar air quality levels as Euro VI diesel vehicles, but can they offer a positive business case?

Gas HGVs have higher initial capital costs and higher maintenance costs than diesel HGVs. However, the good news is that the **fuel cost savings available from gas can negate these other costs** under certain operational conditions. Even though the MPGe in gas vehicles is worse than diesel, the fuel costs per unit of gas energy are significantly lower than diesel. This results in **lower fuel costs per unit of distance in gas vehicles compared to diesel**. Cenex has used the sources of information in Table 13 to calculate total cost of ownership (TCO) for both gas and diesel vehicles. The reader must consider that capital and maintenance costs depend heavily on vehicle OEMs and the contracts with their clients.

Table 13: Sources of information for TCO calculations

Sources of information	Diesel vehicles	Gas vehicles
Capital cost	Cenex contacts with industry	
Resale value	Freight Transport Association (FTA)	Assumed 50% of diesel vehicle's resale value due to low market maturity
Fuel costs	Fuel economy from vehicle testing, typical wholesale diesel price (£1/litre)	Fuel economy from vehicle testing, typical range of current gas prices
AdBlue costs	Typical wholesale AdBlue price	
Maintenance costs	Cenex contacts with industry	

Different fleets operate under different conditions: they keep the vehicles for certain periods, drive specific distances and get their fuel from various suppliers at different prices. Therefore, the following tables show a sensitivity analysis varying these 3 inputs to display the TCO savings from a single gas vehicle compared to diesel with the same colour coding used throughout the report. Please note that these savings are based on whole life costs, i.e. for the whole ownership periods indicated at the top of the tables. Table 14 and Table 15 show the sensitivity matrixes for the CNG vehicles, where the distances on a light blue shading indicate the average UK annual distance for each vehicle type according to the Department for Transport (DfT). Most of the analysed annual distances are over 100,000 km to represent the predominant trunking operation of articulated HGVs, while the annual distance of 60,000 km was included to describe the operation of some rigid HGVs that carry out urban and regional deliveries.

Table 14: TCO savings for CNG SI Artic

TCO savings gas vs diesel (£)					
Vehicle type: CNG SI Artic			Ownership period (years)		
		Annual distance (km)	3	5	7
Gas price (£/kg)	0.6	60,000	-£25,400 (-28%)	£6,500 (4%)	£26,300 (11%)
		120,000	£4,100 (3%)	£55,500 (20%)	£94,000 (25%)
		160,000	£23,500 (12%)	£87,800 (25%)	£138,700 (29%)
		200,000	£42,800 (18%)	£119,800 (28%)	£183,400 (32%)
	0.7	60,000	-£31,100 (-34%)	-£3,000 (-2%)	£13,000 (6%)
		120,000	-£7,300 (-5%)	£36,400 (13%)	£67,300 (18%)
		160,000	£8,200 (4%)	£62,400 (18%)	£103,200 (21%)
		200,000	£23,800 (10%)	£88,100 (21%)	£139,000 (24%)
	0.8	60,000	-£36,800 (-40%)	-£12,500 (-7%)	-£300 (0%)
		120,000	-£18,800 (-12%)	£17,400 (6%)	£40,700 (11%)
		160,000	-£7,000 (-4%)	£37,000 (10%)	£67,700 (14%)
		200,000	£4,800 (2%)	£56,400 (13%)	£94,600 (16%)

Table 15: TCO savings for CNG SI Rigid

TCO savings gas vs diesel (£)					
Vehicle type: CNG SI Rigid			Ownership period (years)		
		Annual distance (km)	3	5	7
Gas price (£/kg)	0.6	60,000	-£29,000 (-32%)	-£3,700 (-2%)	£13,500 (7%)
		120,000	-£4,400 (-3%)	£37,000 (16%)	£69,500 (22%)
		160,000	£11,600 (7%)	£63,500 (22%)	£106,300 (27%)
		200,000	£27,600 (14%)	£89,900 (26%)	£142,800 (31%)
	0.7	60,000	-£32,800 (-36%)	-£10,000 (-6%)	£4,800 (2%)
		120,000	-£11,900 (-8%)	£24,500 (10%)	£51,900 (16%)
		160,000	£1,600 (1%)	£46,800 (16%)	£82,800 (21%)
		200,000	£15,000 (7%)	£69,000 (20%)	£113,500 (25%)
	0.8	60,000	-£36,500 (-40%)	-£16,300 (-10%)	-£4,000 (-2%)
		120,000	-£19,400 (-14%)	£11,900 (5%)	£34,300 (11%)
		160,000	-£8,400 (-5%)	£30,100 (10%)	£59,400 (15%)
		200,000	£2,500 (1%)	£48,100 (14%)	£84,200 (18%)

At a CNG price of £0.60/kg, CNG vehicles would start paying back from year 2 at 160,000 km per year (or 100,000 miles). At a higher CNG price of £0.70/kg, CNG vehicles would be required to drive 200,00 km per year (124,000 miles) to pay back from year 2. Table 16 and Table 17 show the same sensitivity analysis for the LNG vehicles; please note that the LNG price is typically higher than CNG due to the additional supply chain requirements of LNG. However, the LNG price is expected to become closer to the CNG price in the future with the deployment of large-scale refuelling stations.

Table 16: TCO savings for LNG SI Artic

TCO savings gas vs diesel (£)					
Vehicle type: LNG SI Artic			Ownership period (years)		
		Annual distance (km)	3	5	7
Gas price (£/kg)	0.65	60,000	-£47,700 (-52%)	-£17,600 (-10%)	£300 (0%)
		120,000	-£21,000 (-13%)	£26,600 (9%)	£61,400 (16%)
		160,000	-£3,500 (-2%)	£55,700 (16%)	£101,700 (21%)
		200,000	£13,900 (6%)	£84,600 (20%)	£141,900 (24%)
	0.75	60,000	-£53,400 (-58%)	-£27,100 (-15%)	-£13,000 (-6%)
		120,000	-£32,400 (-21%)	£7,600 (3%)	£34,700 (9%)
		160,000	-£18,800 (-9%)	£30,400 (9%)	£66,200 (14%)
		200,000	-£5,100 (-2%)	£52,900 (12%)	£97,500 (17%)
	0.85	60,000	-£59,100 (-64%)	-£36,600 (-21%)	-£26,300 (-11%)
		120,000	-£43,900 (-28%)	-£11,400 (-4%)	£8,100 (2%)
		160,000	-£34,000 (-17%)	£5,000 (1%)	£30,600 (6%)
		200,000	-£24,100 (-10%)	£21,200 (5%)	£53,100 (9%)

Table 17: TCO savings for LNG CI Artic

TCO savings gas vs diesel (£)					
Vehicle type: LNG CI Artic			Ownership period (years)		
		Annual distance (km)	3	5	7
Gas price (£/kg)	0.65	60,000	-£39,500 (-36%)	-£13,500 (-8%)	£7,400 (3%)
		120,000	-£6,900 (-4%)	£40,300 (14%)	£82,100 (21%)
		160,000	£14,500 (7%)	£75,800 (21%)	£131,500 (27%)
		200,000	£35,700 (14%)	£111,100 (26%)	£180,600 (31%)
	0.75	60,000	-£44,000 (-40%)	-£21,100 (-12%)	-£3,200 (-1%)
		120,000	-£16,000 (-9%)	£25,100 (9%)	£60,900 (16%)
		160,000	£2,400 (1%)	£55,600 (15%)	£103,200 (21%)
		200,000	£20,500 (8%)	£85,800 (20%)	£145,300 (25%)
	0.85	60,000	-£48,600 (-45%)	-£28,700 (-16%)	-£13,800 (-6%)
		120,000	-£25,100 (-14%)	£10,000 (3%)	£39,700 (10%)
		160,000	-£9,800 (-4%)	£35,400 (10%)	£74,900 (15%)
		200,000	£5,400 (2%)	£60,600 (14%)	£109,900 (19%)

At an LNG price of £0.65/kg, LNG vehicles would be required to drive 195,000 km per year (121,000 miles) to pay back from year 2. At a higher LNG price of £0.75/kg, LNG vehicles would start paying back from year 2 at 225,000 km per year (or 140,000 miles). Table 18 shows the annual distance the gas vehicles need to drive to start making TCO savings after year 2. The minimum, maximum and average values represent the range of possibilities across different vehicle types.

