Natural Gas Pathway Analysis for Heavy Duty Vehicles

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Contents

1. Key Findings

- Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG) have the potential to reduce Greenhouse Gas (GHG) emissions over the Well-to-Motion (WTM) pathway by 13% (LNG) - 20%(CNG) for dedicated engines and 16% (LNG) - 24%(CNG) for High Pressure Direct Injection engines per vehicle in the 2035 timeframe in comparison to the reference baseline diesel pathway.
- Cycle specific powertrain technology selection and pathway optimisation are key to providing GHG emission benefits over given usage cycles, with High Pressure Direct Injection and Dedicated gas engines providing the highest benefit.
- Retrofit dual fuel engines have been shown to have high methane emissions, often being worse than baseline diesel powertrains on a GHG emission basis. Effective testing procedures and legislative certainty are required to ensure emissions conformity and facilitate market development.
- Providing methane catalysis at real world operating temperatures, i.e. below 350°C, is essential to prevent uncombusted methane making its way out of the tailpipe in powertrains that cannot control methane slip and is a key technology that enables a pathway benefit.
- Employing ‘best practices’ at LNG, CNG and L-CNG stations is a key driver to providing pathway benefits. Vapour recovery systems should be implemented at all LNG stations and the economic proposition and expected utilisation should be aligned. CNG stations should be connected to the highest pressure tier of the grid where possible or employed in combination with a L-CNG station as an easy step to reduce emissions associated with compression, at least until the carbon intensity of the grid is significantly lower than today.
- The economic proposition for natural gas in the HGV fleet hinges upon the fuel duty differential and currently only the long haul segment is economic in the near term. Fuel duty tax stability is key to enable market confidence to invest in natural gas vehicles and the necessary supporting infrastructure.

2. Introduction

This report presents the results of a comprehensive modelling exercise of natural gas Well-to-Motion (WTM) pathways relevant for heavy duty vehicles, to understand the impact on Green House Gas (GHG) emissions of natural gas vehicles forming part of the HDV fleet in the UK. This aims to provide insights into the potential to reduce GHG emissions by using natural gas in heavy duty vehicles based on a detailed review of each stage of a number of WTM natural gas pathways. Emission savings on a fleet level were quantified using an uptake model based on the economic attractiveness of natural gas solutions relative to other powertrains.

The use of natural gas in heavy duty vehicles is often proposed as part of a low carbon transition to help the UK meet its legally binding CO_2 emission reduction targets. It offers moderate CO_2 reduction in the short and medium-term at a significantly lower cost than zero emission alternatives, which are not currently economically and operationally feasible for most heavy duty vehicle cycles.

Trends in recent years in the HDV market (on-highway heavy goods vehicles (HGVs), off-highway and marine) show modest gas vehicle/vessel penetration and natural gas being promoted as a 'future HDV fuel'. In the current landscape this is a consequence of low gas prices and rising conventional fuel costs. This is in addition to gas being marketed as a 'green alternative' and being used by vessel operators in dual fuel mode in emission control areas (ECA's) to meet NOx and SOx emissions regulations.

Heavy Duty Vehicles are very difficult to decarbonise, mainly due to the large distances they travel with large payloads requiring energy dense fuels that do not take up freight space and weight. This is especially relevant in the larger HGV categories and in marine.

Many potential alternative fuel options are less energy dense than the incumbent fuels such as hydrogen fuel cells or batteries. These are currently not practical and require significant improvements in the future to become realistic solutions in their own right. Alternatives that require less on board energy storage have also been studied, but these require significant infrastructure development such as catenary type charging and electrification networks for HGVs[1].

Biofuels are an option for the HDV market and could offer a direct replacement for diesel. However, questions remain about the availability and scalability of genuinely sustainable biofuels to the transport sector.

These solutions could offer long-term deep decarbonisation routes but require significant disruption to the fuel supply chain and a divergence in investment and manufacturing from vehicle Original Equipment Manufacturers (OEM's). While some of these solutions may be feasible on land in the future, the marine sector offers a different set of challenges which have yet to be addressed.

UK natural gas sources are very diverse, a trend that is set to increase in the future with the UK's natural gas self-sufficiency dwindling since the late 1990's. Liquefied natural gas (LNG) has enabled the shipment of millions of tonnes of gas around the world and when combined with the merging of various sources of gas in the EU network, makes it extremely difficult to predict the exact origins of UK gas sources in the future.

There are numerous vehicle engine technologies available to operators, and in the HGV market many have fitted retrofit systems to existing diesel vehicles to create dual fuelled vehicles. Until

[1] https://qz.com/714381/siemens-says-it-can-power-unlimited-range-electric-trucks-using-a-150-year-old-technology/

recently very few on-highways Original Equipment Manufacturers (OEM's) offered competitively priced natural gas variants, but the marine picture is slightly different with most engine producers offering dedicated and dual fuel natural gas variants.

Complexity in the pathways leads to uncertainty about the ultimate environmental benefits of natural gas, which pathways should be favoured to maximise any potential benefits and whether there are pathways that should be avoided due to low emissions savings or even emissions increases. Addressing the uncertainty through a model-based approach and significantly increasing the understanding of the emissions and economics of liquefied and compressed natural gas will allow the suitability of natural gas in the HDV sector to be assessed. The focus is on providing insights into:

- Potential GHG emission savings by using natural gas in HDVs
- Potential ways to optimise natural gas pathways
- Research and technology requirements for pathways optimisation
- Implications for the UK refuelling infrastructure
- Economics of natural gas technologies for HDVs.

It is recognised that natural gas has the potential to bring with it air quality benefits, however, air quality was not within the scope of this analysis, which focused on the greenhouse gas impacts of natural gas. While air quality benefits are out of scope for this project, LowCVP recently produced a report for the DfT on 'Emissions Testing of Gas-Powered Commercial Vehicles' in which they evaluated natural gas vehicles against diesel equivalents. PEMS (Portable Emission Measurement Systems) testing was conducted on several vehicles, highlighting in particular the test of a Euro VI dedicated gas HGV vs Euro VI diesel comparator for NOx and other pollutants. In the test the natural gas HGV produced significantly less NOx in real world conditions than the equivalent diesel HGV[2].

N_2O is a potent GHG emission that is generated in Selective Catalytic Reduction (SCR) type aftertreatment systems. There is an increasing concern that the amount of N_2O being emitted has become a factor in the overall vehicle GHG emissions. As part of the aforementioned LowCVP work a dedicated gas HGV was tested against an SCR equipped diesel Euro VI comparator, the gas HGV was shown to produce less N_2O[2].

Natural gas vehicles and vessels are routinely selected in the ETI's energy system modelling environment (ESME)[3] as a cost effective way to mitigate carbon emissions. However, this modelling and indeed the wider industry does not portray emissions from the whole supply chain (including outside the UK), emissions that could in some instances be more potent as a greenhouse gas than CO_2 such as methane and N_2O. As part of this project, methane was the only gas other than CO_2 investigated and assessed against the relevant pathways.

The WTM model captures land-based heavy duty vehicles as well as ships and many of the outputs shown are for both of these sectors for the time period 2015-2035. In places, this report is more focussed on land vehicles than ships, given that industry stakeholders and policymakers have more influence on how the natural gas vehicle market evolves in the UK than they do for shipping, which is more international in nature.

[2] Brian Robinson, "Emissions Testing of Gas-Powered Commercial Vehicles", LowCVP, January 2017.

[3] www.eti.co.uk/esme

3. Modelling Methodology

The modelled pathway stages are shown in Figure 1.

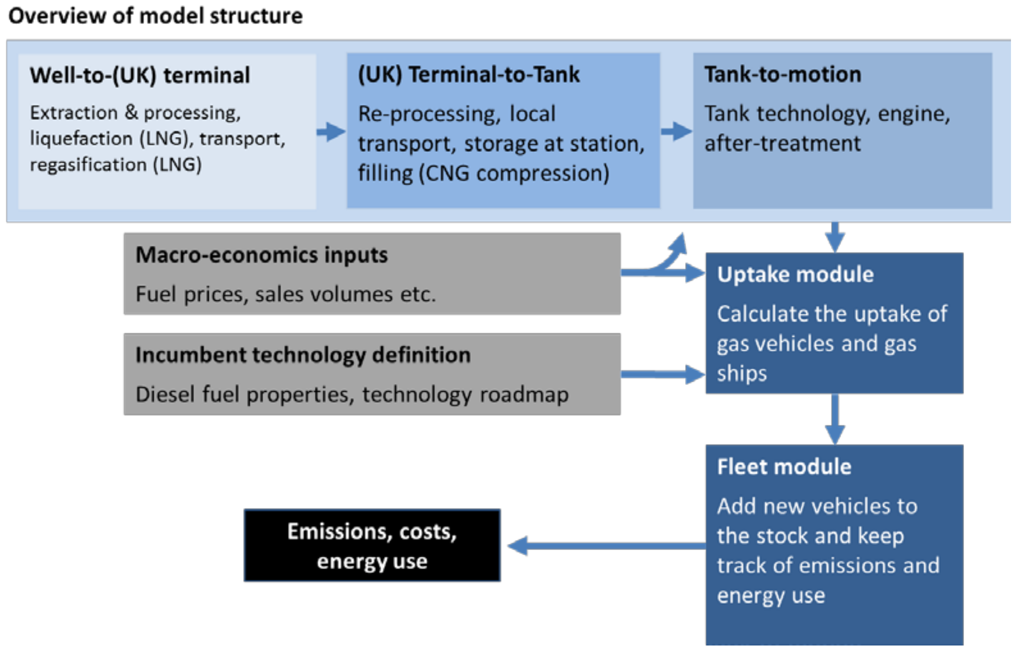

Figure 1 - Overview of the WTM model

In modelling the possible technology options and associated emissions in the gas pathway, the analysis was structured into three principal scenarios (base case, worst case and best case) involving coherent sets of assumptions that define emissions at all stages. The use of three different scenarios reflects the ranges in operational parameters and uncertainties associated with the emissions at each individual stage of the WTM pathways. Alternative scenarios are also used to analyse special cases, such as the impact of fuel duty on the economics of gas vehicles.

The base case scenario has been developed as a result of an extensive literature review and consultation with industry stakeholders. While it is not practical to list all relevant references, some of the key data sources included publications by the Department of Energy and Climate Change[4], UK gas distribution network operators[5] and the European Commission[6]. Direct communications with industry stakeholders at all levels - starting with the UK natural gas import terminal operators[7] through to the leading natural gas engine manufacturers - ensured that the assumptions used in the base case are up to date and representative. The projections in the base case scenario are aligned with the central forecasts published by National Grid[8], the Committee on Climate Change[9], the Department

[4] D. MacKay and T. Stone, "Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use," *DECC*, no. September, 2013.
[5] National Grid, Northern Gas Networks, SGN, and Wales&West Utilities, "Joint Gas Distribution Networks Discussion Document on Potential Benefits of Smart Metering on Shrinkage Measurement and Reduction," no. January, 2015.
[6] European Comission Joint Research Centre, *Well-to-Wheels analysis of future automotive fuels and powertrains in the european context*. 2014.
[7] "Direct communications with Grain LNG." 2015.
[8] National Grid, "Future Energy Scenarios," no. July, 2015.
[9] Committee on Climate Change, "The Fifth Carbon Budget: The next step towards a low-carbon economy," no. November, 2015.

for Transport[10] and the Department of Energy and Climate Change[11]. Coefficients and conversion factors used in the modelling were sourced from the tables published by the Department of Energy and Climate Change[12] and the Intergovernmental Panel on Climate Change[13].

The introduction of internally consistent themed scenarios significantly reduces the number of relevant combinations. Each scenario maintains a common set of dimensions:

- The type of fuel used in the vehicle – baseline diesel, CNG and LNG (e.g. sales of diesel, CNG and LNG HDVs are reported separately).
- HDV segments – single decker bus, double decker bus, MGV (<8 tonnes), MGV (8-18 tonnes), on-road construction, long haul, distribution, municipal, off-road construction, off-road tractor and shipping sectors including dry cargo, containership, RoPax (Ferries), chemical tankers and Offshore Support Vessels (OSV).
- The gas refuelling stations supplying natural gas are broken down into major distribution hub, haulier depot, bus & Refuse Collection Vehicle (RCV) depot, ship coastal station and LNG ship terminal. Each HDV segment is associated with a type of refuelling station. For instance the long haul HGV segment is associated with using major distribution hub refuelling stations whereas the bus segments and municipal HGV segment are associated with using BUS and RCV depot refuelling.
- The type of natural gas engine (e.g. dedicated stoichiometric, dual fuel fumigation) is consistent with the needs of that segment, for example dual-fuel engines are available in long haul and other on-road HGV segments, but are not available in bus segments as substitution rates would be very low due to the transient nature of their use.

These dimensions represent individual pathways within each scenario and are discussed in detail in sections 5, 6 and 7. All of the principal scenarios are based on plausible inputs, but different probabilities are assigned to elements within each scenario. The base case scenario should be treated as the most probable development scenario, whilst worst case and best case scenarios are intended to show less likely but plausible lower and upper bounds. An overview of each scenario is presented in Table 1. The key assumptions behind the results presented in this report are reported in the appendix.

Scenario	**Scenario Overview**
Base Case	The base case reflects current market trends, technology status and expected development pathways. Pathway emissions are assumed to be at the mean of the collected data. A moderate efficiency loss is considered in comparison to a diesel internal combustion engine (ICE) when using natural gas. Methane slip in the dedicated gas engines meets EURO VI with a margin of 0.25gCO_{2eq}/kWh compared to 0.5gCO_{2eq}/kWh allowed by EURO VI, while dual fuel engine just meet the limit.
Worst Case	Pathway emissions are assumed to be at the top of the identified range of values. Poor infrastructure development results in increased emissions during the distribution stage.

[10] Department for Transport, "Road Traffic Forecasts (English regional plus Welsh traffic growth- and speeds forecasts)," 2015.
[11] DUKES 2016, "6.1 Commodity balances 2015."
[12] Department of Energy & Climate Change, "UK Government GHG Conversion Factors for Company Reporting." 2016.
[13] IPCC, *Climate change 2007 - The Physical science basis*. 2007.

	Vehicle technology development does not accelerate as expected and environmental practices are poor, in particular leading to high methane slip. This means meeting the EURO VI limit for dedicated, high pressure direct injection (HPDI) and multi-point sequential port injection (MPSI) and up to 2.1gCO_{2eq}/kWh for retrofitted solutions which do not comply to EURO VI. Increased efficiency losses are considered in comparison to a diesel ICE when using natural gas.
Best Case	Pathway emissions are reduced through accelerated infrastructure development, high utilisation and by following best practices. Only a small efficiency loss is considered in comparison to a diesel ICE when using dedicated natural gas engines (2%) and HPDI dual fuel engines have efficiency parity with diesel. All natural gas engines are considered to have no methane slip[14].

Table 1 - Overview of the principal scenario themes

[14] Based on OEM consultations and OEM estimates.

4. Emissions Overview

Each stage of the WTM pathway is presented separately in sections 5, 6 and 7. An overview of the entire WTM pathway emissions is provided first in order to put individual contributions in the context of the overall emissions. Selection of a typical WTM pathway for a high-level overview is a non-trivial task as natural gas can be transported, distributed, dispensed and combusted in a number of different ways resulting in many possible combinations, each representing a unique pathway with a certain level of emissions associated with every stage.

The WTM pathways for LNG and CNG are quite complex, as such it is more practical to select a single representative combination of an HDV segment and a natural gas engine for the purpose of a high-level WTM emissions analysis. A dedicated natural gas long haul HGV has been selected as an example because it represents a good entry market for natural gas from an economic standpoint. The dedicated stoichiometric engine is the only natural gas technology that has met the EURO VI emissions standard (as of May 2017) and the long haul HGV segment has the largest share of all UK HDV CO_2 emissions.

Unlike dual-fuel HGVs, dedicated gas HGVs cannot fall back on diesel and use the existing diesel refuelling infrastructure. Therefore, the appropriate infrastructure and sufficiently high range are essential requirements for dedicated gas HGVs. The existing infrastructure of CNG/LNG/L-CNG refuelling stations – 17 stations across the UK with public access predominantly in the Midland and around London, already allows the currently available dedicated CNG HGVs (e.g. Iveco Stralis NP with 570 km CNG-only range[15]) to operate on long haul routes in the UK, excluding some regions in the South West and East of England[16].

The entire WTM pathway emissions for a dedicated long haul HGV are shown in Figure 2 for the three principal scenarios. In all cases, the emissions are shown in gCO_{2eq}/km and are separated into several stages. The dashed black line shows emissions of a diesel reference vehicle.

[15] Iveco, "New Stralis NP TCO2 Champion," 2016.

[16] Element Energy for LowCVP, "Infrastructure Roadmap - methane," 2015.

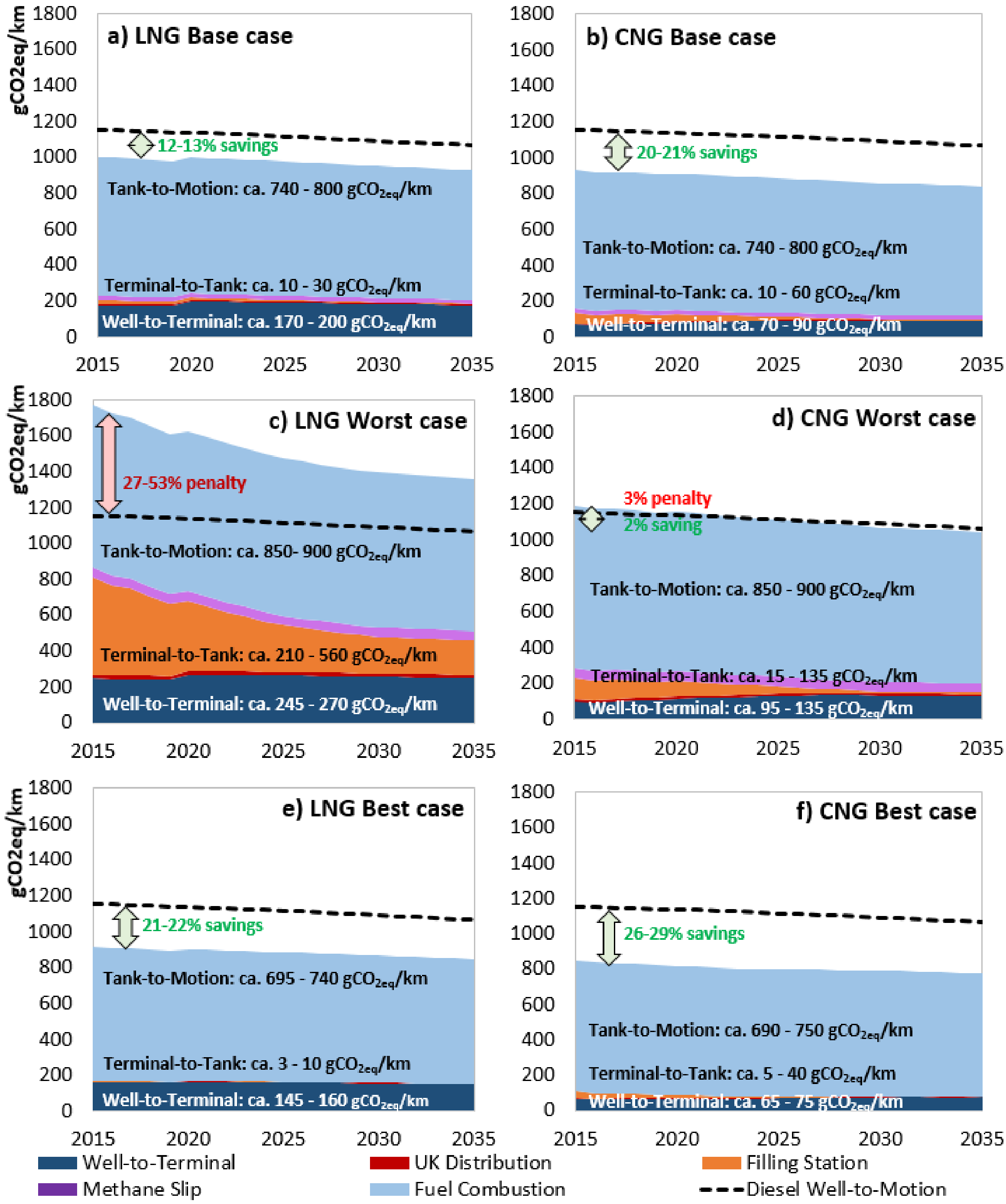

Figure 2 - Comparison of the total WTM emissions for an LNG and a CNG long haul vehicle with a dedicated natural gas engine in all scenarios

The LNG pathway achieves around a 13% emissions savings in the base case scenario compared to the diesel reference case. Well-to-Terminal (WTT) emissions increase slightly from 2020 as the US takes an increasing share of LNG imports to the UK. The WTM savings are largely achieved via 21% lower CO_2 content (on energy basis) of natural gas compared to diesel. Emissions savings from using a lower CO_2 content fuel are slightly offset by methane slip (release of un-combusted methane to the atmosphere from a natural gas vehicle) and the lower efficiency of a natural gas engine compared to a diesel baseline.