Table 18: Required annual distance for gas vehicles to pay back in 2 years

			Annual km to pay back in 2 years		
Gas price (£/kg)	CNG	LNG	Min	Max	Average
	0.60	0.65	160,000	245,000	198,000
	0.70	0.75	200,000	310,000	240,000

Across different fuel types (CNG/LNG) and engine technologies (SI/CI), gas vehicles can generally provide TCO savings from year 2 at 160,000 km/year.

6 Conclusions

- The trial data shows that MPGe in the SI gas vehicles is 15-28% worse than their diesel comparators because SI engines are inherently less efficient than the CI engines used in the diesel vehicles. The MPGe in the LNG CI vehicles is only 3% worse than their diesel comparators because these gas trucks use the same engine technology as the diesel trucks.

- The range on a full tank from the CNG vehicles is 35 to 39% lower than their diesel comparators, whereas the range from the LNG SI vehicles is 45% higher than their diesel comparators. The range on the LNG CI vehicles is 18 to 36% lower than their diesel comparators.

- The data collected in both the in-service trial and vehicle tests suggests that gas vehicles are optimised to perform at their best compared to diesel in long haul operations carrying large payloads.

- The trial data shows that SI gas vehicles can either produce positive or negative WTW GHG savings if they use standard gas without any biomethane blend. The CNG SI vehicles using standard gas yield -4 to 10% GHG savings compared to diesel, while the LNG SI vehicles would produce savings of -1%. The SI gas vehicles would require a 25% bio-blend to produce at least a 17% GHG saving. The CI LNG vehicles yield a 13% GHG saving using standard gas. As all trial gas vehicles use a 100% bio-blend for the majority of time, their GHG savings compared to diesel are around 80%.

- The DEFRA emission factors for CNG, LNG and biomethane were used in the calculations. It is recommended that future versions of the emissions factors differentiate between bio-CNG and bio-LNG rather than the current single factor for biomethane.

- Gas vehicle reliability is comparable to diesel vehicles as gas vehicles generate similar maintenance events per year, although it generally takes longer to repair the faults in the gas vehicles.

- Drivers feel generally positive about gas vehicles and refuelling and think that they are more comfortable to drive, present less engine noise and vibration, better engine braking and a better environmental performance than diesel. Their most common complaints about SI gas vehicles are lack of range (CNG only), handling steep inclines, acceleration from standing and lack of refuelling stations. The most frequent complaints about CI gas vehicles are lack of range and refuelling stations, while the power performance aspects (inclines and acceleration) as regarded as similar to diesel.

- The results from vehicle testing show that SI gas vehicles can provide WTW GHG savings ranging from -9 to 23% depending on drive cycle and payload using fossil gas. Vehicle testing shows that CI gas vehicles can achieve GHG savings from 6 to 14% without the need of biomethane.

- The vehicle tests have shown that the methane slip in all gas vehicles was minimal and made very little contribution (0 to 1%) to WTW GHG emissions. The N_2O contribution to WTW GHG emissions from the tested diesel comparators ranges from 1 to 5%.

- Testing has also shown that gas vehicles emit similar levels of NOx as their diesel comparators. These pollutant levels were generally low for both gas and diesel vehicles because all trial vehicles comply with Euro VI standards. Moreover, the SI gas vehicles only use one aftertreatment system while the diesel and CI gas vehicles use 3 (including the need for AdBlue) to achieve similar Euro VI results in terms of exhaust pollutants. PN was similar or lower in the LNG vehicles compared to diesel, while PN was significantly higher in the CNG SI Rigid vehicle compared to diesel. This vehicle's PM emissions were however lower than diesel.

- Although the capital and maintenance costs are higher in the gas vehicles, their reduced fuel cost per unit of distance produces TCO savings against their diesel comparators if reasonable gas prices are available. Across different fuel types (CNG/LNG) and engine technologies (SI/CI), gas vehicles can generally provide TCO savings from year 2 at 160,000 km/year.

In summary, the implications from this report for UK fleets are that gas Euro VI HGVs can offer TCO savings compared to diesel Euro VI HGVs at similar levels of air quality performance. There are still some challenges regarding range on a full tank and WTW GHG emissions savings. To solve these, more refuelling stations are required and a minimum biomethane blend of 25% should be introduced to ensure that GHG savings are achieved across the gas fleet. GHG savings of up to 80% are available at higher bio-blends showing that gas vehicles fuelled by biomethane can offer a strong contribution to the UK's 2050 net zero carbon target using technology which is proven, reliable, mature and cost effective.

7 References

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8 Appendix 1: Formulae

$$MPGe = \frac{Distance\ (mi)}{Gas\ consumed\ (kg) * \frac{Gas\ NCV\ (\frac{MJ}{kg})}{Diesel\ NCV\ (\frac{MJ}{L})} * \frac{1}{4.546\ L\ of\ diesel\ in\ a\ gallon}}$$

Where:

- MPGe = Miles per gallon of diesel equivalent
- NCV = Net calorific value as provided by (2)

$$Substitution\ ratio\ (SR) = \frac{Gas\ consumed\ (kg) * Gas\ NCV\ (\frac{MJ}{kg})}{Gas\ consumed\ (kg) * Gas\ NCV\ \left(\frac{MJ}{kg}\right) + Diesel\ consumed\ (L) * Diesel\ NCV\ (\frac{MJ}{L})}$$

9 Appendix 2: Driver attitudes towards gas vehicles and the environment

Table 19: Key for survey questions on attitudes and opinions

Key	
5	Strongly agree / Very positive
4	Agree / Positive
3	Don't know
2	Disagree / Negative
1	Strongly disagree / Very negative

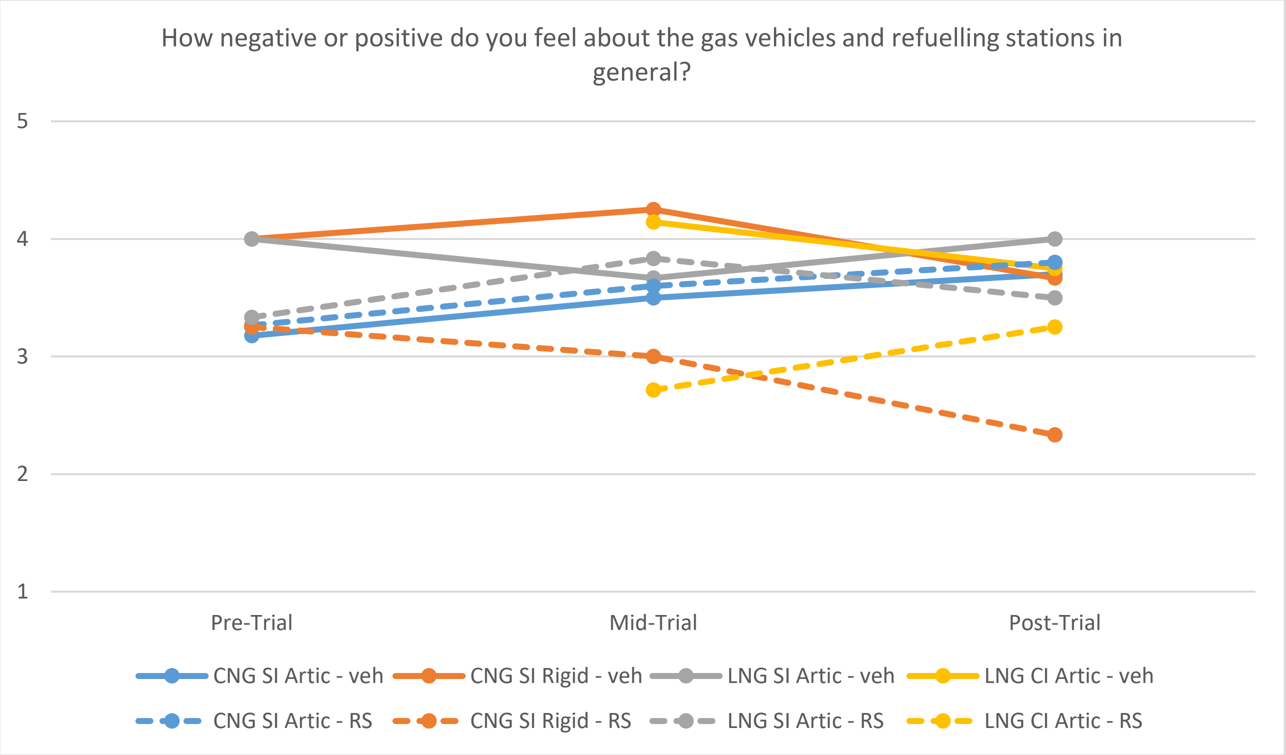

Figure 27: General feel for gas vehicles and refuelling stations

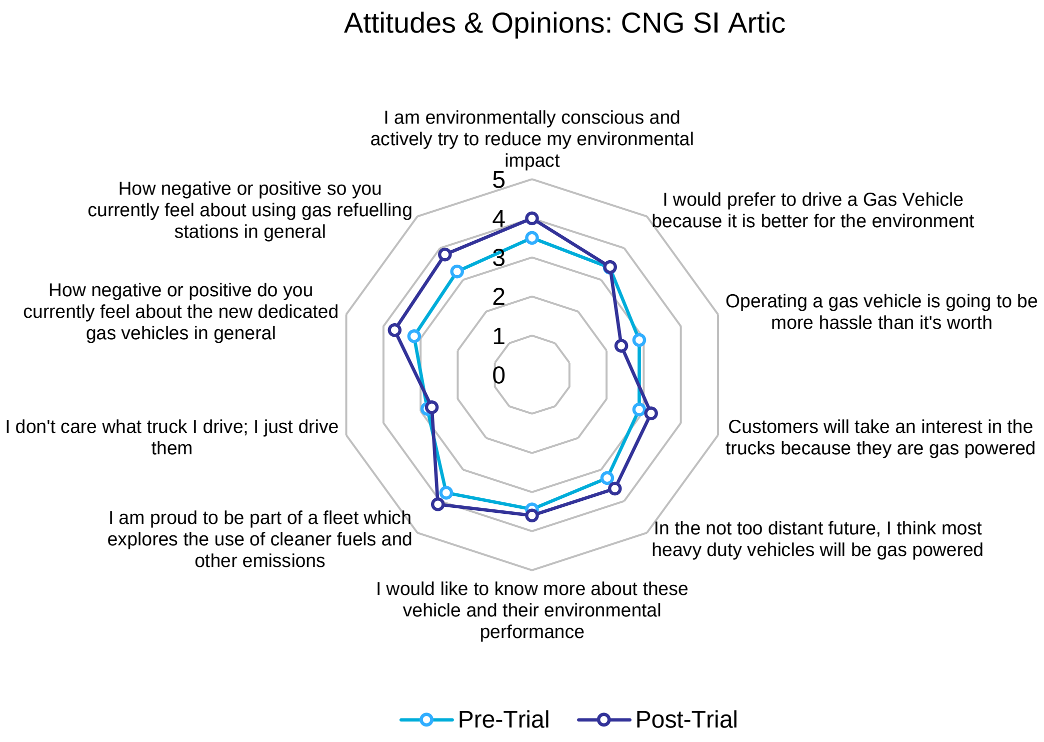

Figure 28: Attitudes and opinions from CNG SI Artic drivers

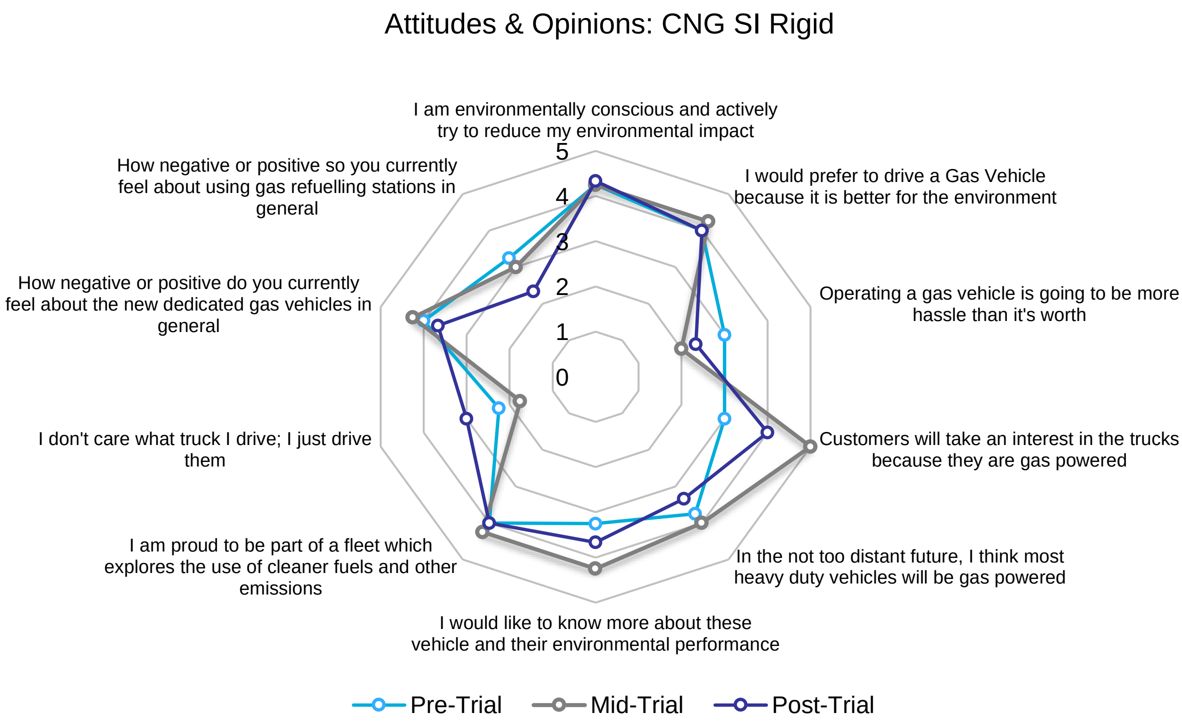

Figure 29: Attitudes and opinions from CNG SI Rigid drivers

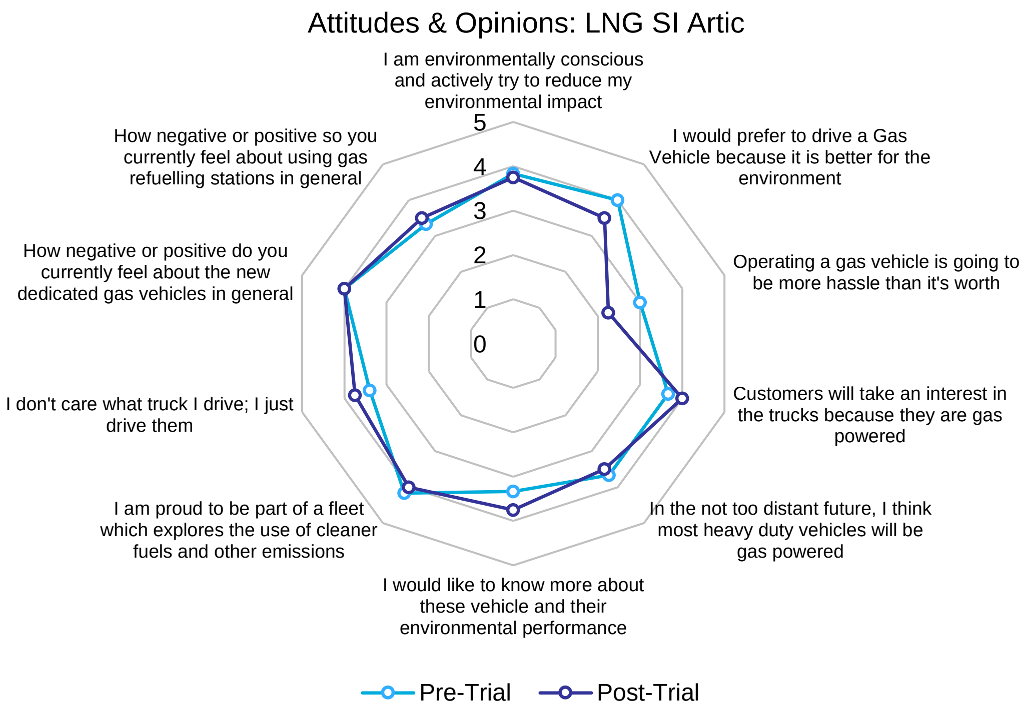

Figure 30: Attitudes and opinions from LNG SI Artic drivers

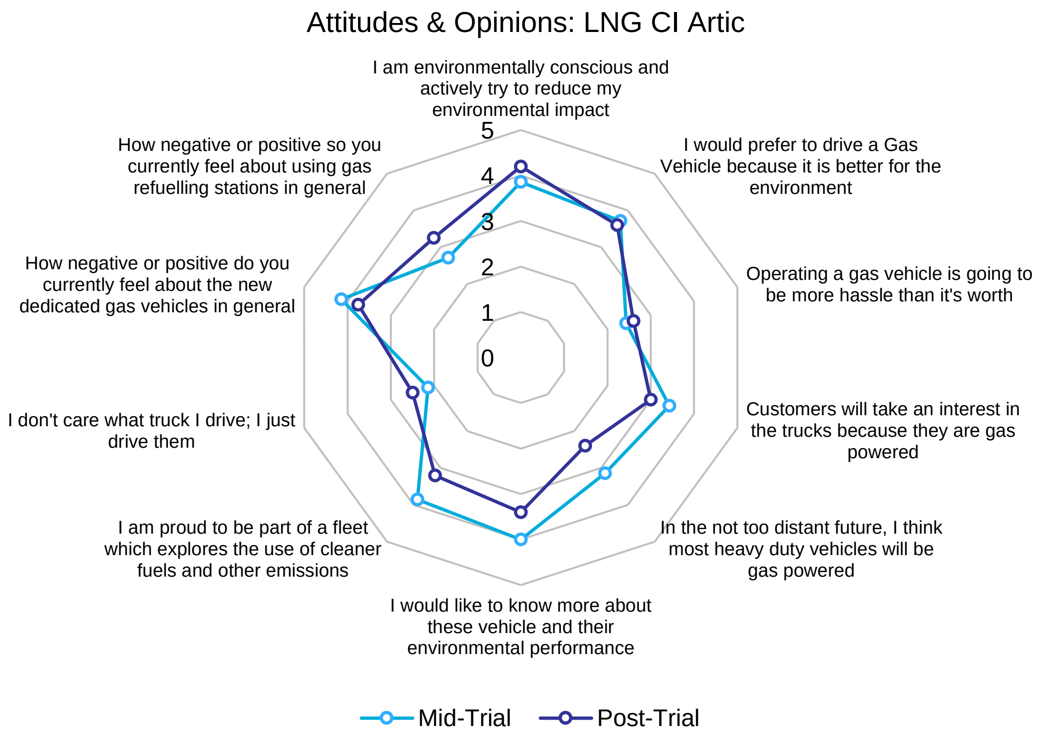

Figure 31: Attitudes and opinions from LNG CI Artic drivers

10 Appendix 3: Test results per vehicle

Note: The 'Combined' test results are for the whole drive cycle, i.e. the total amount of emissions from the urban, rural and motorway phases are added and divided by the sum of their distances. All results are averaged across 3 to 5 test repeats performed for each drive cycle phase.

10.1 CNG SI Rigid old generation and Diesel old generation comparator: Dynamometer tests at 50% payload

Table 20: GHG dyno test results for CNG SI Rigid old gen

g/km	Tailpipe CO_2			N_2O			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Urban	1275	1126	13%	0	0.247	-100%	0.019	0	N/A	1275	1200	6%	1502	1462	3%
Rural	844	799	6%	0	0.097	-100%	0.008	0	N/A	844	828	2%	994	1014	-2%
Motorway	558	577	-3%	0	0.040	-100%	0.092	0	N/A	560	589	-5%	660	723	-9%
Combined	830	786	6%	0	0.111	-100%	0.048	0	N/A	831	819	1%	979	1003	-2%

Table 21: Fuel economy dyno test results for CNG SI Rigid old gen

	Fuel units/100km			MJ/100km			MPGe		
Phase	Gas (kg)	Diesel (L)	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Urban	46.5	42.5	N/A	2084	1526	37%	4.9	6.6	-27%
Rural	30.8	30.2	N/A	1380	1083	27%	7.4	9.4	-21%
Motorway	20.4	21.8	N/A	912	781	17%	11.1	13.0	-14%
Combined	30.3	29.7	N/A	1359	1066	27%	7.5	9.5	-22%

Table 22: Pollutant dyno test results for CNG SI Rigid old gen