The worst case scenario emissions are markedly different between LNG and CNG pathways. Assumptions behind the worst case LNG scenario lead to a significant increase in the Terminal-to-Tank (TTT) emissions. Combined with a relatively high methane slip (particularly for the fumigation and multi-port dual fuel solutions that are assumed to be retrofitted), this results in a sharp increase in emissions for the LNG pathway. It should be noted that this worst case for LNG is intended to highlight the risk of high emissions if it is badly implemented. This high emissions case is relatively easy to avoid with high quality refuelling infrastructure and low methane slip vehicles.

In the worst case CNG pathway emissions savings by using a lower CO_2 content fuel are completely offset by the higher TTT emissions, in part due to emissions associated with electricity needed for compression. The TTT emissions decrease towards 2035 as the UK electricity grid is decarbonised.

The best case scenario indicates that the potential for emissions savings is very significant at 21-22% for LNG and 26-29% for CNG compared to the diesel reference. This can be achieved by using best practices during WTT stages, thorough optimisation of TTT stages and elimination of methane slip and efficiency losses from natural gas engines.

5. Well-to-Terminal Emissions

Well to Terminal emissions are defined as any emissions (CH_4 and CO_2) arising from the natural gas extraction and processing, liquefaction in the case of LNG, transport to the terminal within the UK and any regasification in the case of LNG.

UK gas is sourced from many different locations, in different forms and transported using various transportation methods including pipe from the UK Continental Shelf (UKCS), imports through the Norwegian and continental interconnectors or through LNG imports from Qatar and in the future also the USA.

- UK Continental Shelf (UKCS) – At around 34% (in 2015), the UKCS is currently still a significant source of gas for the UK (65% of UKCS gas was consumed in the UK in 2015[17] with the remaining 35% exported to continental Europe and Ireland[17]). It is expected that the UKCS will remain a significant contributor to gas consumption in the 2035 timeframe although this is expected to decline over the time horizon of this study[18].
- Norwegian Imports – At around 40% (in 2015) of gas consumed in the UK, Norway is the largest source of imported gas, and is expected to continue to remain a major source of gas over the time horizon for this study[17].
- Continental Imports – 5% (in 2015) of natural gas is imported from continental Europe via two interconnectors at Bacton, one from the Netherlands and one from Belgium. The comingled nature of gas via the interconnectors makes it impossible to determine the original source of the molecules. However, based on the gas flows across Europe it is reasonable to assume that these imports are a combination of gas from Norway, the Netherlands and continental LNG imports[19].
- LNG Imports – Qatar has been the predominant source of LNG into the UK for a number of years (with 92.6% of LNG imports, making up around 19% of supply in 2015[17]). It is expected to continue to be a part of the mix in the future. The USA is expected to become a significant exporter of LNG to Europe as it continues to exploit significant shale gas resources, some of which is contracted to the UK.

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[17] DUKES 2016 Data Tables 4.1, 4.3, 4.5

[18] National Grid Future Energy Scenarios 2016:

In all of the national grid future energy scenarios No Progression, Slow Progression, Gone Green and Consumer Power gas production from the UKCS declines significantly. In the time horizon for this study this roughly equates to a reduction in UKCS production of between 50% and 90% from 2020 to 2035.

[19] DUKES 2016 Chapter 4

- UK Unconventional Gas – Shale gas has the potential to make a significant contribution to the UK's gas requirement, although the extent to which this will happen and when is highly uncertain for both political and technical reasons. The contribution of coal-bed methane is likely to remain modest.

The UK is expected to heavily depend on imported gas over the time period of this study and this is played out in all of the National Grid future energy scenarios[20]. For the purposes of this study two of the National Grid gas scenarios have been selected, Slow Progression and Gone Green. Each of these scenarios present a decrease in total demand for natural gas in the UK by 10-15% from its current value (2015) of approximately 78bcm by 2035[20]. This change is expected to be driven by a reduction of residential demand and the uptake of low carbon heating and renewable electricity generation[20]. However, this does not take into account any demand from natural gas HDVs.

While trying to quantify the emissions associated with each pathway, it became apparent that there were ranges in the reported values for the same gas source. These variations in reported emissions generally stem from variations in methodologies and assumptions. These assumptions are captured in this work through the use of the aforementioned scenarios, by assuming the upper end of the identified range for the worst case scenario and lower end for the best case scenario. The values for the base case scenario represent the central or mean scenario indicated by reviewing the reported values. Figure 3 shows the assumed values for the base case, worst case and best case scenarios in 2020:

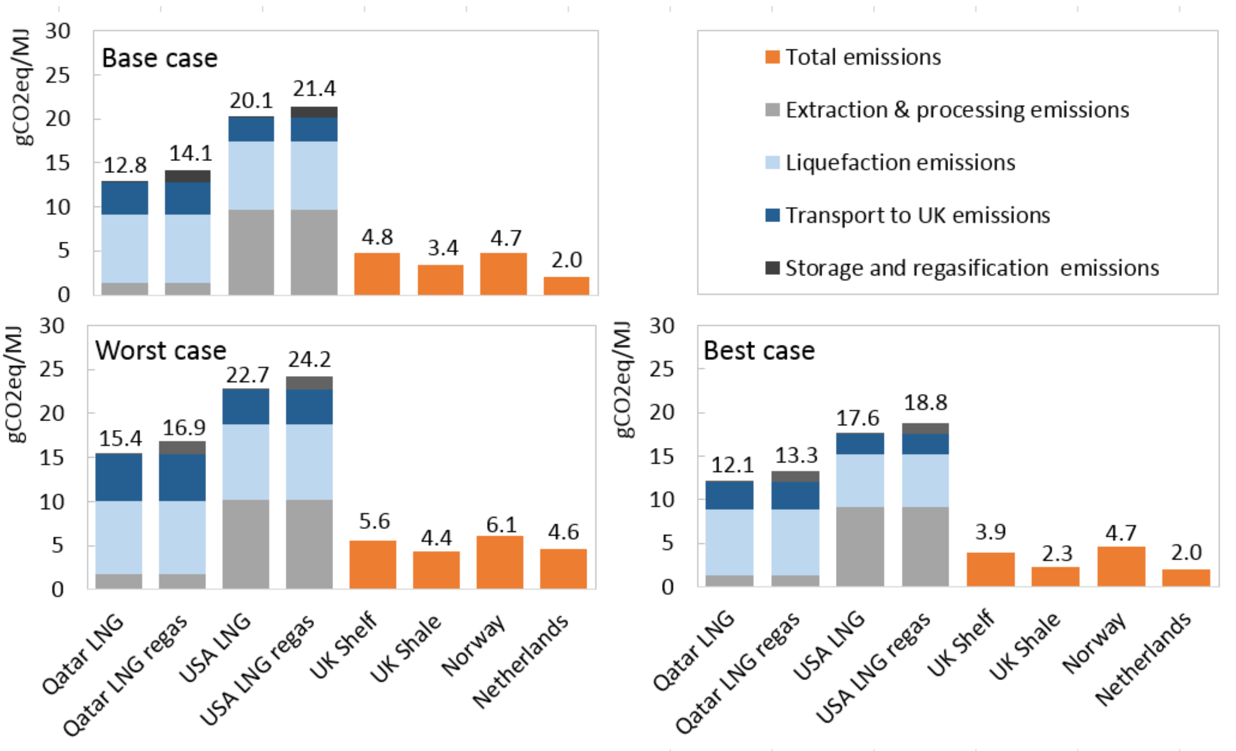

Figure 3 - WTT Emission for the base case, best case and worst case by sources and emission stages (where available)

In each of the National Grid scenarios a group termed 'generic imports' has been replaced by definitive sources. In the base and worst cases generic imports are split out and attributed to US

[20] National Grid, "Future Energy Scenarios," no. July, 2016.

and Qatar LNG, Norwegian and Continental imports. It is assumed that a relatively large portion of LNG imports (25%) originate in the US from 2020 in the Slow Progression scenario. This is justified by the fact that the majority of the LNG capacity holders at the Isle of Grain, the only UK terminal with the capability to dispense LNG to tankers, have bought long-term export volumes from the US[21]. The best case generic imports are split out to US and Qatar LNG, Norwegian and Continental imports. US LNG imports are minimised to 10% of the overall LNG imports in this scenario with a higher share of the generic imports being attributed to Norway. Figure 4 shows the natural gas profiles used for each case.

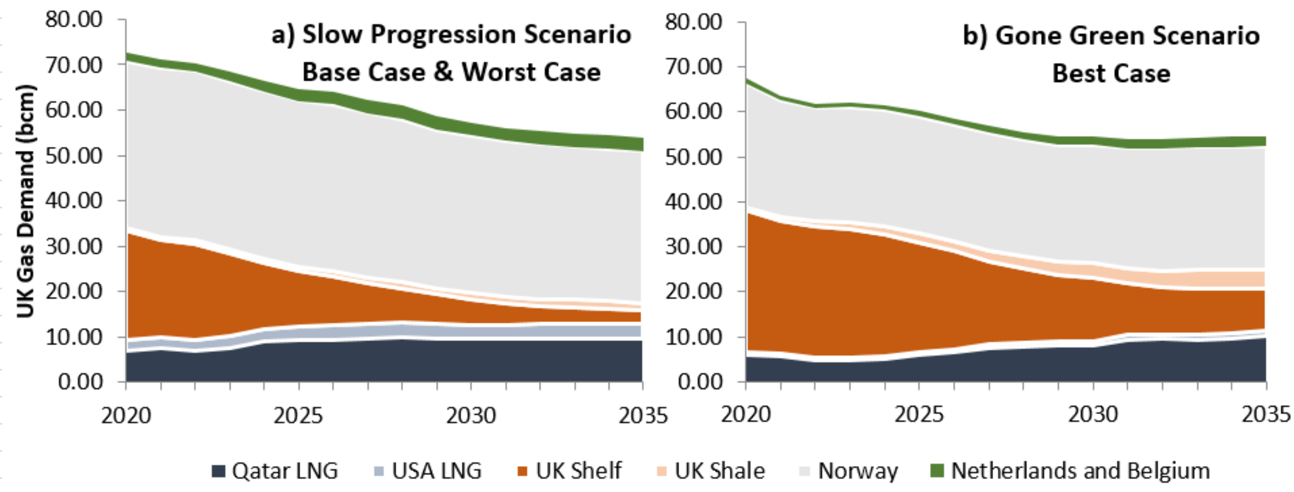

Figure 4 - Natural gas profile for UK in 2020 – 2035

Combining the information for the pathways, shown in Figure 3, with the expected UK gas profiles for each scenario, shown in Figure 4, generates a representation of the expected emissions for each of LNG and CNG in the WTT pathways as shown in Figure 5. LNG pathways have higher WTT emissions compared to CNG pathways in all scenarios due to the higher extraction (US LNG only), transportation and liquefaction steps for LNG compared with the blended gas used in the gas grid. Emissions in each of the CNG and LNG pathways change over time due to the changing sources of UK gas and advances in reducing the emissions for each of the sources.

[21] "Direct communications with Grain LNG." 2015.

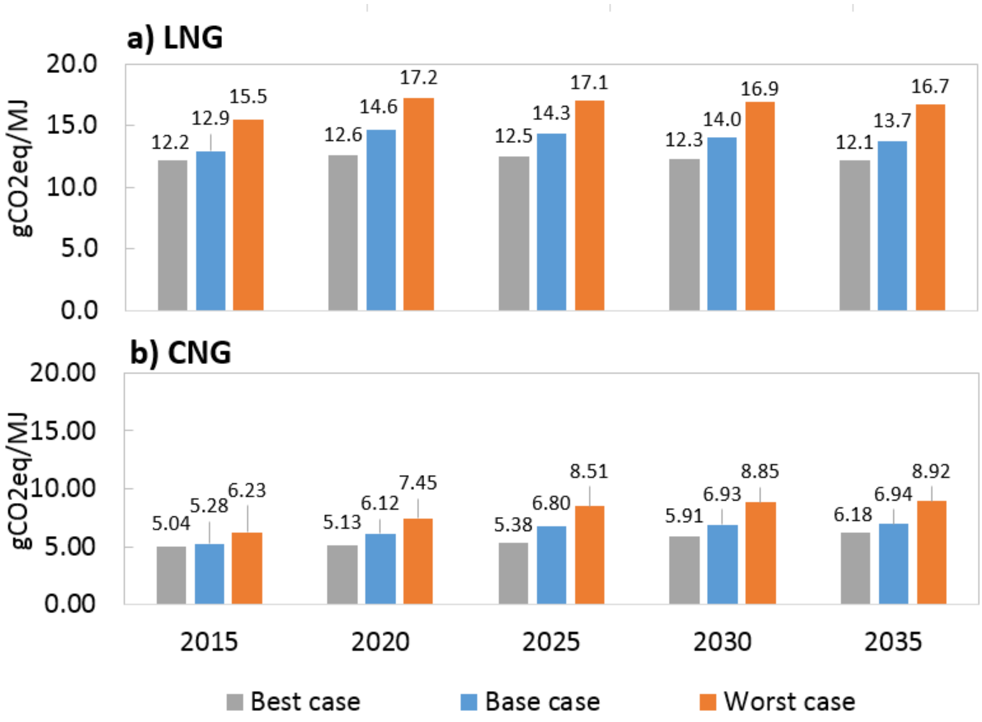

Figure 5 - Comparison of Overall WTT emissions between the principal scenarios for LNG and CNG

6. Terminal-to-Tank Emissions

The TTT stage includes all emissions from natural gas pathways from the terminal up to and including the dispensing of fuel into the natural gas vehicle or vessel. For each pathway of CNG and LNG the following steps are covered:

CNG:

1. Transport through the natural gas grid, including compression in the transmission grid, heating and methane leakage at lower pressure tiers.
2. Emissions from the energy use for gas compression and dispensing at CNG stations.

LNG - Land

1. LNG transport emissions by road tanker from the terminal to the LNG refuelling station.
2. Energy use from LNG (and L-CNG) station operations, such as pumping energy during tanker unloading and filling.
3. Methane emissions from transport and station operations, for example venting of boil off gas or keeping LNG in liquid form.

LNG - Shipping

1. LNG transport emissions by barge from the LNG terminal to a coastal ship refuelling station[22].
2. Energy use from LNG station operations, such as pumping energy use during bunkering.
3. Methane emissions from station operations.

In all pathways the TTT emissions are dominated by the emissions associated with the filling stations as shown in Figure 6. In the base case, emissions are particularly high for the CNG stations connected to low pressure tiers of the gas grid. This is the result of the electricity consumption of the compressors being relatively high at these stations[23], as well as methane leakage being higher in the lower pressure network.

No compression is required at LNG and L-CNG stations but these stations still require a non-negligible amount of energy for pumping or regasifying LNG respectively. LNG stations are assumed to use Liquid Nitrogen (LiN) as a medium for transferring heat to maintain LNG in liquid

[22] This step is excluded if ships are assumed to bunker directly at the LNG terminal, although in all the scenarios presented in this report it is assumed that bunkering occurs at coastal stations.

[23] The analysis assumes the suggested trajectory for the carbon intensity of the electricity grid in the Committee on Climate Change's Fifth Carbon Budget, meaning that a significant level of decarbonisation by 2030 will reduce emissions associated with the filling stations.

form. The emissions associated with the LiN production and transport add approximately 1gCO_{2eq} per MJ of LNG dispensed in the base case scenario.

CNG pathway emissions are expected to increase only slightly in the worst case scenario as a result of the connection to a lower pressure tier of the gas grid. L-CNG pathway emissions are equally assumed to increase only slightly in the worst case scenario due to increased travel distances for the LNG tankers delivering to a relatively poor filling network. In contrast, LNG station experience a significant increase in emissions in the worst case scenario due to two critical factors:

1. The utilisation rate of LNG is assumed to be very low in initial deployment, leading to very high LiN requirements per volume of LNG dispensed to prevent boil-off. Specifically it is assumed that 400 litres of LiN is used every day[24] at a station serving a single HDV. The use of LiN in this scenario is assumed to converge with the base case in 2035 as the utilisation of the station increases. In reality a station with a demand this low and utilisation of LiN this high would not be economically sustainable. However, it is used to show the potentially very high but avoidable emissions from LNG stations.
2. The absence of a vapour recovery system, that could be used to prevent LNG boil-off venting from the HDV tank(s) at the beginning of each refuelling event, means that venting to the atmosphere is unavoidable. As a result 5kg of gaseous methane is assumed to be vented from two tanks with a combined capacity of 250kg of LNG before every refill, contributing 12gCO_{2eq} to the pathway emissions.