	THC (g/km)			CO (g/km)			NOx (g/km)			PM (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Urban	0.107	0.011	847%	0.909	0.079	1056 %	0.615	0.549	12%	Unavailable			2.79 E+12	1.21 E+11	2198 %
Rural	0.056	0.005	1013 %	0.795	0.022	3460 %	0.182	0.147	24%	Unavailable			2.00 E+12	7.94 E+10	2414 %
Motorway	0.129	0.002	6350 %	0.340	0.005	7186 %	0.275	0.207	33%	Unavailable			4.14 E+11	6.69 E+10	519 %
Combined	0.102	0.005	1940 %	0.623	0.029	2023 %	0.338	0.280	21%	0.02	0.01	91%	1.50 E+12	8.51 E+10	1664 %

10.2 CNG SI Rigid new generation and Diesel old generation comparator

10.2.1 Dynamometer tests at 50% payload

Table 23: GHG dyno test results for CNG SI Rigid new gen

g/km	Tailpipe CO_2			N_2O			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Urban	1092	1126	-3%	0	0.247	-100%	0.027	0	N/A	1093	1200	-9%	1287	1462	-12%
Rural	746	799	-7%	0	0.097	-100%	0.035	0	N/A	747	828	-10%	880	1014	-13%
Motorway	526	577	-9%	0	0.040	-100%	0.256	0	N/A	532	589	-10%	626	723	-13%
Combined	742	786	-6%	0	0.111	-100%	0.131	0	N/A	746	819	-9%	878	1003	-12%

Table 24: Fuel economy dyno test results for CNG SI Rigid new gen

	Fuel units/100km			MJ/100km			MPGe		
Phase	Gas (kg)	Diesel (L)	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Urban	39.9	42.5	N/A	1786	1526	17%	5.7	6.6	-15%
Rural	27.2	30.2	N/A	1220	1083	13%	8.3	9.4	-11%
Motorway	19.2	21.8	N/A	862	781	10%	11.8	13.0	-9%
Combined	27.1	29.7	N/A	1215	1066	14%	8.3	9.5	-12%

Table 25: Pollutant dyno test results for CNG SI Rigid new gen

	THC (g/km)			CO (g/km)			NOx (g/km)			PM (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Urban	0.058	0.011	412%	1.235	0.079	1470%	0.658	0.549	20%	Unavailable			2.96 E+12	1.21 E+11	2342%
Rural	0.067	0.005	1233%	0.745	0.022	3237%	0.201	0.147	37%	Unavailable			2.02 E+12	7.94 E+10	2449%
Motorway	0.307	0.002	22900%	0.538	0.005	11436%	0.037	0.207	-82%	Unavailable			8.51 E+11	6.69 E+10	1173%
Combined	0.170	0.005	3307%	0.787	0.029	2613%	0.252	0.280	-10%	0.005	0.01	-51%	1.76 E+12	8.51 E+10	1969%

10.2.2 PEMS tests at 60% payload

Table 26: GHG PEMS (60% payload) test results for CNG SI Rigid new gen

g/km	Tailpipe CO_2			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	514	610	-16%	0.001	0	N/A	476	595	-20%	568	737	-23%
Regional	744	878	-15%	0.005	0	N/A	692	856	-19%	825	1060	-22%
Urban	917	985	-7%	0.004	0	N/A	853	961	-11%	1017	1190	-15%
Combined	654	752	-13%	0.002	0	N/A	607	734	-17%	724	908	-20%

Table 27: Fuel economy PEMS (60% payload) test results for CNG SI Rigid new gen

	Fuel units/100km			MJ/100km			MPGe		
Phase	Gas (kg)	Diesel (L)	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	18.7	22.9	N/A	840	824	2%	12.1	12.3	-2%
Regional	27.2	33.0	N/A	1220	1185	3%	8.3	8.6	-3%
Urban	33.6	37.1	N/A	1504	1330	13%	6.7	7.6	-12%
Combined	23.9	28.3	N/A	1070	1015	5%	10.1	10.5	-4%

Table 28: Pollutant PEMS (60% payload) test results for CNG SI Rigid new gen

	THC (g/km)			CO (g/km)			NOx (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	0.032	0.009	258%	0.448	0.191	134%	0.064	0.318	-80%	2.10E+11	1.08E+11	94%
Regional	0.247	0.008	2921%	1.239	0.234	429%	0.079	0.569	-86%	6.59E+10	2.84E+11	-77%
Urban	0.201	0.011	1736%	1.822	0.378	382%	0.145	0.536	-73%	4.24E+10	2.54E+11	-83%
Combined	0.117	0.009	1170%	0.926	0.242	283%	0.086	0.422	-80%	1.41E+11	1.79E+11	-21%

10.2.3 PEMS tests at 100% payload

Table 29: GHG PEMS (100% payload) test results for CNG SI Rigid new gen

g/km	Tailpipe CO_2			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	616	653	-6%	0.003	0	N/A	572	637	-10%	681	788	-14%
Regional	879	959	-8%	0.005	0	N/A	818	935	-13%	975	1158	-16%
Urban	1147	1134	1%	0.005	0	N/A	1066	1106	-4%	1271	1369	-7%
Combined	791	827	-4%	0.004	0	N/A	735	806	-9%	876	998	-12%

Table 30: Fuel economy PEMS (100% payload) test results for CNG SI Rigid new gen

	Fuel units/100km			MJ/100km			MPGe		
Phase	Gas (kg)	Diesel (L)	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	22.5	24.6	N/A	1008	881	14%	10.1	11.5	-13%
Regional	32.2	36.0	N/A	1441	1294	11%	7.0	7.8	-10%
Urban	41.9	42.6	N/A	1879	1530	23%	5.4	6.6	-19%
Combined	28.9	31.1	N/A	1296	1116	16%	8.4	9.6	-13%

Table 31: Pollutant PEMS (100% payload) test results for CNG SI Rigid new gen

	THC (g/km)			CO (g/km)			NOx (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	0.126	0.005	2193%	0.546	0.076	620%	0.101	0.328	-69%	1.20E+12	5.69E+10	2010%
Regional	0.263	0.007	3729%	1.383	0.247	459%	0.102	0.771	-87%	1.41E+12	2.66E+11	429%
Urban	0.233	0.002	14365%	2.250	0.399	464%	0.131	1.077	-88%	1.99E+12	1.72E+11	1054%
Combined	0.180	0.005	3543%	1.107	0.185	498%	0.108	0.591	-82%	1.42E+12	1.29E+11	1004%

10.2.4 Comparison between 60 and 100% payloads

In order to compare the results between 60 and 100% payload, the normalised energy consumption per tonne of payload is shown in Figure 32 and the WTW GHG CO_2e emissions normalised per tonne of payload are shown in Figure 33.

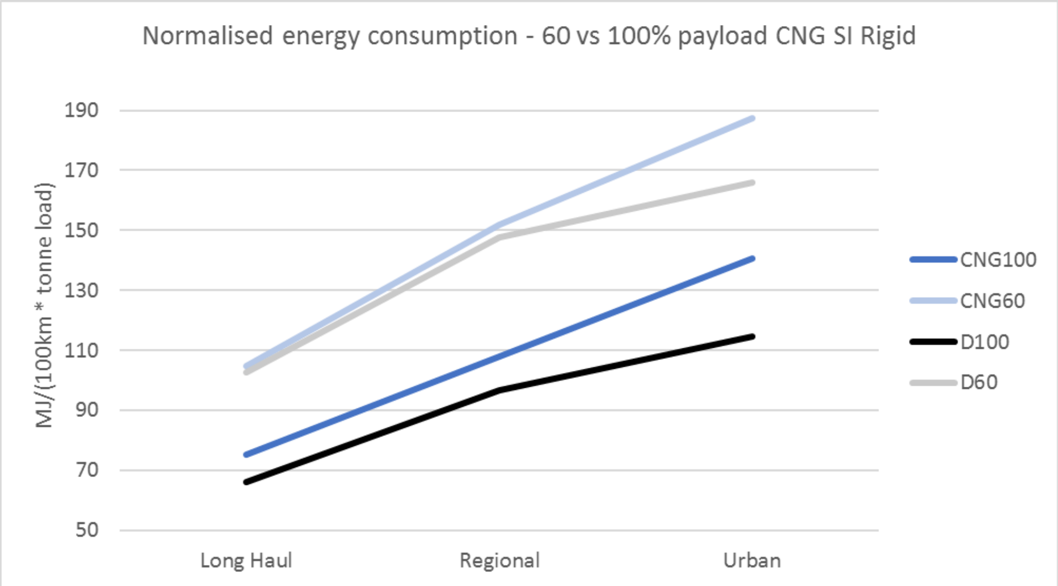

Figure 32: Energy consumption normalised for payload - CNG SI Rigid

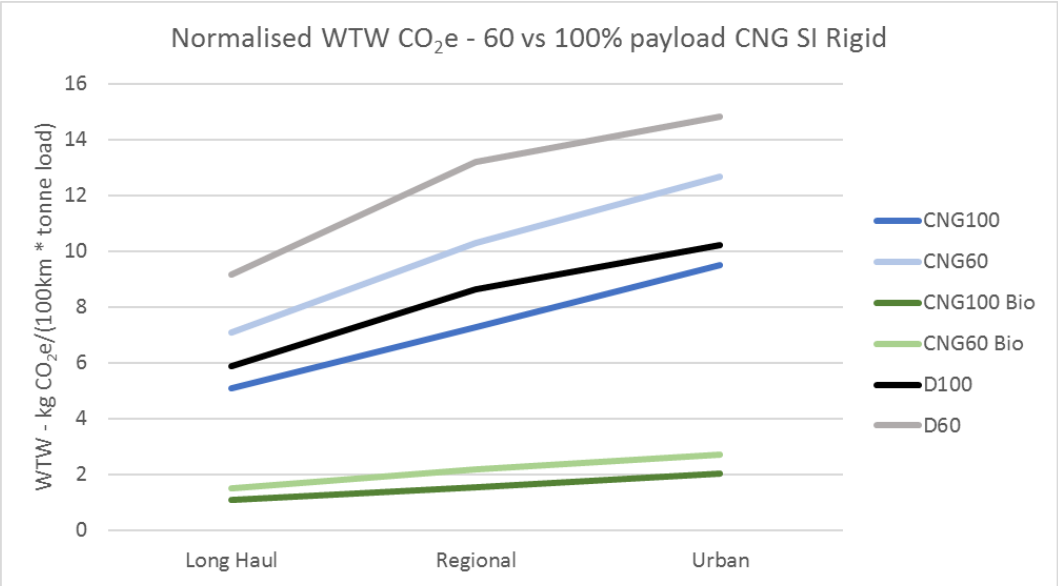

Figure 33: GHG emissions normalised for payload - CNG SI Rigid

Figure 32 shows the higher energy required to transport each unit of load when moving from Long Haul to the Urban drive cycle. This is due to the frequent accelerations present in the Urban cycle and hence higher inertia forces involved. From this graph and Figure 33 it can also be appreciated how the 'per load' energy and 'per load' WTW GHG emissions are lower as the payload increases from 60 to 100% because the usage of the trailer capacity is being optimised. Moreover, the difference in energy consumption between CNG and diesel gets smaller as the cycle moves from Urban to Long Haul.