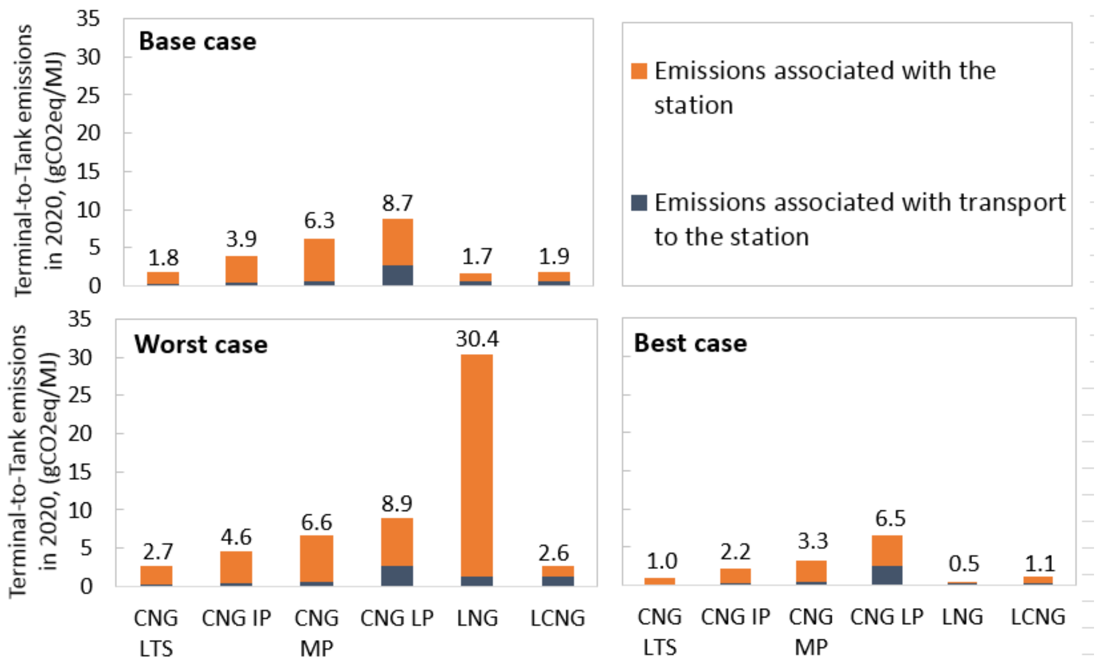

Figure 6 - TTT emissions by station type for all scenarios in 2020

In the best case scenario LNG is transported over shorter distances whilst best practices are used at all stations to prevent any methane leakage.

[24] Based on a consultation with a major distributor and the suggested worst case where a station is very poorly utilised.

CNG stations are expected to be connected to a mix of grid pressures[25] and the pathway emissions are a weighted average of the associated tier emissions as shown in Figure 6. Figure 7 shows the share of CNG connections in each of the three scenarios with the base and best case scenarios assuming that 50% of future CNG stations are connected to the high pressure Local Transmission System. This reflects the current market trajectory. Connecting CNG stations to the lower pressures of the gas grid requires less capital investment. However, connecting to lower grid pressures incurs larger operational expenditures due to the requirement to recompress gas to higher pressures; this forms the basis for the worst case scenario.

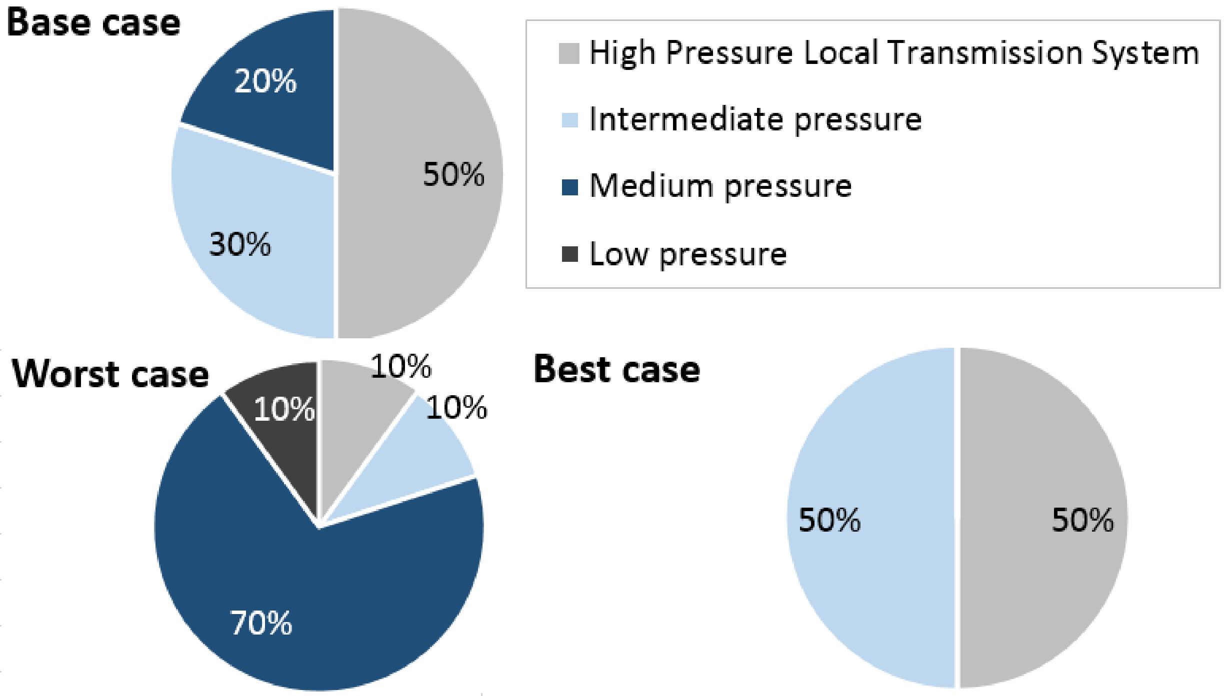

Figure 7 - The share of CNG station connections to the distribution network system of the National Grid across the three scenarios

TTT emissions for LNG pathways are affected by the assumptions for filling infrastructure, utilisation rate and the choice of practices employed at the stations. CNG pathway emissions are most affected by the pressure tier in which they are connected to the gas grid. TTT emissions decrease with time in all scenarios for both the LNG and CNG pathways as shown in Figure 8. In both cases, the electricity grid decarbonisation plays an important role in decreasing the emissions. In the case of LNG, the increase in LNG delivery vehicle efficiency, as well as the eventual increase in station utilisation even in the worst cases scenario, leads to the lower emissions in 2035.

[25] Each pressure tier of the gas grid has a range of pressures depending upon the location for example it is 10 – 42 bar for the LTS.

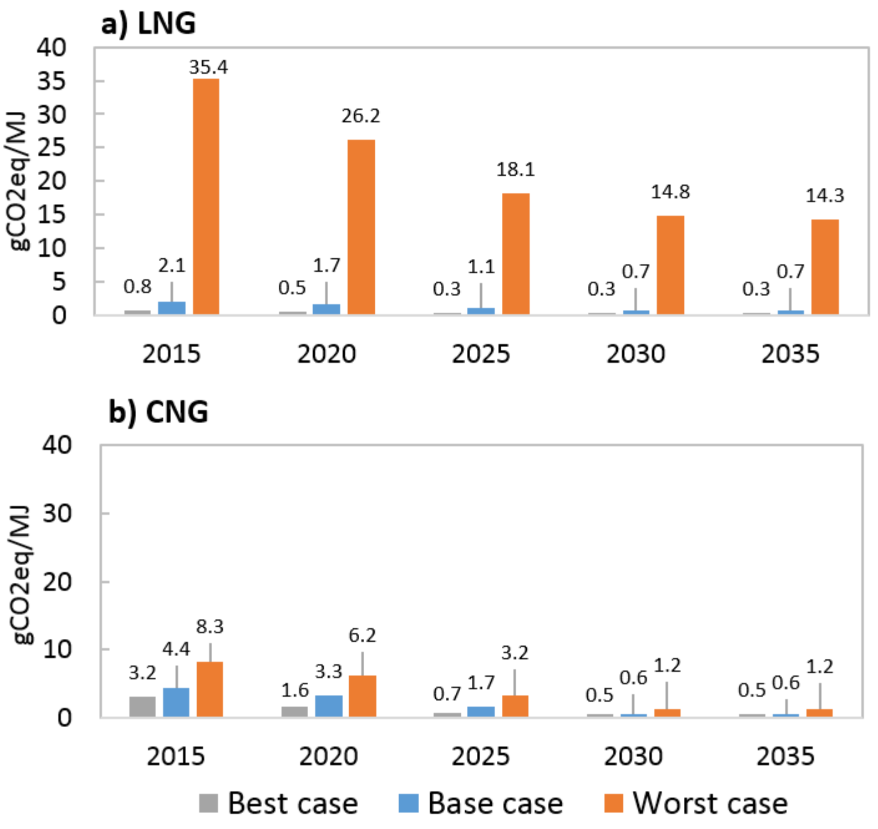

Figure 8 - Comparison of overall Terminal-Tank emissions between the principal scenarios for LNG and CNG

7. Tank-to-Motion Emissions

The final stage of the pathway is to capture tailpipe emissions from the vehicles or vessels in each scenario. This includes AdBlue[26] for diesel engines in the reference case and methane slip from natural gas engines. Methane emissions in the Tank-to-Motion (TTM) pathway result from incomplete combustion of the air/fuel mixture in the engine and can be caused by:

- Losses during valve overlap if a direct path from inlet to outlet ports exists temporarily in the cylinders with long injection timings, this is generally specific to the larger marine engines
- Turbulence (e.g. at high engine revolutions) causing unstable flame propagation in the cylinder that results in local non-stoichiometric zones even if the overall injected mixture is stoichiometric
- Heat losses at the wall in the combustion chamber that slow down the combustion in the boundary layer
- Trapped methane in crevice areas in the combustion chambers

Minimising the inlet/outlet valve overlap and precise control of gas admission to the combustion chamber can significantly reduce methane slip in dedicated gas engines. In some, mainly larger dual fuel engines, this is more difficult to achieve because diesel operation requires additional cooling of the exhaust valves. However, some dual fuel solutions, such as multipoint sequential port injection, have the capability to control gas injection timing and can avoid the valve overlap period. In cases where injection occurs and valve overlap cannot be avoided engines must rely on after-treatment systems for catalytic oxidation of un-burnt methane. Although this is an area of active research, current commercial after-treatment systems do not allow full oxidation of methane at low temperatures (below 400°C), which leads to a high methane slip particularly after a cold start. Generally, a dedicated gas engine running stoichiometric combustion will have higher exhaust temperatures than a dual fuel engine exhaust which runs lean burn operation. However, recent advances in research of catalysts for engine after-treatment systems indicate the emergence of novel materials that allow full methane conversion at temperatures as low as 350°C[27]. Although these materials are yet to demonstrate stable long term operation in commercial systems, this indicates progress in this area and therefore the

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[26] Trademark for the aqueous urea solution that is used in combination with the Selective Catalytic Reduction aftertreatment catalyst (SCR) to reduce emissions of NOx from the exhaust.

[27] M. Hoffmann, S. Kreft, G. Georgi, G. Fulda, M.-M. Pohl, D. Seeburg, C. Berger-Karin, E. V Kondratenko, and S. Wohlrab, "Improved catalytic methane combustion of Pd/CeO<inf>2</inf> catalysts via porous glass integration," *Appl. Catal. B Environ.*, vol. 179, pp. 313–320, 2015.

analysis includes several dual fuel natural gas engine technologies that have not yet met the EURO VI standard, but may meet it in the future and could therefore enter the market.

Many types of gas engine are available to the market, both dual fuel and dedicated solutions. In most dedicated solutions, the combustion process is initiated by spark and shares many similarities to a gasoline engine. This is in contrast to dual fuel solutions which rely on a diesel pilot to burn under compression and ignite the gas. Each of the dual fuel solutions available are detailed here:

- Fumigation (single point port injection) systems inject natural gas into the inlet manifold usually from a single point, where it mixes with the combustion air prior to entering the cylinders. Whilst these systems typically have some level of control over gas injection there is no control of the distribution of gas from cylinder to cylinder. Furthermore it is not possible to avoid gas entering the exhaust ports during valve overlap periods. Typical diesel displacement is in the range of 30-60% over all engine speeds.
- Multi-point port injection involves a computer controlled injection where more than one intake port is used, providing an improvement in gas distribution from cylinder to cylinder when compared to fumigation systems. This type of system offers similar replacement characteristics as fumigation engines above.
- Multi-point sequential port injection (MPSI) systems use multiple gas injectors located near the inlet valves to allow computer control over the timing and amount of gas injected into each cylinder (and in some systems the distribution between each intake valve within each intake port). This additional level of control allows for various gas injection strategies and the ability to avoid the valve overlap period. Typical diesel displacement is 50-80%.
- High Pressure Direct Injection (HDPI) allows substitution of 90-95% of diesel by natural gas. First generation systems could only use LNG and not CNG. HPDI 2.0 is currently in development by Westport and claims to allow CNG operation while offering diesel-level engine efficiency and compliance with Euro VI emissions standards[28]. No on-highway products are currently available for sale, but it is expected that some products may be available to the market in 2018. Caterpillar and Westport have produced HPDI engines for the large engine off-highway and locomotive markets.

To date, only one solution for a natural gas HGV has met the Euro VI standard - the stoichiometric dedicated natural gas engine. Previous OEM strategies attempting to repurpose diesel engines into gas engines have been terminated. One major reason why thermal efficiency and low emission can be met is that natural gas engines are now being designed and built as dual fuel and dedicated gas engines specifically. Many components used in the diesel engine can still be used, but gas specific parts are produced for gas specific use. It is expected that both HPDI and dedicated gas engine variants can meet Euro VI emission criteria, the dedicated stoichiometric at a reasonable cost but generally with an efficiency penalty in respect to a diesel equivalent. Conversely, the HPDI variant is expected to meet emissions criteria with diesel like after-treatment systems, with diesel like efficiency, but this approach is likely to be more costly.

The land vehicle categories represented in the WTM model are shown in Figure 9. Three types of on-highway goods vehicle are captured; small MGVs (<8t), MGVs (8-18t rigid) and HGVs. HGVs are further split into duty cycle such as construction, long haul, municipal and distribution. Buses are captured and modelled as single decker and double decker buses. Although there is very little current activity in natural gas off-road vehicles, they are represented through two archetypes, capturing four vehicle types:

[28] "Westport HPDI 2.0," 2016. [Online]. Available: http://www.westport.com/is/core-technologies/hpdi-2. [Accessed: 23-Aug-2016].

- Off-road tractor: agricultural tractors (e.g. John Deere 6150R);
- Off-road construction: medium wheel loaders (e.g. Caterpillar 966 MWL), hydraulic excavators (e.g. Caterpillar 320E HEX), articulated quarry truck (e.g. Caterpillar 725C)

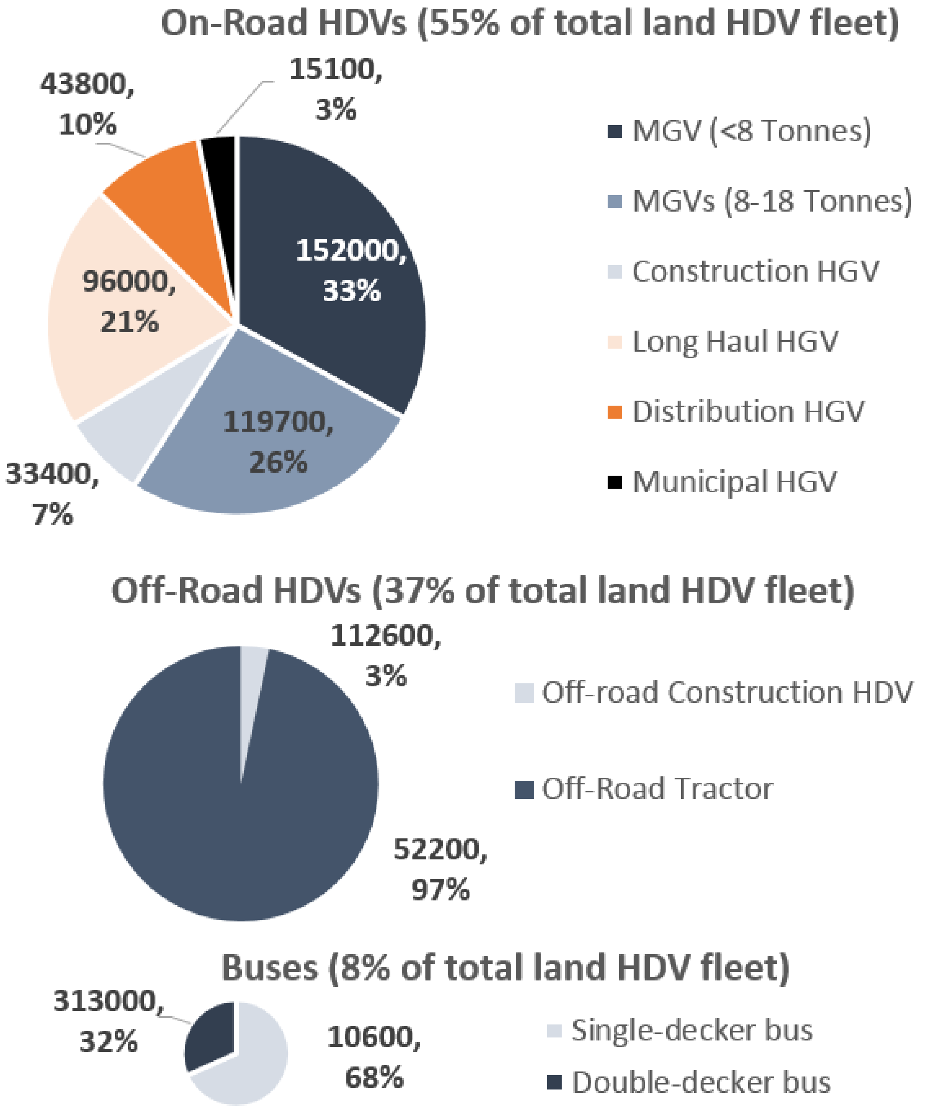

Figure 9 - Land vehicles included in the WTM model by group and by segment within each HDV group. Fleet numbers refer to the approximate number of vehicle currently in the UK vehicle parc based on DfT statistics[29]

To enable analysis of the TTM emission savings, the UK fleet of land HDVs has been separated into several duty cycles. Each vehicle or duty cycle has several vehicle technologies available to take up at different points in time in the model. Table 2 shows this technology availability for the vehicles / duty cycles.

[29] Department for Transport, "Vehicles statistics," 2015. [Online]. Available: https://www.gov.uk/government/collections/vehicles-statistics#publications-2015.

	Stoich	HPDI	MPSI	Multi-port	Fumigation
Single-decker bus	2016	X	X	X	X
Double-decker bus	2016	X	X	X	X
MGV's (8-18 Tonnes)	2020	2020	2020	2020	2020
Construction HGV	2015	2020	2017	2020	2020
Long Haul HGV	2015	2020	2017	2020	2020
Distribution HGV	2015	2020	2017	2020	2020
Municipal HGV	2015	2020	2017	2020	2020
Off-road construction	2020	X	X	2020	2020
Off-road tractors	2020	X	X	2020	2020

Table 2 - Availability for take up of the engine technologies in different HDV segments (and different duty cycles in the HGV segment) assumed for the market analysis, X signifies a technology that is not available.