10.3 LNG SI Artic

10.3.1 PEMS tests at 60% payload

Table 32: GHG PEMS (60% payload) test results for LNG SI Artic

g/km	Tailpipe CO_2			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	912	849	7%	0.000	0	N/A	836	832	0%	1123	1030	9%
Regional	1272	1244	2%	0.001	0	N/A	1176	1215	-3%	1581	1504	5%
Urban	1463	1459	0%	0.001	0	N/A	1420	1426	6%	1909	1765	8%
Combined	1113	1071	4%	0.000	0	N/A	1040	1048	-1%	1398	1297	8%

Table 33: Fuel economy PEMS (60% payload) test results for LNG SI Artic

	Fuel units/100km			MJ/100km			MPGe		
Phase	Gas (kg)	Diesel (L)	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	32.8	32.1	N/A	1468	1151	28%	6.9	8.8	-22%
Regional	46.1	46.8	N/A	2066	1680	23%	4.9	6.0	-19%
Urban	55.7	55.0	N/A	2495	1973	26%	4.1	5.1	-21%
Combined	40.8	40.4	N/A	1827	1449	26%	5.8	7.4	-21%

Table 34: Pollutant PEMS (60% payload) test results for LNG SI Artic

	THC (g/km)			CO (g/km)			NOx (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	0.009	0	N/A	2.533	1.420	78%	0.130	0.092	41%	2.64E+10	6.68E+10	-60%
Regional	0.029	0	N/A	4.011	0.676	494%	0.352	0.056	524%	2.32E+10	1.51E+11	-85%
Urban	0.037	0	N/A	5.635	1.107	409%	0.525	0.216	143%	3.44E+10	1.44E+11	-76%
Combined	0.020	0	N/A	3.545	1.187	199%	0.266	0.112	139%	2.75E+10	1.02E+11	-73%

10.3.2 PEMS tests at 100% payload

Table 35: GHG PEMS (100% payload) test results for LNG SI Artic

g/km	Tailpipe CO_2			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	1000	983	2%	0	0	N/A	933	960	-3%	1254	1188	6%
Regional	1428	1503	-5%	0	0	N/A	1334	1466	-9%	1794	1815	-1%
Urban	1703	1773	-4%	0	0	N/A	1590	1731	-8%	2138	2142	0%
Combined	1250	1272	-2%	0	0	N/A	1167	1242	-6%	1569	1537	2%

Table 36: Fuel economy PEMS (100% payload) test results for LNG SI Artic

	Fuel units/100km			MJ/100km			MPGe		
Phase	Gas (kg)	Diesel (L)	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	36.6	37.0	N/A	1639	1327	23%	6.2	7.6	-19%
Regional	52.3	56.5	N/A	2344	2028	16%	4.3	5.0	-13%
Urban	62.4	66.7	N/A	2794	2394	17%	3.6	4.2	-14%
Combined	45.8	47.9	N/A	2050	1718	19%	5.2	6.3	-17%

Table 37: Pollutant PEMS (100% payload) test results for LNG SI Artic

	THC (g/km)			CO (g/km)			NOx (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	0	0	N/A	2.424	1.150	111%	0.116	0.151	-23%	2.55E+10	1.32E+11	-81%
Regional	0	0	N/A	4.838	0.850	469%	0.270	0.186	46%	2.89E+10	6.95E+11	-96%
Urban	0	0	N/A	5.319	1.682	216%	0.674	0.166	306%	6.86E+10	4.29E+11	-84%
Combined	0	0	N/A	3.596	1.201	199%	0.273	0.162	68%	3.58E+10	3.22E+11	-89%

10.3.3 Comparison between 60 and 100% payloads

Figure 34 and Figure 35 show normalised energy consumption and GHG emissions in the same format as presented earlier for CNG SI Rigid.

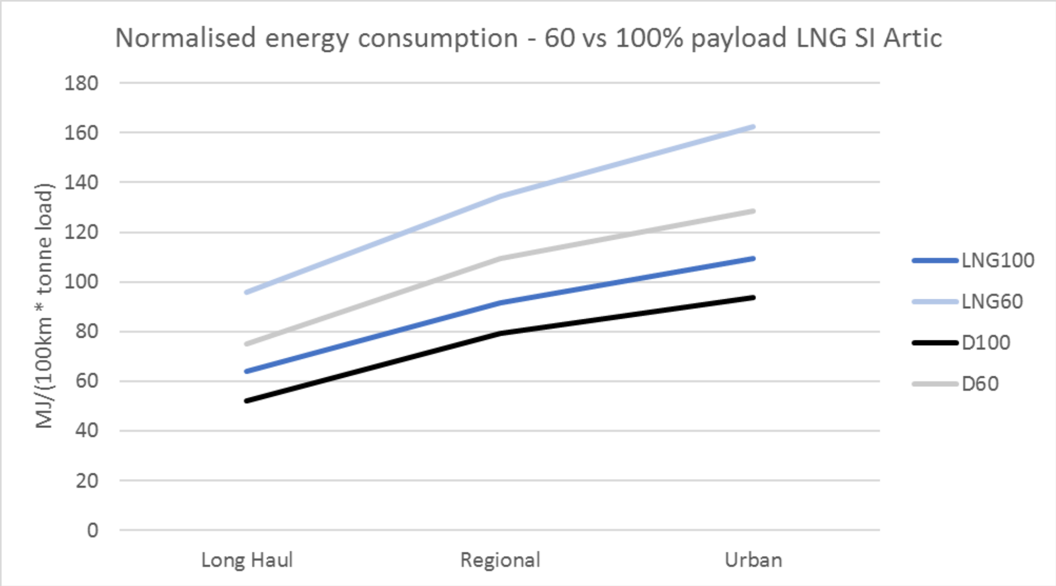

Figure 34: Energy consumption normalised for payload - LNG SI Artic

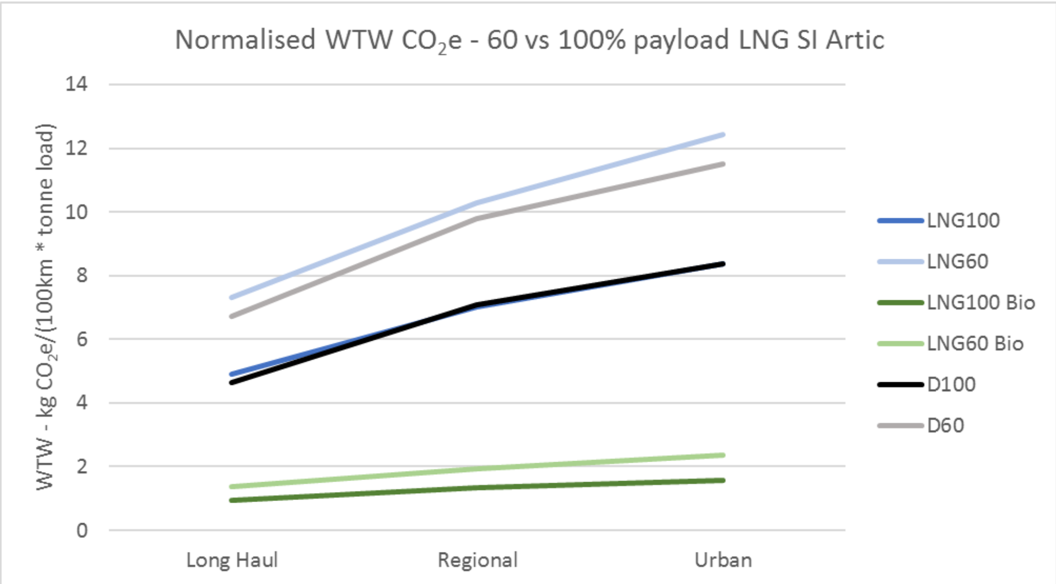

Figure 35: GHG emissions normalised for payload - LNG SI Artic

The conclusions that can be extracted from these results are the same as for CNG SI Rigid:

- Less energy required per unit of payload when moving from Urban to Long Haul
- Less energy required per unit of payload when going from 60 to 100% payload
- The difference in normalised energy usage between gas and diesel reduces when going from Urban to Long Haul
- Additional observation: in this case, unlike for CNG SI Rigid, the difference in normalised energy usage between gas and diesel reduces when going from 60 to 100% payload.