The model does not quantify N_2O emissions as no robust testing methodology has been developed for this greenhouse gas at the time of writing. However, it is acknowledged that due to its high global warming potential of 298[30], even small quantities emitted from the tailpipe may result in a few percentage points increase in diesel WTM emissions. N_2O emissions, although not regulated, are sometimes declared to the US EPA during engine testing[31] and in some instances N_2O can contribute as much as 10% of the overall GHG emissions. This is particularly important to note, considering the expectation that a HPDI dual fuel engine will still require an SCR aftertreatment system to be fitted.

TTM emissions are calculated taking into account the natural gas engine efficiency losses, methane slip and diesel substitution rate. These parameters are specific for each technology type listed above and are different between the scenarios. A literature review, as well as consultations with OEM's and evidence from the Low Carbon Truck Trial presented by CENEX[32] and the Low Carbon Vehicle Partnership[33], has been used to generate the values shown in Table 3. These parameters are assumed to be equal across all duty cycles and therefore the relative emissions savings are the same across all segments.

[30] IPCC, *Climate change 2007 - The Physical science basis*. 2007.
[31] https://www.epa.gov/compliance-and-fuel-economy-data/engine-certification-data
[32] CENEX, "Low carbon Truck and Refueling Infrastructure Demonstration Trial Evaluation", Final Report to the DfT, December 2016
[33] Brian Robinson, "Emissions Testing of Gas-Powered Commercial Vehicles", LowCVP, January 2017.

Engine	Methane slip(gCH_4/kWh)	Efficiency loss (%)	Diesel substitution rate (%)
	Base Case		
Baseline Diesel	0	N/A	N/A
HPDI	0.4	3%	96%
MPSI	0.5	4%	45%
Fumigation dual fuel	0.5	7%	33%
Multi-port dual fuel	0.5	7%	44%
Stoichiometric dedicated gas	0.25	6%	100%
	Worst Case		
Baseline Diesel	0.0	N/A	N/A
HPDI	0.5	5%	90%
MPSI	0.5	8%	40%
Fumigation dual fuel	2.1	18%	30%
Multi-port dual fuel	2.1	8%	30%
Stoichiometric dedicated gas	0.5	24%	100%
	Best Case		
Baseline Diesel	0	N/A	N/A
HPDI	0	0%	97%
MPSI	0	1%	50%
Fumigation dual fuel	0	5%	45%
Multi-port dual fuel	0	5%	45%
Stoichiometric dedicated gas	0	2%	100%

Table 3 - Engine parameter values assumed in the three principal scenarios in 2020

Figure 10 shows TTM emissions for each natural gas engine along with the diesel baseline emissions from the long haul segment in 2020. In the interest of clarity, emissions for the other segments are not shown here. However, the relative performance of engines in other segments is the same as indicated in Figure 10.

In the base case, all natural gas solutions bring positive emissions savings on a TTM basis despite a 3-7% efficiency loss compared to diesel and the additional emissions from methane slip.

The best case scenario assumes a very low efficiency loss from natural gas engines compared to diesel engines (0-5%). Most dual fuel solutions currently on the road are retrofit solutions. Evidence from the Low carbon Truck Trial[32] and from proposed new OEM solutions[34] suggests that closer OEM integration reduces or eliminates any efficiency loses by using natural gas. All natural gas vehicles

[34] International Powertrain Conference Proceedings 2017, David Mumford, Westport Innovations.

are assumed to have zero methane slip. This, in combination with high substitution rates for all natural gas solutions, leads to relatively high emissions savings on a TTM basis.

In the worst case scenario only the HPDI and the dedicated engines lead to the emissions savings on a TTM basis. Low diesel substitution rates, high efficiency losses and significant methane slip in other engines result in TTM emissions increases.

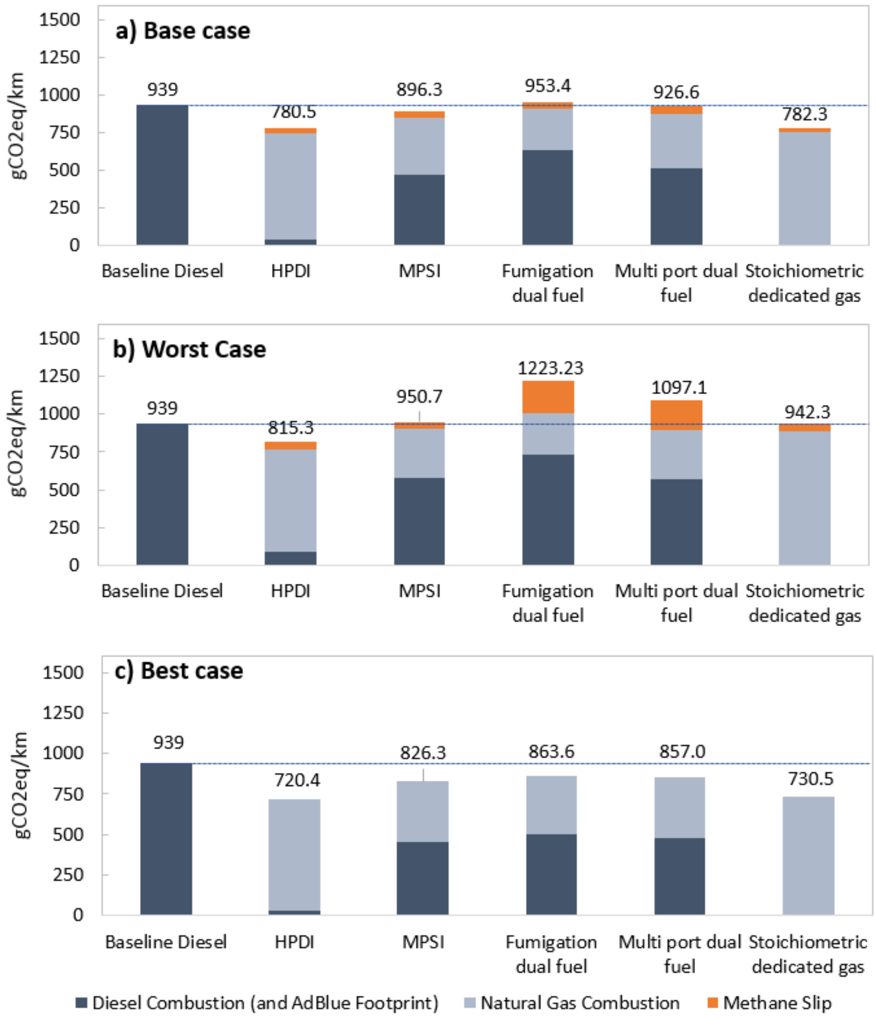

Figure 10 - TTM emissions for each natural gas technology in each case with reference to the baseline diesel emissions for a long haul HGV in 2020.

Ship emissions are modelled using a holistic analysis of the global shipping system indicating how shipping might change in response to developments in fuel prices and environmental regulation (on emissions of SOx, NOx, PM, CO_2)[35]. The scope includes all major ship types and trade flows. Ship types modelled include container ships, dry bulk carriers, chemical tankers, passenger ferries and offshore service vessels. The fleets of container ships, dry bulk carriers and chemical tankers are all global and the fleets of passenger ferries and offshore service vessels are UK. Emissions are UK-specific for all fleets, using the allocation methodology that assign emissions to the UK based on the trade routes.

[35] The modelling of ship emissions is based on the Maritime Model, previously developed by UCL. The Well to Motion model incorporates a version of the Maritime Model to allow generation combined emissions results for the land-based and marine sectors.

8. Implications of Natural Gas HDV Uptake on the UK HDV Fleet Emissions

8.1. Uptake modelling and the implications for natural gas infrastructure development

The uptake (annual sales) of different solutions for land vehicles is calculated in the WTM model based on their attractiveness to operators. 'Attractiveness' is primarily driven by the total cost of ownership (TCO) over the relevant time horizon[36]. The sales of natural gas HDVs have been capped at a few hundred sales per year in 2016-2018 to reflect limited availability of vehicles as HDV manufacturers begin to ramp-up production. Additionally, the purchase of gas vehicles was assumed to attract a 'penalty' that increases the perceived cost even when the gas vehicles have competitive TCOs. This reflects uptake barriers such as fleet managers' reluctance to try new technologies and uncertainty over vehicle residual values, etc. The penalty is gradually decreased to zero by 2035.

Uptake projections are calculated using a logit-based choice model. A logit model generates probabilities or market shares of discrete choices such as whether or not a particular product is chosen[37]. The logit approach allows technologies to 'compete', since the market shares predicted by the model vary smoothly in proportion to their relative TCO. This provides a better representation of the real-world market compared to a 'winner takes all' approach, where the technology with the lowest overall cost takes 100% of the market.

Currently, very few HGV fleets in the UK have natural gas vehicles. Those that do include John Lewis Partnership, DHL and Howard Tenens, however, many fleet operators either have not considered natural gas or do not think this is a solution suitable for their fleets. This introduces a significant amount of uncertainty to the estimation of the future share of fleet operators considering natural gas. Currently, fleet operators view the relatively undeveloped infrastructure and the range limitations as the main reasons for not adopting natural gas for their fleets. However, the model assumes that even in the worst case scenario the natural gas market for transport will eventually become sufficiently developed to support the infrastructure needs of most fleet operators. At the same time, some fleet operators will not be able to use natural gas solutions because these solutions may not meet their specific needs, e.g. intermittent usage patterns combined with extra-long ranges. For all of the cases, (base, worst and best), a separate range of uptake scenarios was developed to represent the uncertainty in the likelihood of operators considering purchasing a natural gas vehicle. It is only assumed that 100% of fleet operators in all sectors will consider natural gas solutions in the maximum uptake scenario. In the central scenario, it is assumed 80% of fleet operators consider natural gas in all but the long haul and distribution sector, where 100% of operators consider natural gas solutions. On the other hand, in the minimum uptake scenario, only 50% of all fleet operators will consider natural gas solutions. This approach allows uncertainty in natural gas HDV uptake to be captured in the fleet evolution part of the model, a matrix of the case's and the scenarios in the cases are captured in Table 4.

[36] TCO includes expenditure on fuel, maintenance, as well as losses incurred due to depreciation of the vehicle over the TCO time horizon -7 years for buses, 4 years for on-road HDV's and 6 years for off-road HDV's.

[37] A. S. Hadi and S. Chatterjee, Regression Analysis by Example, 4th Edition. Wiley-Interscience, 2006.

Uptake for Case	Base Case	Best Case	Worst Case
Central Scenario	80% (100% for long haul and distribution)	80% (100% for long haul and distribution)	80% (100% for long haul and distribution)
Minimum Uptake	50%	50%	50%
Maximum Uptake	100%	100%	100%

Table 4 - Percentage of operators considering natural gas in each of the cases

Figure 11 shows that a relatively modest fleet penetration of natural gas vehicles may be expected in the three principal scenarios (base case, worst case and best case) based on the economic proposition of natural gas vehicles and the ranges specified of operators considering natural gas vehicles.

The attractiveness of natural gas vehicles stems from the lower cost of natural gas compared to diesel primarily due to the favourable taxation rates natural gas has over diesel.

Hybrid powertrains are represented through the inclusion of an electric hybrid option for buses (for both the diesel and natural gas configurations). This solution is assumed to bring a 13-14% reduction in fuel consumption per kilometre, but a relatively high cost premium of ca. £100,000 limits its uptake to 5% in the single-decker and double-decker bus segments in 2035. This is in the absence of specific policies such as hybrid only procurement rules.

The initial uptake of natural gas HDVs, shown in Figure 11, is low in the first few years in all scenarios because of the cap on gas HDV sales in the first few years due to limited vehicle availability. The range of sales of gas HDVs grow quickly as soon as the cap is removed after 2018. A market share of new vehicles of between 17% (minimum uptake scenario) and 35% (maximum uptake scenario) is forecasted in 2035 in the base case scenario depending on the fraction of fleet operators considering natural gas. In the central base case natural gas vehicle have a fleet share of 32% in 2035.

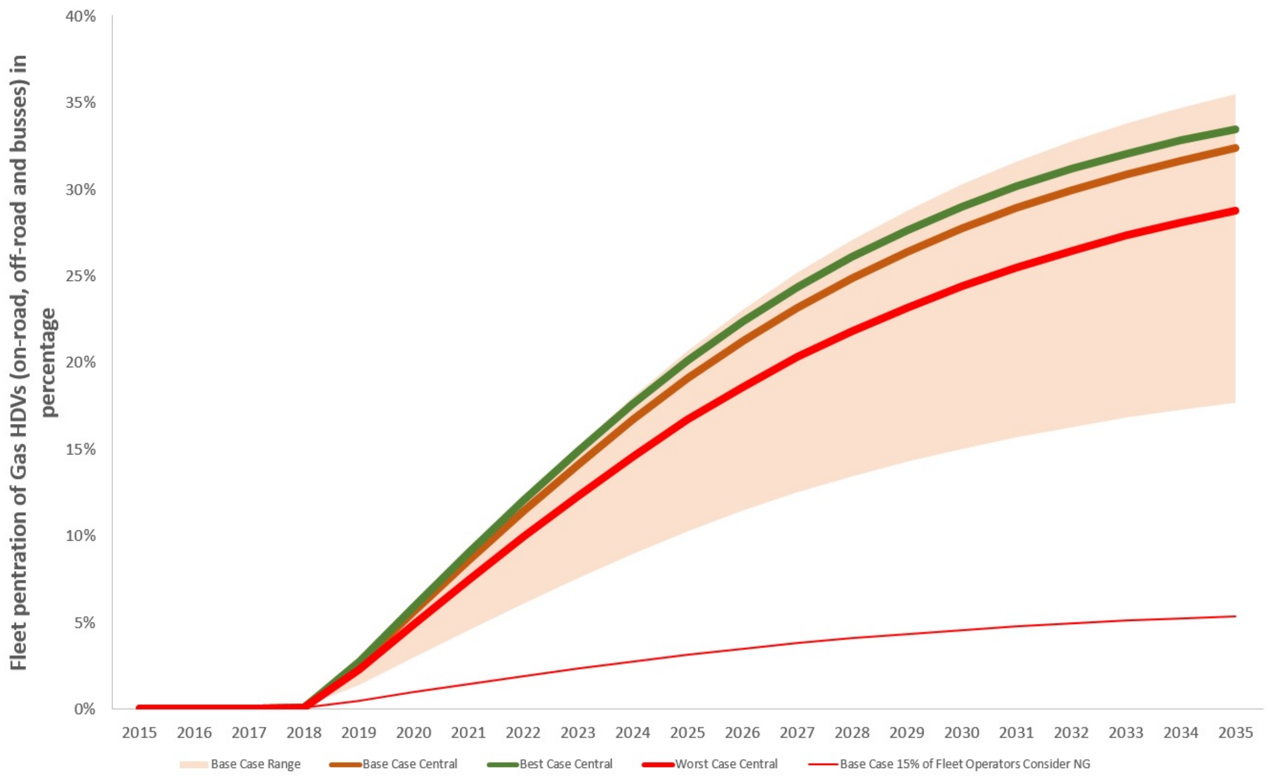

Figure 11 - The penetration of natural gas land HDVs into the UK fleet in the base case scenarios

Uptake is 3.5% lower in the worst case central scenario and 1% higher in the best case central scenario. The difference in uptake between scenarios is the result of different levels of natural gas engine efficiencies, i.e. a lower efficiency of natural gas engines in the worst case scenario means that these will bring lower running cost savings and therefore fewer fleet operators will buy natural gas HDVs.

By 2035 land-based HDVs with dedicated stoichiometric engines could become the largest technology segment after baseline diesel HDVs. The projected share of dedicated gas engines ranges between 7% in the off-road tractor segment and 37% in each of the bus sectors. The long haul HDV segment has a projected share of around 30% in 2035. For reference, the combined share of multi-port and fumigation dual-fuel technologies is only around 7% in the off-road tractor segment, but this rises to around 40% in the long haul segment in 2035. A detailed split of the uptake of each technology in all segments is shown in Figure 12.

The penetration of natural gas HDVs in the range of 17-35% in the base case requires major investments into refuelling infrastructure. A separate scenario with only 15% of fleet operators who consider natural gas HDVs has been included in Figure 11 to represent a world in which the CNG and LNG station infrastructure remains relatively undeveloped and can only serve a relatively low percentage of the fleet operators in the UK. In this case, the uptake of natural gas HDVs reaches only 5% in 2035 for the base case. This level of uptake could be sustained with already existing natural gas refuelling infrastructure where there are 25 private depot stations, with 60% offering LNG, and 17 public forecourts with a similar LNG/CNG mix[38]. However, such marginal uptake of natural gas HDVs reduces the potential for emissions savings on a fleet level.

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[38] Element Energy for LowCVP, "Infrastructure Roadmap - methane," 2015.

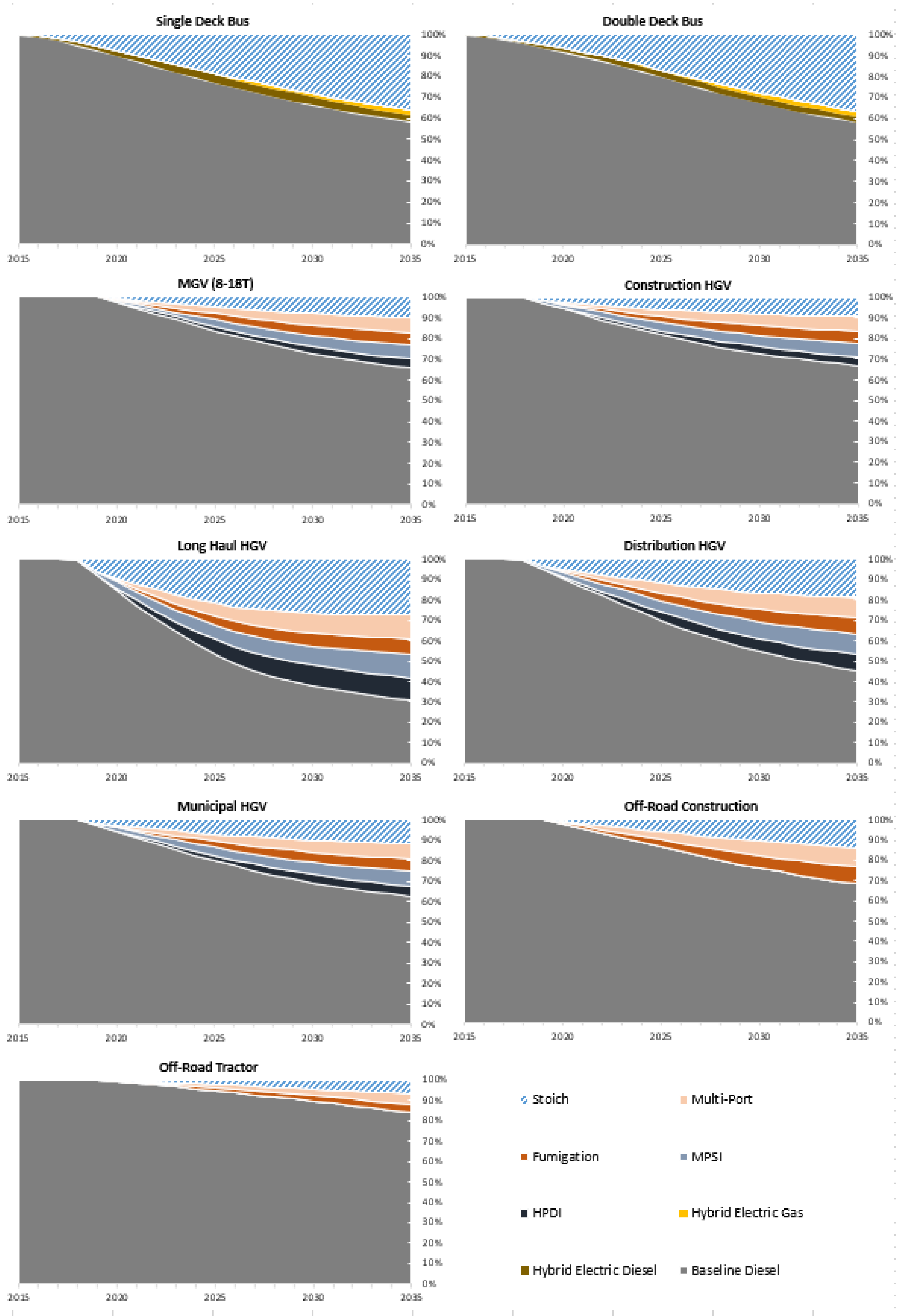


Figure 12 - Fleet Share of different technologies in each of the represented segments for the base case scenario

The infrastructure development required to sustain the uptake of natural gas HDVs under the base case scenario, is shown in Figure 13. This is broadly in line with previous estimates published by Element Energy for the LowCVP Transport Infrastructure roadmap for methane[38]. Figure 13 suggests that 137 major distribution hubs, 153 haulier depots and 78 bus and refuse collection vehicle (RCV) depots would be required to support the UK fleet of natural gas HDVs in 2035. These estimates are based on the assumption that filling stations are constantly operating at 75% load, resulting in 40 tonnes per day dispensed at a major distribution hub, 15 tonnes per day at a haulier depot and 10 tonnes per day at bus and RCV depots.

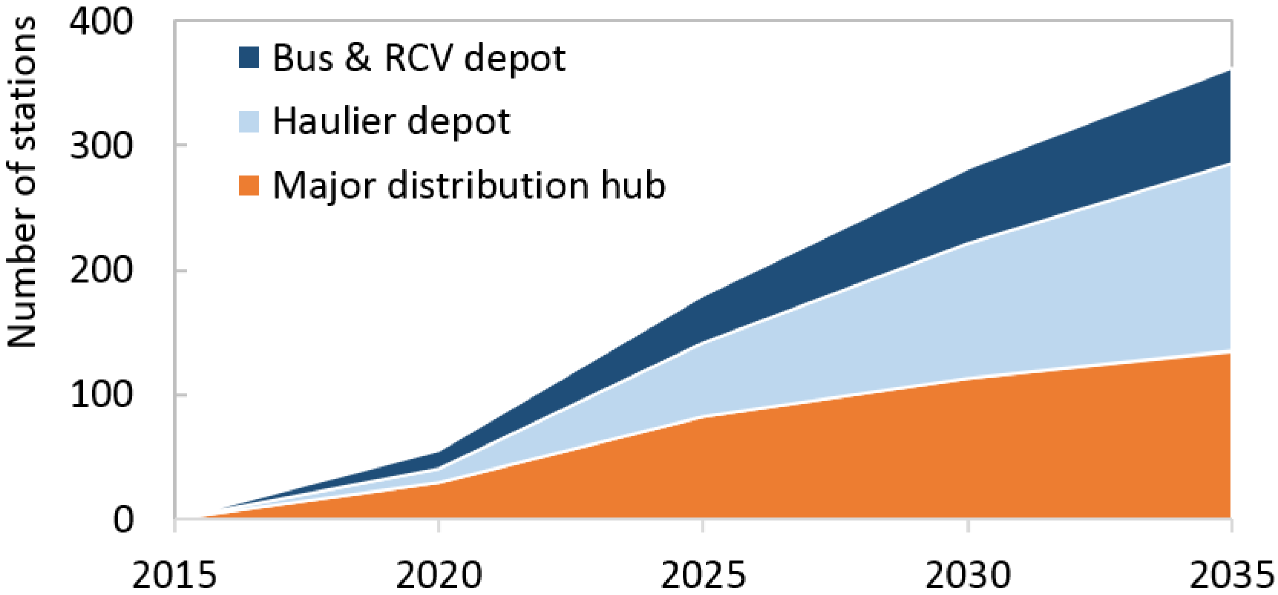


Figure 13 - Total natural gas refuelling stations required to support the uptake of natural gas HDVs in the base case scenario

The development of the natural gas HDV market in the UK partly depends on the development of natural gas infrastructure globally and particularly in EU member states. A harmonised strategy to develop natural gas refuelling infrastructure would reduce the investment uncertainty for businesses and accelerate the uptake of natural gas HDVs in the UK. EU members are now obliged to ensure a sufficient number of CNG and LNG publicly accessible refuelling stations with common standards to allow the circulation of LNG and CNG vehicles[39]. The International Energy Agency estimates that cumulative global investment in refuelling infrastructure for natural gas in road transport should be close to $55 billion over the period up to 2035[40]. However, minimal public spending may be required for the build-up of natural gas transport fuel infrastructure if the governments are able to mobilise private investment. This can be achieved, for example, by supporting early demonstration projects,

[39] European Commission, "Clean fuels for transport: Member States now obliged to ensure minimum coverage of refuelling points for EU-wide mobility," no. September 2014, 2014.

[40] International Energy Agency, "World Energy Investment Outlook," *Int. Energy Agency, Paris, Fr.*, vol. 23, 2014.

such as LNG Blue corridor, that pave the way for large scale development of the market by industry stakeholders.

8.2. Potential emission savings across the fleet in each of the scenarios

Emissions from the entire fleet of land HDVs in the UK were calculated based on the fleet fuel consumption using historical data published by DECC[41, 42]. Energy consumption projections for 2015-2035 are based on the Department for Transport (DfT) traffic projections and the number of operating hours per year for off-road machinery[43]. The total emissions from land HDVs in the UK are estimated at 40 million tonnes of CO_{2eq} in 2015. This includes all on-road HDVs, off-road HDVs and buses, but excludes minibuses and vehicles with a gross weight of less than 3.5 tonnes.

Figure 14 shows how emissions change on a fleet level in each of the modelled cases against the baseline diesel scenario. In the first few years low volume sales of natural gas vehicles[44] and the fact that all existing vehicles are still 100% diesel, mean that there is little change in emissions in any scenario. However, post-2020 both the base and the best case scenarios offer positive emissions savings on a fleet level. On the other hand, poor practices in the worst case scenario lead to an increase in emissions, emphasising the importance of using best practices.

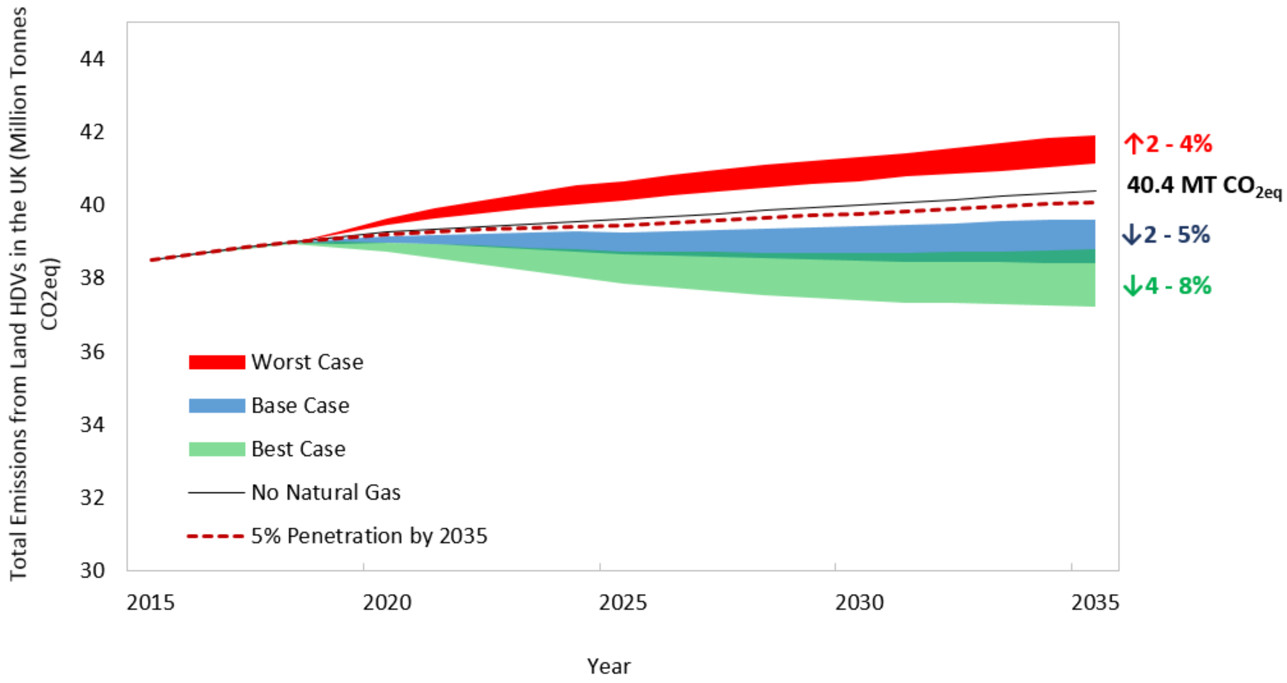


Figure 14 - Emissions from the overall UK fleet of HDVs, including both natural gas and diesel solution in the principal scenarios. The percentages refer to the increase/reduction in emissions in 2035 compared to the scenario of 0% uptake of natural gas HDVs

[41] Department of Energy & Climate Change, “Energy Consumption in the UK (ECUK) - Table 2.02.” 2014.
[42] DECC does not publish energy use by off-road vehicles. Hence it was estimated using the historic data from elsewhere (NETCEN for Department for Transport, “Non-Road Mobile Machinery: Usage, Life and Correction Factors,” 2004.)
[43] Department for Transport, “Road Traffic Forecasts (English regional plus Welsh traffic growth- and speeds forecasts),” 2015.
[44] HDV’s sales are capped to 100-500 units until 2018 and buses are capped to 100-700 units until 2017.

Figure 14 suggests that fully optimised pathways have a potential to offer 8% emissions savings on a fleet level in 2035, while poor practices can result in up to a 4% increase in emissions. However, even in the best case the total emissions savings on a fleet level are noticeably smaller than on a vehicle level. This is due to the fact that even if all fleet operators consider natural gas solutions, the penetration of gas vehicles does not exceed 37% in 2035 as per Figure 11. The scenario in which the penetration of natural gas vehicles reaches only 5% in 2035, and everything else is assumed to be as in the base case, achieves only 0.7% fleet emissions saving. This is shown by the dashed red line in Figure 14.

A part of the emissions in Figure 14 are associated with methane leakage. Methane is converted into CO_{2eq} using the GWP_{100} factor of 25, as mentioned in the appendix. However, the impact of using a higher GWP_{100} factor for methane (36[45] as per the 5th IPCC report[46]) has also been investigated. It was found that using a GWP of 36 reduces the emissions saving by 1% in the base case.

All of the modelled scenarios assume some level of decarbonisation of the UK electricity grid by 2035. However, if the UK electricity grid carbon level were to remain at the level of 400 gCO_{2eq}/kWh until 2035, this would cause the emissions saving on a fleet level to decrease by 1% in all scenarios. Primarily, this would be due to an increase in CNG pathway emissions caused by the requirement to compress natural gas at refuelling stations resulting in a higher emission footprint. This shows the importance of decarbonising the UK electricity grid in order to maximise the emissions saving from natural gas HDVs.

8.3. Analysis of alternative natural gas distribution pathways in the UK

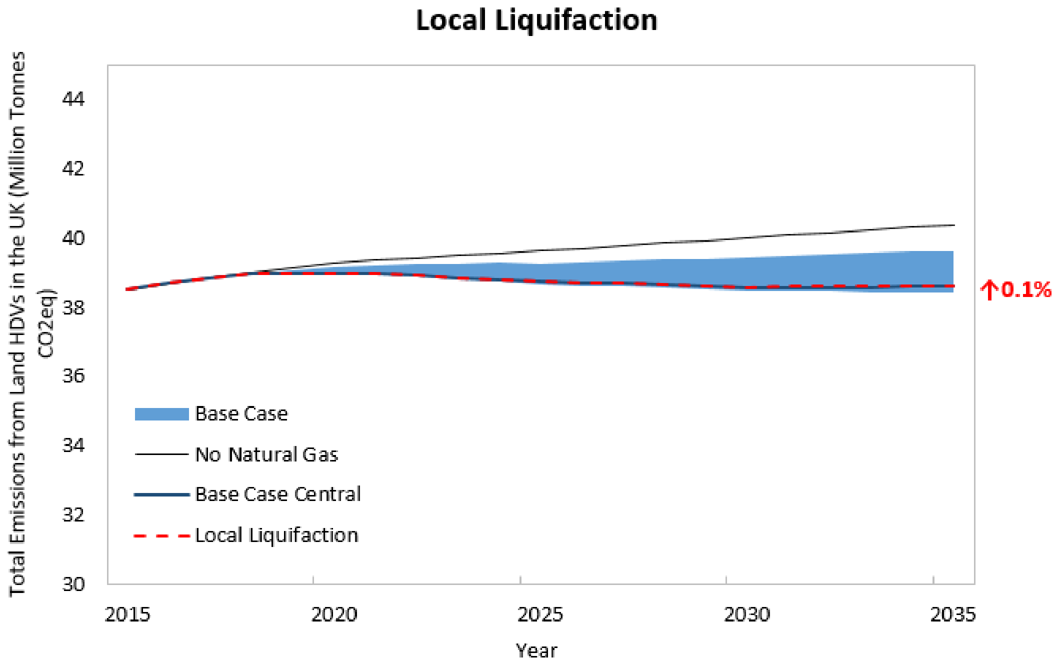
All of the three scenarios assume that no natural gas is liquefied in the UK, i.e. the only LNG available for HDVs is the natural gas that has been imported to the UK in that form. With the termination of operations at the only UK liquefaction facility in Avonmouth in 2016, this represents the most probable development scenario given that one can buy LNG at a small premium to the gas price from Isle of Grain. However, the additional scenario discussed in this section is designed to explore a hypothetical pathway which includes a local liquefaction step. In addition, LNG stations with regasification facilities are considered. This scenario is justified by the fact that there are a number of L-CNG stations in the UK that can locally regasify LNG and dispense natural gas to CNG vehicles. The results of the additional analysis are discussed with the following point in mind:

a) The feasibility of using local liquefaction. Natural gas is assumed to be distributed solely through the National Grid and liquefied locally to produce LNG (i.e. 100% of stations have local liquefaction facilities).
b) The case of an L-CNG station. It is assumed that there are no filling stations connected to the national grid. CNG is dispensed at L-CNG stations, where LNG is locally re-gasified (i.e. CNG is dispensed from L-CNG stations only).

All other parameters were assumed to be the same as for the base case scenario. Results shown in Figure 15 suggest that both the local liquefaction and the use of L-CNG stations slightly decrease the potential emissions savings. In the case of L-CNG stations, emissions associated with the filling

[45] This number includes climate–carbon feedbacks and CO_2 from methane oxidation.
[46] G. Myhre, D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, "Fifth Assessment Report of the Intergovernmental Panel on Climate Change - Capter 8: Anthropogenic and Natural Radiative Forcing," *Clim. Chang. 2013 Phys. Sci. Basis.*, pp. 659–740, 2013.

stations themselves are lower because of the absence of the gas compression stage and relatively small emissions from the regasification stage – this can be clearly seen in Figure 6. However, since L-CNG stations need to use LNG, emissions reductions on a station level are more than offset by the higher WTT emissions in this pathway (Figure 3). The opposite happens in the case of local liquefaction as an increase in emissions at the filling stations, due to the additional liquefaction stage, is almost compensated by the lower WTT emissions. The WTM emissions savings in the pathway with a local liquefaction are only marginally lower than in the base case.



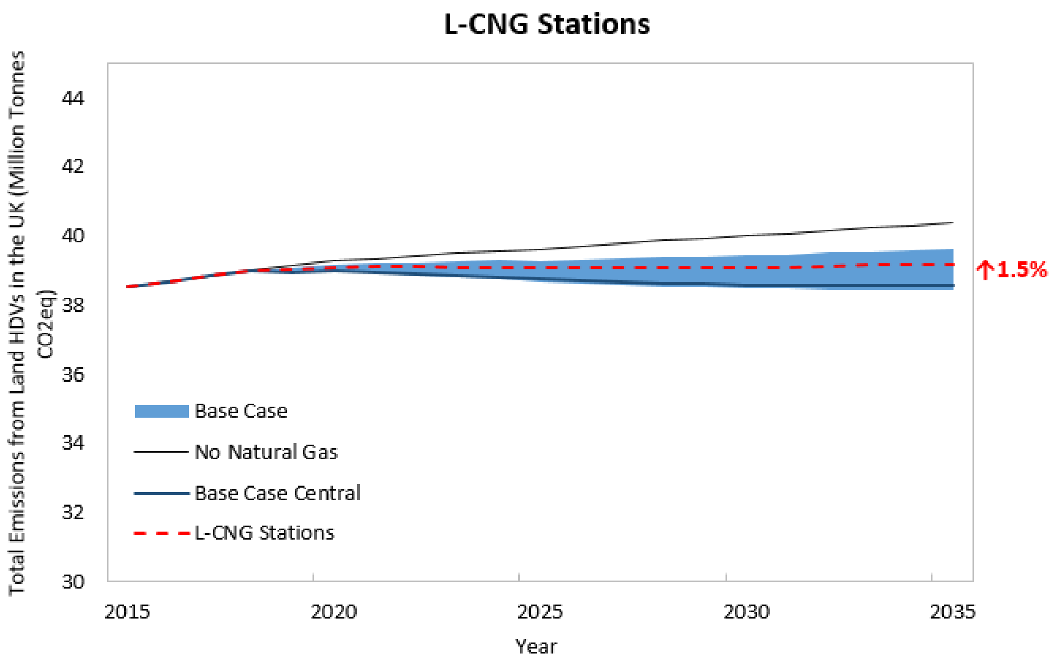


Figure 15 - Emissions from the entire UK fleet of HDVs, including natural gas and diesel solutions for the specific cases of local liquefaction and L-CNG stations. Percentage points refer to the increase/reduction in emissions in 2035 compared to the base case scenario

It is emphasised that both the local liquefaction and L-CNG pathways offer positive emission savings compared to the case of diesel HDVs. Thus, from the point of view of emission savings benefits, these solutions may be sensible in some cases, e.g. if the required infrastructure for other solutions do not exist. Further comments on the economic aspects of these options are provided in Section 9.2. Another available option is a CNG ‘daughter’ station, to which CNG can be delivered by road from a ‘mother’ station connected to grid.