10.4 LNG CI Artic: PEMS tests

10.4.1 PEMS tests at 60% payload

Table 38: GHG PEMS (60% payload) test results for LNG CI Artic

g/km	Tailpipe CO_2			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	653	777	-16%	0.021	0.003	677%	619	759	-19%	827	940	-12%
Regional	935	1041	-10%	0.019	0.001	1407%	885	1017	-13%	1182	1259	-6%
Urban	1092	1319	-17%	0.025	0.002	1517%	1027	1288	-20%	1375	1594	-14%
Combined	813	955	-15%	0.021	0.002	908%	768	933	-18%	1026	1155	-11%

Table 39: Fuel economy PEMS (60% payload) test results for LNG CI Artic

	Fuel units/100km				MJ/100km			MPGe		
Phase	LNG vehicle		Diesel comparator	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
	Gas (kg)	Diesel (L)	Diesel (L)							
Long Haul	22.5	1.8	29.3	N/A	1070	1051	2%	9.5	9.7	-2%
Regional	31.9	2.8	39.2	N/A	1528	1407	9%	6.6	7.2	-8%
Urban	38.2	2.1	49.6	N/A	1785	1782	0%	5.7	5.7	0%
Combined	28.0	2.1	36.0	N/A	1329	1291	3%	8.0	8.2	-3%

Table 40: Pollutant PEMS (60% payload) test results for LNG CI Artic

	THC (g/km)			CO (g/km)			NOx (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	0.110	0.014	678%	0.905	1.133	-20%	0.561	0.266	111%	7.02E+10	7.54E+10	-7%
Regional	0.100	0.007	1414%	0.403	1.011	-60%	0.750	0.442	70%	1.66E+11	9.62E+10	73%
Urban	0.130	0.008	1501%	0.348	0.998	-65%	0.659	0.377	75%	1.56E+11	7.63E+10	104%
Combined	0.112	0.011	907%	0.671	1.076	-38%	0.624	0.330	89%	1.10E+11	8.02E+10	37%

10.4.2 PEMS tests at 100% payload

Table 41: GHG PEMS (100% payload) test results for LNG CI Artic

g/km	Tailpipe CO_2			CH_4			TTW CO_2e			WTW CO_2e		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	766	1069	-28%	0.036	0.003	1283%	725	1044	-31%	969	1292	-25%
Regional	1220	1419	-14%	0.040	0.004	898%	1155	1384	-17%	1542	1713	-10%
Urban	1485	1773	-16%	0.059	0.003	1624%	1397	1730	-19%	1870	2142	-13%
Combined	1025	1302	-21%	0.042	0.003	1256%	968	1270	-24%	1294	1573	-18%

Table 42: Fuel economy PEMS (100% payload) test results for LNG CI Artic

	Fuel units/100km				MJ/100km			MPGe		
Phase	LNG vehicle		Diesel comparator	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
	Gas (kg)	Diesel (L)	Diesel (L)							
Long Haul	26.3	2.1	40.2	N/A	1253	1444	-13%	8.1	7.0	15%
Regional	41.6	3.6	53.4	N/A	1993	1915	4%	5.1	5.3	-4%
Urban	51.9	2.8	66.7	N/A	2426	2394	1%	4.2	4.2	-1%
Combined	35.3	2.6	49.0	N/A	1676	1758	-5%	6.6	6.0	9%

Table 43: Pollutant PEMS (100% payload) test results for LNG CI Artic

	THC (g/km)			CO (g/km)			NOx (g/km)			PN (#/km)		
Phase	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel	Gas	Diesel	% gas vs diesel
Long Haul	0.189	0.014	1283%	0.837	1.001	-16%	0.495	0.584	-15%	8.48E+10	7.70E+10	10%
Regional	0.210	0.021	898%	0.397	0.503	-21%	0.948	0.710	33%	2.25E+11	1.42E+11	59%
Urban	0.310	0.018	1623%	0.430	0.871	-51%	0.601	1.037	-42%	1.81E+11	8.99E+10	101%
Combined	0.220	0.016	1256%	0.650	0.862	-25%	0.618	0.712	-13%	1.37E+11	9.42E+10	45%

10.4.3 Comparison between 60 and 100% payloads

Figure 36 and Figure 37 show normalised energy consumption and GHG emissions in the same format as presented earlier.