The mother and daughter station concept involves a grid-connected mother station and an off-grid daughter station. The daughter station is supplied with the gas transported from the mother station in road tankers. As this concept involves an additional transport stage, the WTM emissions are affected by the additional compression from road tanker into ground storage and the combustion of fuel to transport gas in the road tanker. However, if the mother station is connected to a high pressure grid, there still may be benefits in terms of emissions compared to a direct connection to a lower pressure tier. Additionally, this concept allows dispensing of CNG in locations where grid connection is not practical. An example of a daughter station in the UK is the refuelling station near Scunthorpe operated by Brit European. Natural gas from the CNG Fuels station in Crewe (that is connected to the intermediate pressure National Grid pipeline) is transported to the Scunthorpe station in road tankers.

8.4. UK Shipping Emissions

The uptake of LNG ships shown in Figure 16 is based on UCL's maritime model that was incorporated into the WTM model and is assumed to be driven by regulation (e.g. new regulation of SO_x and NO_x emissions) and then by economics (e.g. a higher fuel price encouraging uptake of technology or a change in operating speed). Taking the fleet's existing specification as a baseline, the profitability of a number of modifications (e.g. retrofitting scrubbers) applied both individually and in combination is considered. The combination that returns the greatest profit within the user-specified investment parameters (time horizon for return on investment, cost of capital and representation of any market barriers) is used to define a new specification for the existing fleet for use in the next time-step.

Figure 16 shows the uptake of LNG ships separately in all of the analysed ship categories. The growth of the global fleet of ships is driven by the growth in transport demand that is expected to continue globally under GDP and population growth expectations. This is particularly the case for containerised goods. Dry cargo ships are expected to increase and the fleet of chemical tankers is expected to decline before growing at a low rate from 2020, as energy systems shift away from fossil fuels to more renewables.

High uptake of LNG solutions in most of the segments by 2035 is primarily driven by a price differential between the baseline fuels (heavy fuel oil and marine distillate oil) and LNG. Relatively low uptake of LNG in the Offshore Support Vessel (OSV) category reflects a low fleet turnover in the UK.

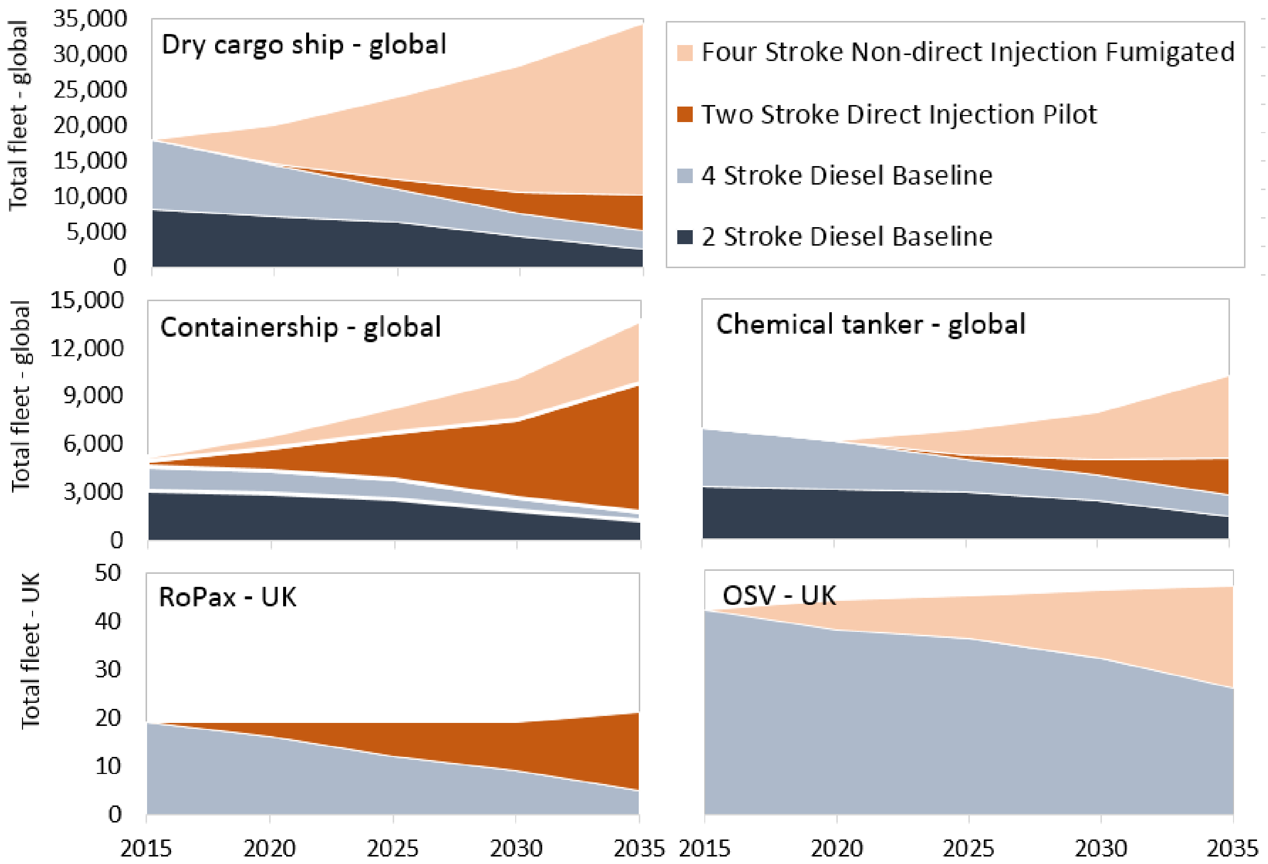


Figure 16 - The fleet of ships by category type. Dry cargo, containerships and chemical tanker fleets are global and RoPax and OSV fleets are UK based

The UK-centric shipping demand scenario is derived from the Committee on Climate Change's (CCC) forecasts that take into account that the UK is already an advanced economy and has decoupled trade in tonnes from GDP to a large extent. UK-specific ship fleet emissions are therefore not expected to have a linear coupling to global transport demand.

Ship emissions allocated to the UK are shown Figure 17 for the three principal scenarios against the baseline case where ships continue to utilise current fuels. The difference between the scenarios is due to the Well-to-Tank differences for LNG pathways as well as different specific fuel consumption and the methane slip assumptions under each scenario. TTM emissions constitute approximately 80% of the WTM emissions in 2015-2020. The share of TTM emissions falls to 70% in 2035 as the Well-to-Tank emissions do not decrease substantially by 2035 but the specific fuel consumption of all engines decreases noticeably.

The contribution of each ship type to the total ship emissions are shown in Figure 18 which includes emissions from the whole WTM pathway. The penetration of LNG ships becomes noticeable beyond 2020 resulting in a visible reduction in emissions as they penetrate further in the 2030-2035 timeframe. A partial shift to LNG in the base case scenario is not sufficient to reduce absolute CO_2 equivalent emissions in 2035 below the current level. However, the uptake of LNG powertrains reduces the total emissions by 14% in 2035 compared to a scenario without LNG ships.

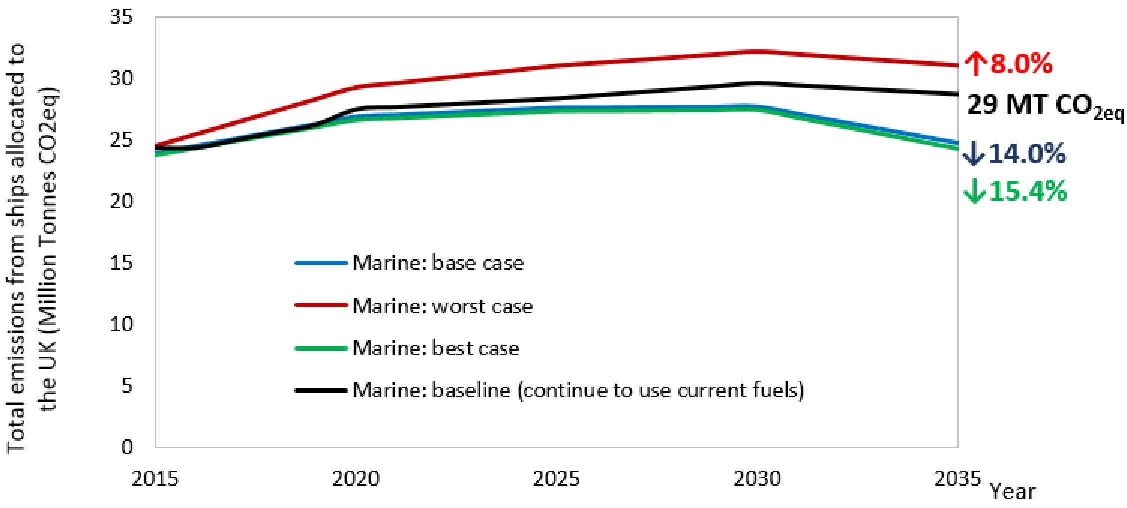


Figure 17 - Ship emissions allocated to the UK for each of the scenarios

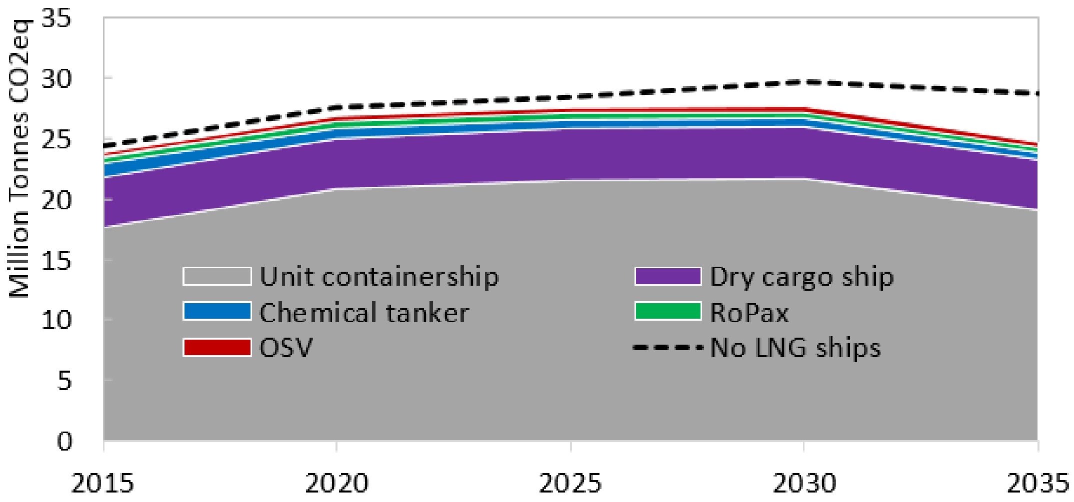


Figure 18 - Ship emissions allocated to the UK, by ship category in the base case scenario. The black dashed line shows a reference case of a 0% uptake of LNG ships.

Changes to the emissions from shipping can take some time to be realised. This is because of the comparatively long-life of ships and their associated infrastructure (ports and bunkering facilities), and the consequent fleet inertia and technology lock-in. Over recent decades, the majority of ocean going ships have had economic lives of between 25 and 30 years, being scrapped at the point where the cost to keep the ship in service exceeds their value. Since the global financial crisis, many of the shipping markets have been in depression, values have been low and scrapping of ships has often occurred below the fleet's long-run average age, leading to slightly higher rates of fleet and technology turnover. However shipping markets, like many markets, operate in cycles. As a result, over the course of this model's outputs, it would be reasonable to expect that any short-run higher turnover may be countered by a period in which ship's lives would be extended slightly longer than average.

Technology change, particularly when enforced through regulation, can also be an important criterion in a scrappage decision. This is because it can add an extra component to the cost of keeping the ship in service, and tip the balance between cost and value towards scrapping sooner than average. Examples include the regulation on double-hulled tankers, which caused premature scrappage or repurposing of many single hulled tankers, and the forthcoming regulation on ballast water management (requiring all ships to be fitted with new technology to treat ballast water). It is possible that energy efficiency developments or regulation (whether at the IMO or elsewhere) could have a similar impact. When markets are in depression, more energy efficient ships may be preferred by the charterers, forcing owners to either retrofit to increase energy efficiency or scrap them. However, if freight rates are high and so too are revenues and values, employment of the fleet (whether energy efficient or not) will be high, extending the economic lives of ships and possibly even disincentivising the take-up of energy efficiency retrofits.

9. Analysis of the Economics of Natural Gas Land HDVs

9.1. Savings for a Single Vehicle by Segment

The economic case for natural gas land-based HDVs has been analysed based on the total cost of ownership (TCO) to the fleet operator. The TCO includes expenditure on fuel, maintenance, as well as losses incurred due to depreciation of the vehicle over the TCO time horizon. This equates to four years for on-road HDVs, six years for off-road HDVs' and seven years for buses[47] as well as assumptions on the depreciation rate for land HDVs, shown in Table 6 in the appendix. A residual value of 20% was assumed for all land HDVs apart from long haul and regional distribution HDVs, which are assumed to retain only 10% of their original value at the end of the first operating period (i.e. the operating time with the owner who made the original investment decision). This is due to the high annual travel distance.

It is acknowledged that, apart from the capital and the running costs (including maintenance), other considerations may play a role when fleet operators make the decision of buying natural gas HDVs. These include the additional training, the cost of extra garage equipment and the opportunity to sell the vehicle, all of which may be perceived as additional risks or costs associated with natural gas HDVs.[48] These are not directly included in the choice model. However, the variation in the share of fleet operators who consider natural gas for their fleets (between 50% and 100%, shown in Table 4) indirectly captures the readiness to take the risks or make the additional investments that the adoption of a new technology entails.

Most natural gas engines and their after-treatment systems are not inherently more complex than those found in diesel HDVs. However, small scales of production make them more expensive at the moment. Fuel cylinders for natural gas vehicles also add to the cost of natural gas HDVs. Therefore, cheaper fuel is essential to achieve running cost savings to establish a successful business case for natural gas HDVs. In the future, economies of scale are expected to reduce the purchase cost premium, and make fleet operators less dependent on ongoing fuel savings to achieve an acceptable total cost of ownership.

Average TCOs for dedicated (stoichiometric CNG) and dual fuel (CNG fumigated) HDVs along with the TCO for the baseline diesel HDVs are shown in Figure 23 in the appendix for all segments in 2020 and 2035. Note that the TCO for HPDI and MPSI solutions will be lower than for the fumigated dual fuel engines because of higher efficiency and higher substitution rates, but lower than for the dedicated engines because these vehicles cannot run on gas alone and have a higher purchase cost premium. The purchase prices and assumed annual mileages (for diesel vehicles) that were used in the TCO calculation are given in Table 7 in the appendix. Additionally, Table 8 in the appendix lists the assumed price premiums for each natural gas solution in 2020 and 2035.

In 2020 the dedicated natural gas HDV capital expenditure premium is assumed to be ca. £25,500 and the dual fuel HDV premium is ca. £30,000. However, based on DECC fossil fuel projections[49], assuming no changes to fuel duties and employing a filling station bottom-up cost model, CNG is expected to give a 61% discount over diesel on an energy basis in 2020. Furthermore when the efficiency loss of the natural gas engine is taken into account this translates into slightly lower running

[47] TCO time horizon that is used to make a decision on the purchase of a new HDV is different from the expected lifetime of the vehicle, which is typically longer and may span across several owners.

[48] In the case of dual fuel vehicles, the kit could be taken off and retrofitted to a new vehicle, which would spread the capital cost.

[49] Department of Energy & Climate Change, "DECC 2015 Fossil Fuel Price Assumptions," no. November, p. 23, 2015.

cost savings of 58%. Nevertheless, these savings are still sufficient to make the dedicated HDVs cost competitive in all segments in 2020. Lower utilisation rates may result in 15-25% higher gas prices. Equally, the natural gas price will be 8% higher if the CNG stations connected to the medium pressure gas grid dominate the market, due to the additional electricity cost for gas compression. The modelled LNG price is 15-20% higher than the CNG price based on the bottom-up algorithm for the dispensed gas cost calculation implemented in the WTM model. Dual fuel engines have higher premiums and partly run on diesel, and therefore a higher annual mileage is required to compensate the cost premiums.

By 2035, the capital cost premium for dual fuel HDVs is expected to decrease to on average £25,000 and the premium for dedicated HDVs to an average of £17,000. If the natural gas price discount to diesel is factored in, dual fuel HDVs become economically viable in the distribution and municipal segments. However, even though the analysis shows that the dual fuel solution is economically feasible for the municipal vehicles, there is large uncertainty in the substitution rates in this and other more transient duty cycle. How a vehicle is used, or the typical operating cycle, very much influences the type of powertrain that is suitable and in the case of dual fuel the substitution rate and the amount of exhaust heat required to increase the aftertreatment temperature. In general the more transient the cycle, the lower the substitution rate and the more favourable the higher pressure direct injection and dedicated gas engines become. However, dedicated gas engines suffer higher efficiency losses in comparison to a comparable diesel vehicle the more transient the cycle becomes mainly due to throttle losses. Lower than expected substitution rates may render dual fuel solutions unsuitable for this segment. Relatively low running costs in the off-road segments mean that the dual fuel solutions may not be suitable from a TCO perspective and lower priority should be given to encouraging uptake in these sectors.

Long haul is the only segment where dual fuel HDVs are economically feasible in 2020, under the selected assumptions. Travelling 120 000 km per year, a dual fuel CNG HGV on a long haul duty cycle has the potential to save £12,000 per year (in 2020)[50]. Thus, the £30,000 cost premium is compensated by the running costs after three years, and on a four year TCO basis the dual fuel HDV in this segment is competitive. This is expected to be achieved through a high fuel price differential calculated based on the DECC fossil fuel price projections[26] and also assuming an optimal utilisation rate of 75% for all natural gas filling stations.

Annual driving distances in segments other than long haul are significantly lower (a regional distribution duty cycle with 75 000 km/year is the second longest) and therefore results in lower running cost savings. However, even if one solution is slightly more expensive than the alternative, the logit model will allocate a proportional amount of the market to the more expensive solution to reflect real-life market behaviour.

Long haul and distribution segments may offer a good entry point for natural gas HDVs considering the economics. The present analysis assumes that there is no payload penalty for natural gas HDVs, which is reasonable based on a recently introduced CNG HDV designed for a long haul segment[51]. The OEM (Iveco) states that the natural gas HGV has the same payload as an equivalent diesel HGV. Equally, a reasonably high driving range of 1500 km for the LNG and 570 km for the CNG option makes this an acceptable solution for the long haul or distribution segments. Scania is currently the

[50] 120 000 km is not the highest observed mileage; some long haul HGVs travel over 300 000 km per year, making the economics of gas HGVs even more advantageous.

[51] Iveco, "New Stralis NP TCO2 Champion," 2016.

only other OEM to have a Euro VI compliant dedicated gas CNG HGV on the market in Europe. Scania and Volvo have both made announcements that they will continue to develop dedicated and dual fuel HGVs, with Volvo looking to introduce a dual fuel 44t HGV in 2018.

9.2. Savings at a Fleet Level and the Impact of Fuel Duty

The total annual spending on the UK fleet of land HDVs may be a good proxy for evaluating the business case for natural gas vehicles. The sum of the running costs (including fuel spending and maintenance) of the entire fleet and the cost of all new vehicles in the fleet provides an estimate of what fleets operating land HDVs are expected to spend. Figure 20 shows that the widespread use of natural gas land HDVs reduces total annual spending in all cases. The uncertainty in the future fuel prices and the costs of land HDVs is not modelled directly in this instance, but is likely to be captured by the spread presented in Figure 20. This calculation aims to reflect the spending of fleet operators and therefore does not include the investment cost of additional infrastructure that operators opting for depot refuelling might incur[52].

As a result of lower spending on fuel, the total annual savings for UK businesses (and public fleets) operating land HDVs amount to 3-6.6% in 2035 in the base case and up to 7.7% in the best case scenario. However, part of these savings are due to the fuel duty differential between natural gas and diesel, meaning that the UK tax income from HDVs will decrease as the fleet operators switch to natural gas.[53] Currently, the diesel duty is set to 57.95 p/L (or 1.6 p/MJ) and the natural gas duty is set to 24.7 p/kg (or 0.5 p/MJ). A relatively high uptake of natural gas HDVs may lead to the changes in fuel duty. The effect of changing the fuel duty for natural gas on the uptake of gas land HDVs has been analysed in more detail below.

Figure 21 shows the estimated prices for CNG, LNG and diesel (without VAT) for three separate cases: (a) fuel duty differential as now (2017), (b) equal duty on CO_2 basis, (c) equal duty on an energy basis. The CNG and LNG prices are calculated based on a bottom-up approach to the capital and operational costs of a major distribution hub. The modelled CNG pump prices are aligned with indicative prices in May 2016 published by a UK CNG station operator[54]. Diesel pump prices are calculated based on the price of diesel in the UK in May 2016 published by DECC[55].

The difference between the pump price of natural gas and the price of diesel is determined largely by the fuel duty differential as shown on Figure 21. Increasing the fuel duty for natural gas to bring it on the same level as diesel fuel duty on energy basis will almost certainly eliminate any discount. This is also likely to make natural gas a more expensive option on a per km basis due to the loss of efficiency of the current natural gas engines. A fuel duty that is calculated based on CO_2 content will mean that natural gas is still cheaper than diesel as the former has a lower CO_2 content per unit of energy. However, it will increase the running costs for fleet managers operating natural gas HDVs compared to present day.

[52] The cost of infrastructure is however captured in the calculated cost of dispensed gas. Infrastructure capex is spread over 15 years in the gas price bottom up model.

[53] Note that ships are exempt from fuel duty and therefore this is pertinent to land vehicles only.

[54] CNG Fuels, "Industry news - customer pricing," 2016. [Online]. Available: http://www.cngfuels.com/newsroom/. [Accessed: 03-Aug-2016].

[55] Department of Energy & Climate Change, "DECC 2015 Fossil Fuel Price Assumptions," no. November, p. 23, 2015.

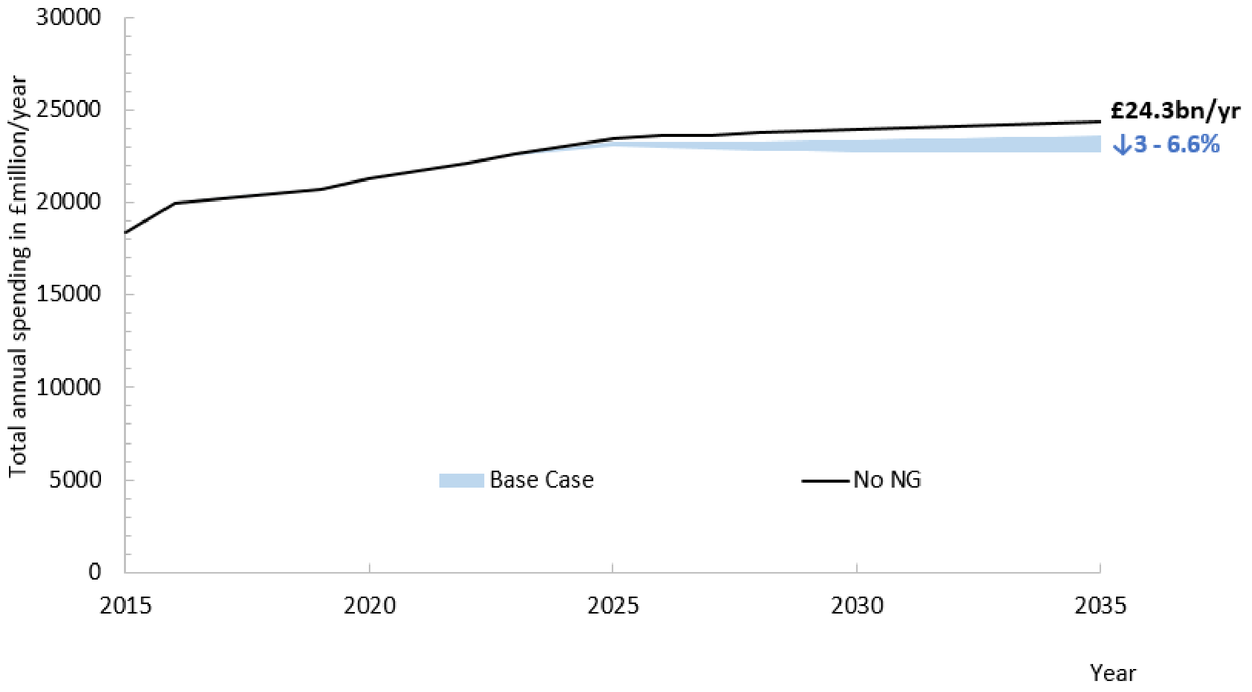


Figure 19 - Total UK land HDV fleet annual spending in the base case (i.e. current rate of taxation)

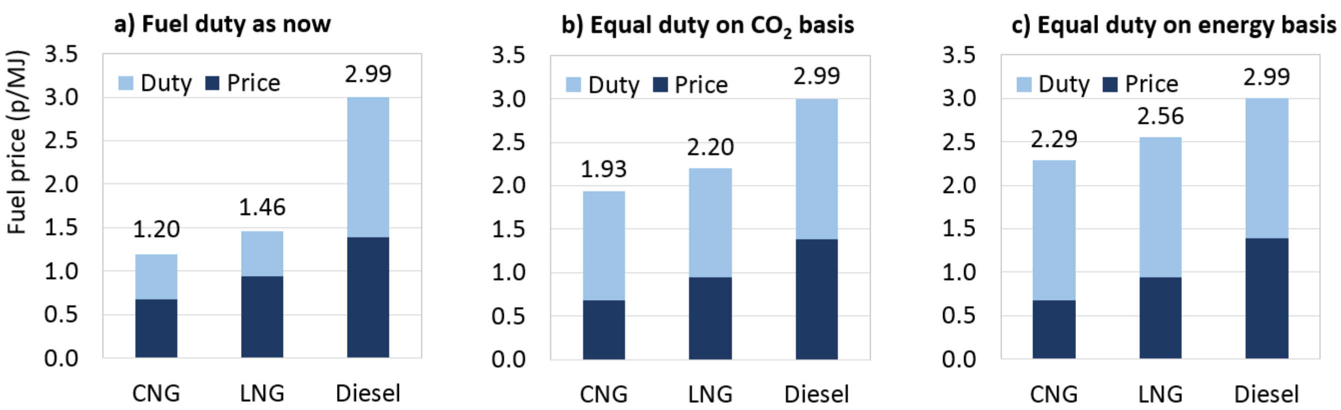


Figure 20 - Fuel prices for three different approaches to fuel duty

Figure 22 shows that elimination of the fuel duty differential will initially increase the total spending on HDV fleet as the fleet managers who buy gas HDVs are paying a premium. The spending converges to the same level as the case without natural gas HDVs in 2035. This is partly because of a low uptake of natural gas HDVs due to a poor economic proposition, but also because the price of natural gas is close to the price of diesel in this scenario and therefore the uptake of gas HDVs has a lower impact on spending. Nevertheless, the price of natural gas may be expected to stay slightly lower than the price of diesel if the commodity cost increases as per the DECC fossil fuel assumptions[56] in the central

[56] Department of Energy & Climate Change, "DECC 2015 Fossil Fuel Price Assumptions," no. November, p. 23, 2015.

scenario. This would balance out the capital cost premium for natural gas HDVs over their lifetime (note that typically this is noticeably longer that the TCO horizon).

Figure 22 also suggests that up to 2025, assigning the fuel duty based on the CO_2 content of the fuel would have a very similar effect as eliminating the fuel differential altogether. This is because the Capex premium for gas HDVs is still high and a relatively low commodity cost makes the potential savings from running a fleet on natural gas less significant. Post-2025, commodity prices are expected to increase in the central scenarios and the natural gas HDV cost premium is to decrease, reducing the total spending.

Lower uptake of natural gas HDVs due to the increase in fuel duty is likely to result in the emissions savings at the lower range of the base case scenario shown in Figure 14.

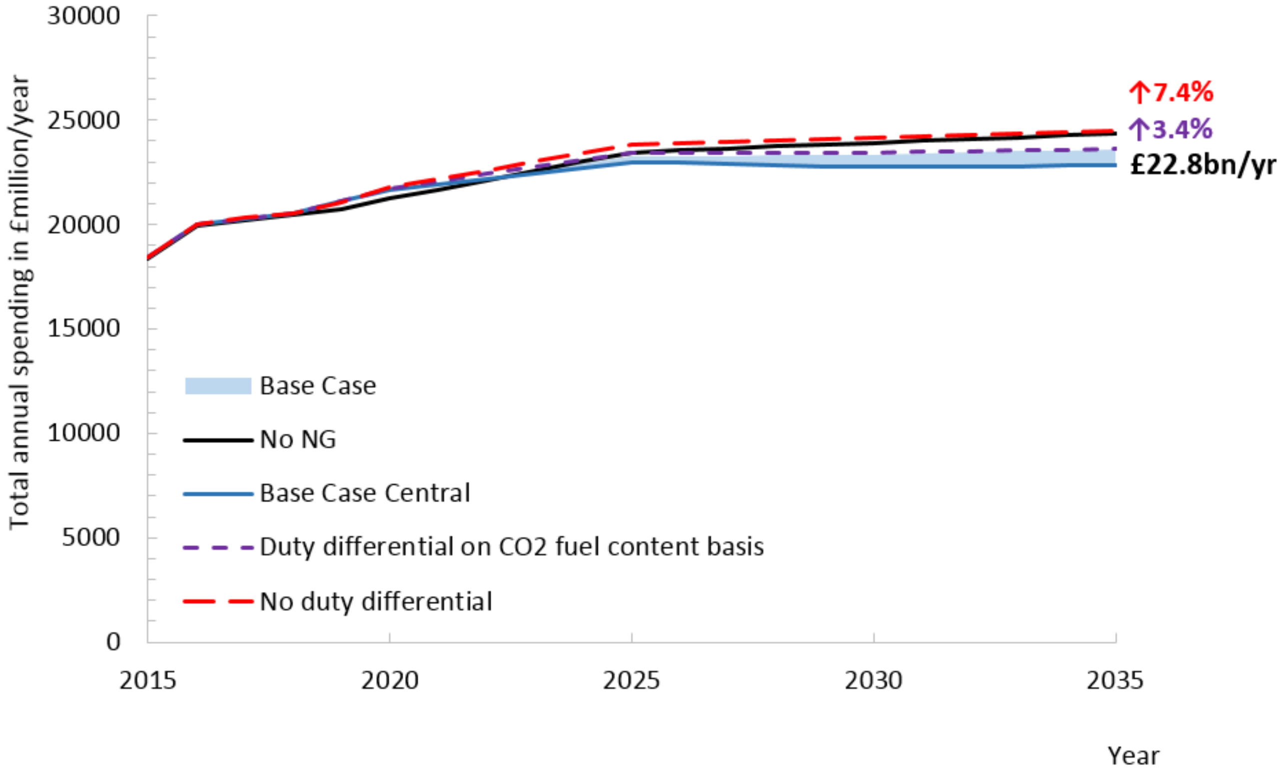


Figure 21 - Comparison of the total spending in the base case at the scenarios with custom fuel duty for natural gas (base case: 24.7p/kg, no duty differential: 77p/kg, duty differential on a fuel CO_2 content basis: 60p/kg)

10. Conclusions

10.1. Emissions Savings at the Vehicle / Vessel

At the vehicle level, emissions savings from natural gas in the base case are 12-13% for a long haul dedicated HGV using LNG. In the case of LNG, savings from lower CO_2 content natural gas are slightly offset by the higher Well-to-Tank emissions of LNG pathways and modest CH_4 slip. CNG pathways have lower WTT emissions and therefore a dedicated CNG HGV on a long haul duty cycle provides 20% emissions savings in 2017. This figure increases slightly to 21% in 2035 as the electricity grid is decarbonised and hence the emissions from gas compression in the CNG pathways are slightly reduced.

In the worst case scenario, dedicated LNG HGVs on a long haul duty cycle may cause 27-53% higher WTM emissions compared to diesel HGVs. This is mostly due to high use of liquid nitrogen in an underutilised station, high methane slip from gas engines and venting of methane boil-off from HDV tanks before each refill. However, this can be avoided relatively easily if station designs include vapour recovery and if stations are only installed where there is an acceptable minimum LNG demand, for example a utilisation rate of over 75% of the designed capacity would lead to a liquid nitrogen rate close to zero.

For CNG pathways, the worst case scenario results in negligible emissions savings relative to diesel. The emissions component with the highest uncertainty is methane slip. However, the latest evidence[57] suggests that methane slip for dedicated engines is on the lower end of the range assumed in the WTM model.

In the best case scenario, a dedicated LNG HGV offers 21-22% and a dedicated CNG HGV 26-29% emissions savings on a long haul duty cycle. Similar savings may be achieved in other duty cycles. Emissions savings achieved by a dual fuel HDV will depend on the substitution rates, but generally are lower than those for the dedicated natural gas solutions.

10.2. Emissions Savings at the Fleet Level

Approximately two thirds of the total HDV emissions in the UK are due to land transport, with the rest of emissions from the marine sector. A very high uptake of natural gas HDVs is required to achieve fleet emissions savings approaching those available on a vehicle level. With around 32% of natural gas vehicles in the land HDV fleet and 80% of ships running on LNG in 2035, 5% fleet emissions savings can be achieved in the base case relative to 2015. For land vehicles, high uptake will require significant investment in infrastructure, with up to 300 new refuelling stations required by 2035. The majority of this investment should be able to be financed by the private sector, given sufficient confidence in the utilisation rate of the natural gas stations. Current refuelling station infrastructure could sustain up to 5% fleet penetration which would reduce HDV fleet emissions by less than 1%. There is currently only one CNG station (Leyland) supplied by the LTS grid but there are plans for other similar stations located at major distribution depots. These will have very high capacity and could make a significant change in the market place as they are being supported and promoted by the gas distribution network owners.

A best case scenario could result in up to 8% emissions savings for HDVs, but would require a thorough optimisation of natural gas pathways. Most notably best practices during natural gas extraction and processing, decarbonisation of UK grid electricity, well-developed filling station

[57] Brian Robinson, "Emissions Testing of Gas-Powered Commercial Vehicles", LowCVP, January 2017.

infrastructure, no methane slip and natural gas engines with close to the same efficiency as their diesel counterparts.

Onshore shale gas has the potential to be a low WTT fuel given the focus of the Environment Agency on methane leaks and the proximity to the gas grid and customers, avoiding compression energy associated with UKCS gas and imports from Norway and the EU.

For land HDVs, emissions savings in the best case scenario are limited to 9%. To increase emission savings additional regulation and incentives for operators to take up natural gas vehicles would be needed.

In the marine sector, penetration of natural gas vessels is dictated largely by the economic life of most ocean-going vessel which is generally between 25 to 30 years leading to very slow turnover rates. In each of the base and best case scenarios natural gas provides a 14%-15% reduction in GHG emission in 2035. If best practices are not followed the large amounts of methane slip and increased upstream pathway emissions could lead to natural gas being up to 8% worse than the HFO and MDO it replaces. Changes in legislation, specifically around the emission control area's (ECA's), could drive retrofits or bring forward decisions to scrap vessels earlier than would have otherwise occurred.

10.3. Economic Proposition

From an economic standpoint, the best entry point for natural gas land HDVs are long haul and distribution segments. High annual driving distances in these segments maximise the potential savings from the reduction in running costs when operating on natural gas. The cost premium of a dedicated CNG HGV is estimated to be £25,000 in 2020. Currently, this upfront costs can be repaid in around 2–2.5 years by the running costs savings, estimated as £10,000-15,000 per year in the long haul segment. However, the fuel price differential and higher utilisation of the gas filling stations are expected to reduce the payback period noticeably in 2020. Running cost savings are expected to increase further by 2035 as the spread between diesel and natural gas prices increases. This represents a business case for dedicated natural gas HDVs with a caveat that the driving range may be limited for CNG solutions, although Scania have delivered 800 km range capable models in 2016. Another of the leading HGV OEMs offers a EURO VI long haul natural gas HGV with a range of 570 km for the CNG option and 1500 km for the LNG option[58].

In general dual fuel HDVs have slightly higher upfront costs, e.g. £30,000 for a fumigation solution, and offer lower running cost savings. Nevertheless, a dual fuel CNG HGV running on a long haul duty cycle is estimated to save £12,000 per year in the base case scenario and therefore is economically viable on a 3+ year TCO horizon. However, dual fuel HGVs have yet to demonstrate compliance with EURO VI standards, the only dual fuel solution expected to meet and demonstrate meeting the emission criteria in the short term is HPDI. Although the total cost of ownership for the dual fuel solutions were found to be higher than for the diesel counterparts in segments other than long haul in 2020, the decrease in upfront costs is likely to make those economically viable in most on-road segments by 2035.

The business case for natural gas land HDVs was found to depend strongly on the fuel duty differential. Eliminating the fuel duty differential altogether is likely to significantly reduce the attractiveness of natural gas to fleet operators. For example, a dedicated CNG HGV on a long haul duty cycle would save only £9,000 per year (in 2020) on running costs, and a dual fuel HGV would

[58] Iveco, "New Stralis NP TCO2 Champion," 2016.

save only £3,000 per year without the fuel duty differential. The savings on other duty cycles would be even smaller, making dual fuel vehicles economically uncompetitive in all segments. Dedicated HGVs would be economically viable only in the long haul segment.

Linking the fuel duty to the CO_2 content of the fuel could be an alternative approach at the stage when natural gas HDVs have reached high fleet penetration. This could help reduce forgone tax revenues from the deployment of gas vehicles, while keeping both dedicated and dual fuel options viable in the long-term. In such case, a dedicated CNG HGV on a long haul duty cycle would save £15,000 on running costs per year and a dual fuel HGV would save £6,000 per year (in 2020). Fuel duty tax stability will need to be ensured to enable market confidence to invest in natural gas vehicles and the necessary infrastructure.