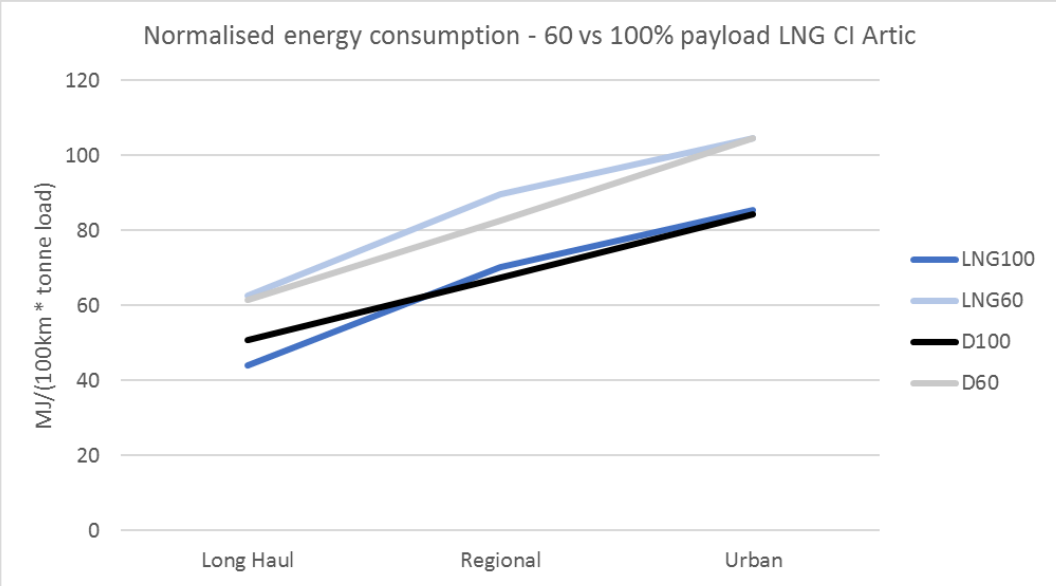

Figure 36: Energy consumption normalised for payload - LNG CI Artic

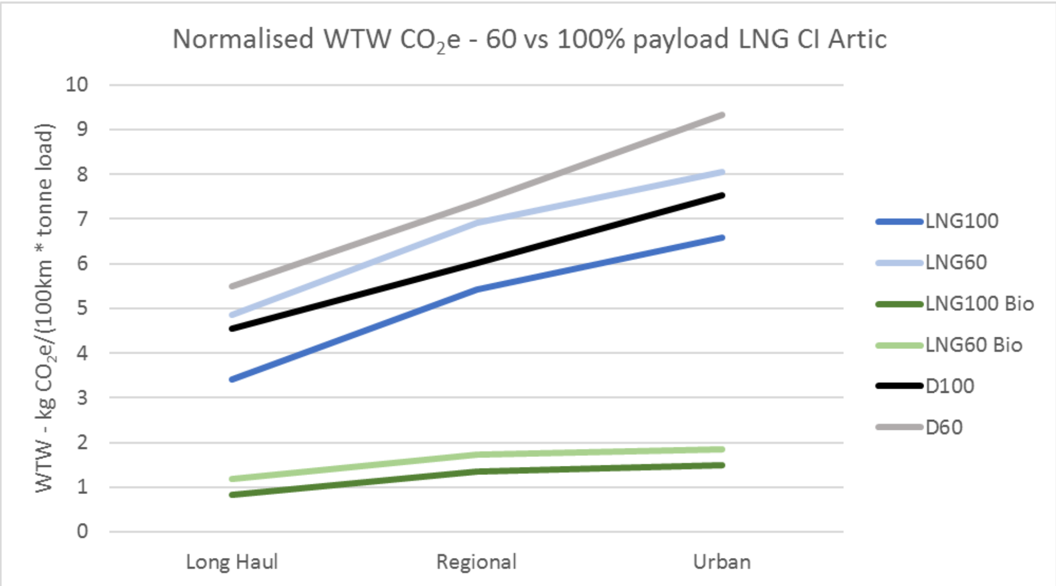

Figure 37: GHG emissions normalised for payload - LNG CI Artic

In this case, the difference in energy used per unit of payload is similar when comparing LNG against diesel (except for the 100% payload Long Haul cycle as explained in section 4.2.1 because both vehicles share the same CI engine technology.

11 Appendix 4: NOx comparison against Euro V

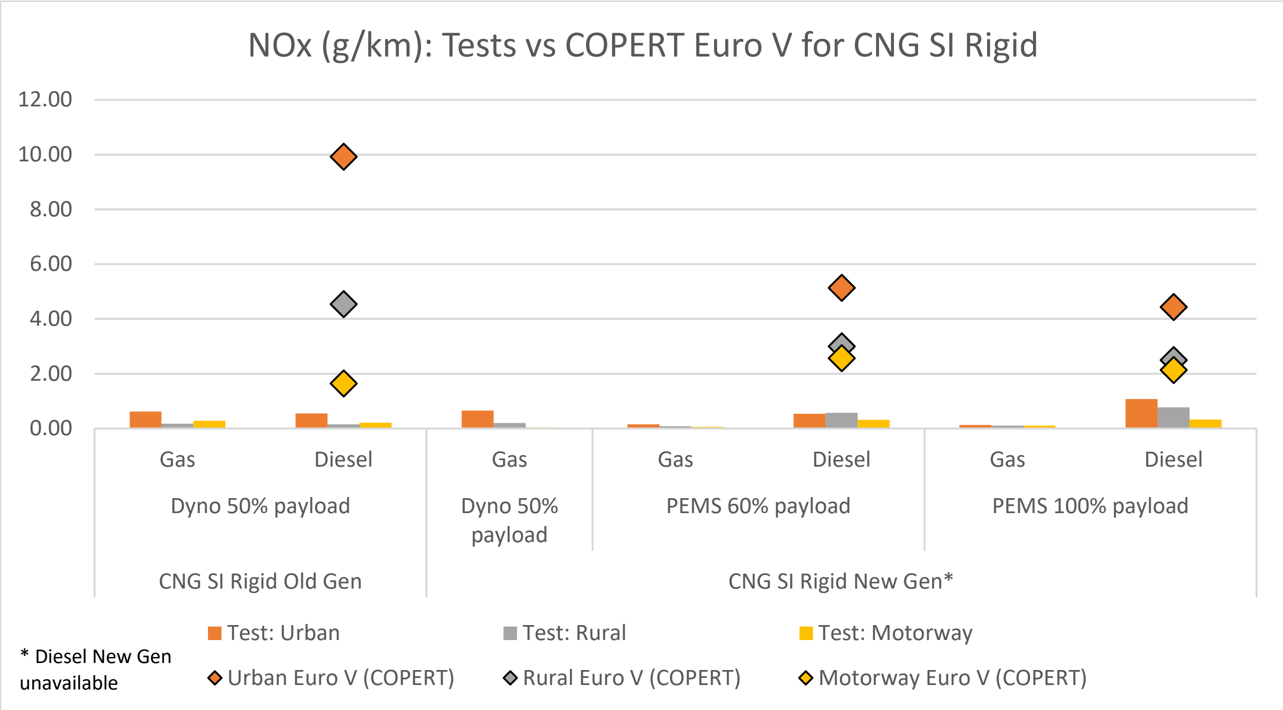

Figure 38: Summary of tested NOx emissions for CNG SI Rigid vs Euro V

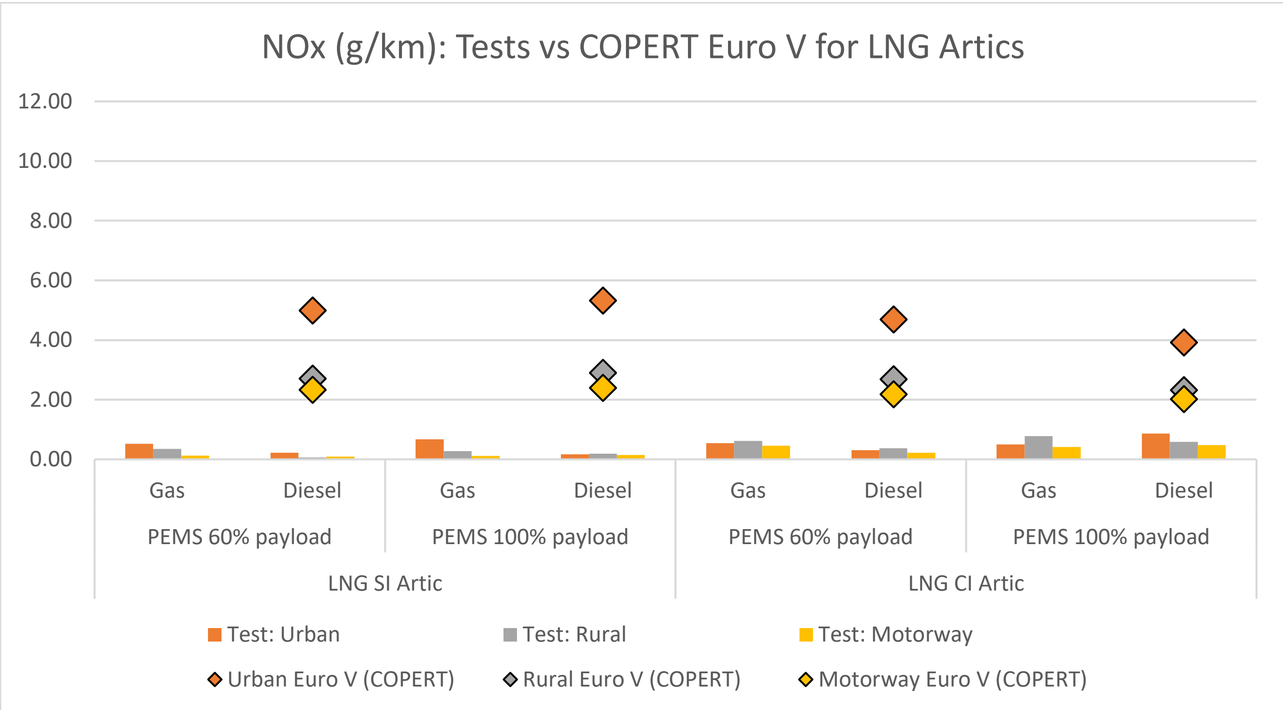

Figure 39: Summary of tested NOx emissions for LNG Artics vs Euro V

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