10.4. Research and Technology Needs

Methane slip reduction remains an important development area for natural gas HDVs, one that is more relevant to dual fuel and lean burn dedicated variants than stoichiometric dedicated versions. Evidence from the Low Carbon Truck Trial[59] suggests that dual fuel trucks, which are MPSI retrofit solutions, are up to 25 times over the Euro VI requirement for methane tailpipe emissions. More controlled, higher pressure direct injection would likely lead to less methane slip from the combustion chamber, but this remains a challenge that OEMs need to overcome. Optimisation of the fuel injection timing and the cylinder pressure may also help reduce methane slip, but an efficient low temperature catalyst is required to meet EURO VI standards at cold start (temperatures below 350°C). New low temperature methane catalysts are particularly required for dual fuel land vehicles and for ships, whose engine exhaust temperatures may never reach the optimum operational temperatures for current catalyst systems over the duty cycle they operate, especially in dual fuel operation.

In addition to new technologies for reducing methane slip, robust testing procedures for N_2O emissions are required. N_2O may be emitted in very small quantities from the SCR systems of diesel vehicles, but can significantly increase GHG emissions due to its very high GWP_{100} of 298[60]. This is of particular importance to the HPDI dual fuel variants that will still require SCR systems. N_2O is generated from the aftertreatment system when SCR catalysts are used to reduce the NO_x tailpipe emissions, and is particularly evident in warm cycles rather than in cold cycles. The type of SCR catalyst used also has an effect, N_2O can be expected to contribute up to 10% of overall GHG emissions in a copper SCR system and half this for a Vanadium system. However, this is very much dependant of engine and aftertreatment configuration and this should serve as an example of an oversized high conversion efficiency system; these values would be less in systems that utilise EGR[61].

No dual fuel solutions that meet EURO VI emission requirements are currently available. In the case of dual fuel conversions, the testing procedures for recertifying retrofitted vehicles are also not in place. This means that currently it is not possible to determine whether converted diesel EURO VI HGVs meet EURO VI requirements for natural gas HDVs or not. Thus, legislative certainty in this area is desirable to facilitate the dual fuel HDV market development, and avoid a situation where high methane emissions from converted engines negatively impact the perception of natural gas vehicles overall. The first step towards this has already been taken by introducing an accreditation scheme for

[59] Brian Robinson, "Emissions Testing of Gas-Powered Commercial Vehicles", LowCVP, January 2017.
[60] IPCC, *Climate change 2007 - The Physical science basis*. 2007.
[61] http://www.erc.wisc.edu/documents/symp17/2017_Cat_Paulson.pdf

aftermarket technologies[62]. The scheme introduces the process for testing the emissions of retrofitted systems under realistic HGV operating scenarios.

The suitability of engine technology in each segment very much depends on the operating cycle. More transient cycles, such as the bus or municipal HGV suit dedicated or higher pressure direct injection dual fuel engines. Fuel consumption, substitution ratio and efficiency losses are also heavily dependent upon the types of cycle the vehicle is operated over and is something which is required to be drawn out in more detailed pieces of work to identify specific segment needs.

10.5. Implications for the UK Energy System

The expected fleet emissions savings from natural gas vehicles of 2-5% by 2035 in the base case are not sufficient on their own to deliver the deep reductions to meet carbon budgets/climate goals for the UK. Thus, substantial efficiency improvements in ICE HGVs are required alongside any fuel switching. At the same time electric powertrains could offer substantially higher savings in duty cycles for which they are suitable e.g. busses and urban deliveries. This accounts for a large number of vehicles but a small amount of the overall sector CO2 emissions but could be affected by individual city legislation limits on air quality.

The choice between using natural gas as a bridge technology versus placing greater focus on vehicle/logistical efficiency and ultra-low emission solutions depends on the level of greenhouse gas savings to be achieved. In that context, natural gas offers a useful additional CO_2 reduction measure for vehicles where zero emissions solutions are not yet viable (such as in large, long haul HGVs). In addition, the fact that natural gas infrastructure is profitable, given sufficient utilisation, means that the rollout of natural gas vehicles is not dependent on large amounts of additional public support (aside from maintaining the duty differential). This reduces the risk to policymakers associated with having to effectively choose between natural gas and other GHG reduction options, since natural gas vehicle deployment can be led by the private sector. Instead of large-scale financial support, the role of policymakers and regulators should be to ensure fuel duty stability and that vehicles and refuelling stations meet high environmental standards. This would enable overall GHG savings towards the upper end of the ranges shown in this study.

10.6. Biomethane

Whist biomethane has not been part of this analysis it is recognised that biomethane has been strongly linked to reducing emissions in HGVs in particular. A supplementary analysis to include biomethane is being worked on by the ETI. Utilising knowledge gained through its Bioenergy Programme this will aim to add further insight into the use of gas in the HDV sector in early 2018.

[62] LowCVP, “HGV accreditation scheme,” 2016. [Online]. Available: http://www.lowcvp.org.uk/projects/commercial-vehicle-working-group/hgv-accreditation-scheme.htm. [Accessed: 23-Aug-2016].

11. Acronyms

BCM	Billion Cubic Meters
Capex	Capital Expenditure
CCC	Committee for Climate Change
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO2eq	Carbon Dioxide equivalent
DECC	Department of Energy and Climate Change
DfT	Department for Transport
ECA	Emission Control Area
EE	Element Energy
EGR	Exhaust Gas Recirculation
ESME	Energy System Modelling Environment
ETI	Energy Technologies Institute
Euro VI	The sixth iteration of European HGV tailpipe emission limits introduced in January 2013.
GDP	Gross Domestic Product
GWP100	Global Warming Potential (on a 100 year basis)
HDV	Heavy Duty Vehicle
HFO	Heavy Fuel Oil
HGV	Heavy Goods Vehicle
HPDI	High Pressure Direct Injection
ICE	Internal Combustion Engine
IMO	International Maritime Organisation
JRC	European Commission Joint Research Centre
L-CNG	Liquefied Compressed Natural Gas (filling station)
LiN	Liquid Nitrogen
LNG	Liquefied Natural Gas
LowCVP	Low Carbon Vehicle Partnership
LP	Low Pressure (grid)
LTS	Local Transmission System (High Pressure)
MDO	Marine Diesel Oil
MGV	Medium (Weight) Goods Vehicle
MP	Medium Pressure (grid)
MPSI	Medium Pressure Sequential Port Injection
MT	Million Tonnes
N_2O	Nitrous Oxide
NTS	National Transmission System
NO_2	Nitrogen Dioxide
NOx	Generic term for Nitrogen Oxides
OEM	Original Equipment Manufacturer
OLEV	Office for Low Emission Vehicles
Opex	Operational Expenditure
PEMS	Portable Emissions Measurement System
RCV	Refuse Collection Vehicle
RoPax	Roll-On-Roll-Off-Passenger ship
SCR	Selective Catalytic Reduction
SOx	Generic term for Sulphur Oxides
TCO	Total Cost of Ownership
TTM	Tank-to-Motion
UCL	University College London

UKCS	United Kingdom Continental Shelf (gas)
VAT	Value-added Tax
WHTC	Worldwide Harmonised Test Cycle
WTM	Well To Motion
WTT	Well to Tank

Appendix

A number of assumptions have been created in the process of this project to create the inputs to be used within the model. This has enabled the generation of the scenarios and the results presented within this report. For completeness, some of the key assumptions are presented within this appendix. Some of the tables and figure in this appendix are referred to within the report.

General Assumptions

Using Global Warming Potential (GWP100) factors from the Intergovernmental Panel on Climate Change (IPCC)'s fourth assessment report (GWP100 for CH_4 = 25) is consistent with reporting under the Kyoto Protocol. Although the IPCC has prepared newer versions since, the methods have not yet been officially accepted for use under the Kyoto Protocol. This is the basis upon which all emissions are calculated in this study. The impact of higher GWP for methane is investigated and is discussed in section 8.2.

All financial reporting throughout the report refers to a 2015 monetary value. The calculation of future fuel prices is linked to the DECC commodity price projections[63].

The assumed level of electricity grid decarbonisation in 2035 ranges from 39 gCO_{2eq}/kWh in the base case scenario, to 100 gCO_{2eq}/kWh in the worst case scenario [64], [65].

The prices of baseline shipping fuels are calculated based on the oil price projections in the latest DECC fossil fuel price assumptions [66].

Baseline Well-to-Tank Emissions

For diesel, 15.4 gCO_{2eq}/MJ is assumed for Well-to-Tank emissions and 72.6 gCO_{2eq}/MJ for the fuel CO_{2eq} content, in line with the latest DECC factors for the average biofuel diesel blend[67].

The WTM model contains a representation of the Well-to-Tank emissions of conventional diesel fuel. The default diesel emissions data is drawn from the 2014 JRC Well-to-Tank report[68]. The JRC disaggregates diesel Well-to-Tank emissions into the following categories:

- Production and conditioning at source
- Transportation to market
- Transformation near market
- Conditioning and distribution (including dispensing)

The JRC report also assumes that there is no material change to the composition of diesel fuel in their 2010 to 2020+ time horizon. It also publishes supporting spreadsheets showing high and low

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[63] Department of Energy & Climate Change, "DECC 2015 Fossil Fuel Price Assumptions," no. November, p. 23, 2015.
[64] Committee on Climate Change, "The fifth carbon budget - Chapter 3: The cost-effective path to 2050," 2015.
[65] CCC, "The Renewable Energy Review," no. May, pp. 1–166, 2011.
[66] Department of Energy & Climate Change, "DECC 2015 Fossil Fuel Price Assumptions," no. November, p. 23, 2015.
[67] Department of Energy & Climate Change, "UK Government GHG Conversion Factors for Company Reporting." 2016.
[68] JEC - Joint Research Centre-EUCAR-CONCAWE collaboration, Well to Tank report, Version 4.a, 2014

values as well as their baseline case. The proposed default values for diesel fuel are shown in Table 2.

Well To Tank stage	Energy input (MJ/MJ diesel)	GHG emissions CO_{2eq}/MJ diesel
Production and conditioning at source	0.07	4.7
Transportation to market	0.01	1.0
Transformation (refining) near market (EU)	0.10	8.6
Conditioning and distribution	0.2	1.1
Total - baseline	**0.20**	**15.4**

Table 5 – Well-to-Tank assumptions for conventional diesel fuel

Terminal-to-Tank Emission Assumptions

The analysis presented in the report assumes the suggested trajectory for the carbon intensity of the electricity grid as stated in the Committee on Climate Change's Fifth Carbon Budget[69] Meaning that a significant level of decarbonisation of the electricity grid by 2030, this in turn enables a reduction in emissions associated with the filling stations.

Tank-to-Motion Emission Assumptions

Methane slip from the stoichiometric and HPDI engines are assumed to just meet EURO VI requirements (0.5 gCH4/kWh). On the other hand, the fumigated, multi-port injection and MPSI systems are assumed to be used on the retrofitted EURO VI diesel HGVs and therefore may not be required to comply with EURO VI regulations for gas vehicles as there is currently no re-certification for retrofitted vehicles. The methodology proposed by the Economic and Social Council has been adopted for the provisions concerning the approval of these systems[70]. The maximum methane slip for fumigated and multi-port injection systems is calculated based on their substitution rate up to a maximum of $6gCH_4/kWh$:

$$Methane\ slip\left(\frac{gCH_4}{kWh}\right) = 6.84 \cdot Substitution\ rate(\%)$$

Different fuel consumption values are associated with each duty cycle. At the same time, fuel consumption of natural gas HGVs are linked to the consumption of the baseline diesel HGV by

[69] Committee on Climate Change, "The fifth carbon budget - Chapter 3: The cost-effective path to 2050," 2015.
[70] United Nations - Economic and Social Council, "Proposal for a new Regulation on uniform provisions concerning the approval of Heavy Duty Dual-Fuel Engine Retrofit Systems (HDDF-ERS) to be installed on heavy duty diesel engines and vehicles," *World Forum Harmon. Veh. Regul.*, 2016.

imposing a fuel efficiency penalty or benefit for each of the engine technologies. The efficiency of the baseline diesel HGV is assumed to increase by 10% by 2035. TTM emissions savings are assumed to increase with time, as technology innovation enables both higher engine efficiency and higher gas substitution rates to be achieved. This is in addition to any efficiency improvements attributed to the baseline diesel engine. The reduction in GHG emissions in 2035 is estimated to be 7% in all scenarios compared to the values presented in Figure 10 for 2020. No difference in terms of TTM emissions is assumed between the LNG and CNG pathways.

Shipping Emissions

The demand trends for each shipping segment is based on IPCC projections and the data is derived from the Third IMO GHG Study [71].

Economics of Gas Vehicles

Duty cycle	Average lifetime (years)	Residual value (%)	Average depreciation rate (% / year)
Single-decker bus	13	20	6
Double-decker bus	13	20	6
Small HDVs (8-18 Tonnes)	9	20	9
Construction HDV	9	20	9
Long Haul HDV	6	10	15
Distribution HDV	9	10	10
Municipal HDV	10	20	8
Off-road construction	6	20	13
Off-road tractors	11	20	7

Table 6 - Assumptions on residual value and depreciation rates used for the choice modelling

[71] T. W. P. Smith, J. P. Jalkanen, B. A. Anderson, J. J. Corbett, J. Faber, S. . Hanayama, E. . O'Keeffe, S. . Parker, L. . Johansson, L. . Aldous, C. . Raucci, M. . Traut, S. . Ettinger, D. . Nelissen, D. S. . Lee, S. . Ng, A. . Agrawal, J. Winebrake, M. . J.; Hoen, S. . Chesworth, and A. Pandey, "Third IMO GHG Study 2014; International Maritime Organization (IMO)," London, 2014.

Vehicle segment	Absolute price for a diesel version	Annual mileage (on-road: km/year; off-road: hr/year)
Single-decker bus	£123,039	27599
Double-decker bus	£189,963	27599
Small HDVs (8-18 Tonnes)	£44,122	44247
Construction HDV	£74,913	35398
Long Haul HDV	£93,054	120000
Distribution HDV	£93,054	74819
Municipal HDV	£72,269	18515
Off-road Construction HDV	£74,913	812
Off-Road Tractor	£74,913	992
HDV below 8 Tonnes	£44,122	44247

Table 7 - Purchase prices (excluding VAT) for diesel vehicles in different segments based on Ricardo AEA[72] research and OLEV bus scheme guidance, and the average mileage assumed in each segment for TCO calculations

Natural gas vehicle cost premiums:	2020	2035
HPDI (LNG)	£28,500	£22,000
MPSI (LNG)	£33,000	£27,000
MPSI (CNG)	£31,800	£25,400
Fumigation (LNG)	£32,000	£27,000
Fumigation (CNG)	£30,000	£25,400
Multi-Port (LNG)	£32,000	£27,000
Multi-Port (CNG)	£30,000	£25,400
Stoichiometric Gas (LNG)	£27,000	£18,200
Stoichiometric Gas (CNG)	£25,500	£16,700

Table 8 - Total capital cost premiums for natural gas vehicles by powertrain, this includes an engine cost premium, cylinder cost premium and aftertreatment cost premium

[72] Ricardo-AEA for the Commitee on Climate Change, "A review of the efficiency and cost assumptions for road transport vehicles to 2050," *AEA/R/ED57444*, no. 1, 2012.

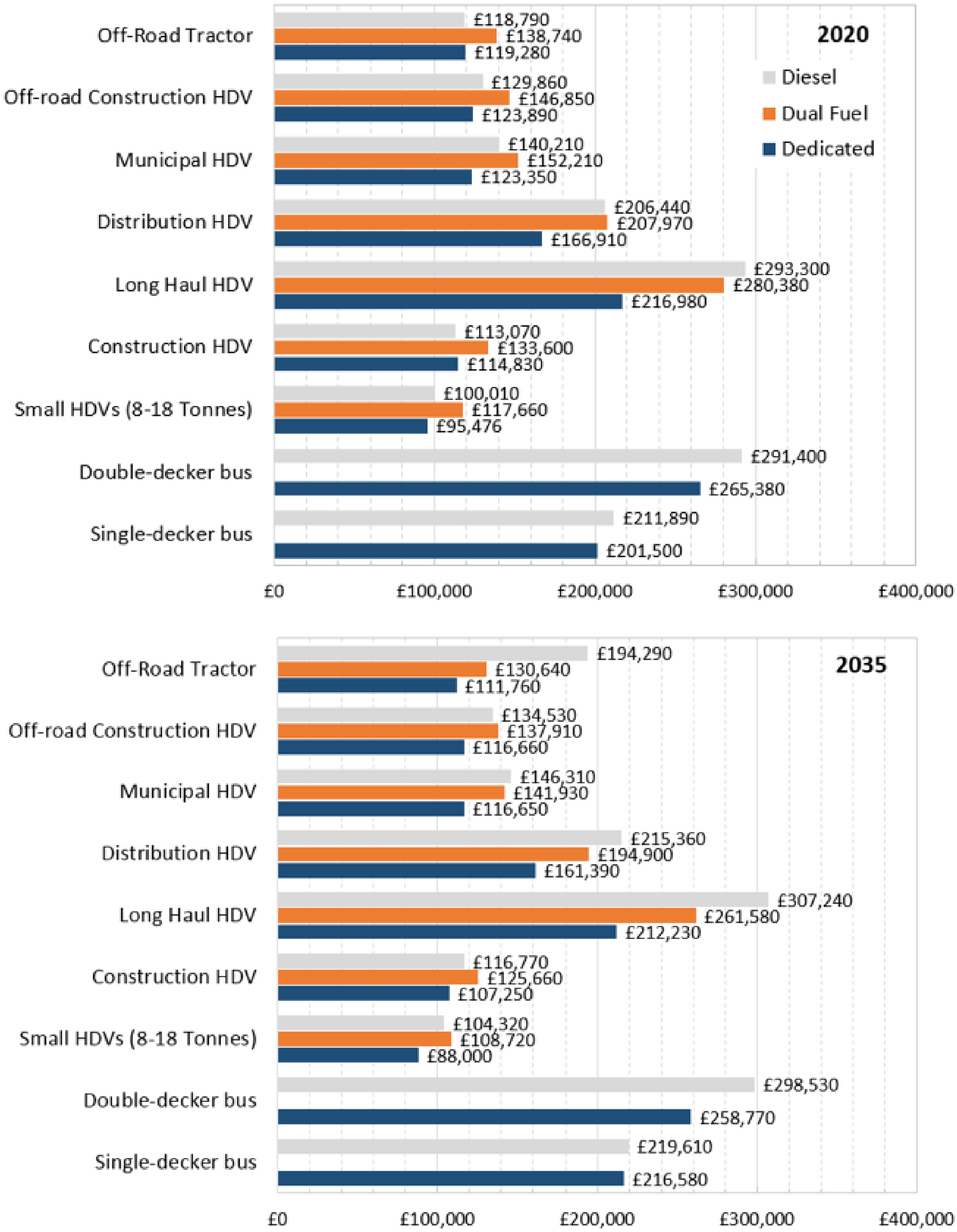

Figure 22 - The Total Cost of Ownership (TCO) of a dedicated and a dual fuel natural gas HDV verus a diesel counterpart in each segment in 2020 and 2035. TCO is calculated over 4 years for on-road HDVs, 6 years for off-road HDVs and 7 years for buses. Fuel tax is as it is now, with a differential in duty between diesel and natural gas.