Life cycle environmental impacts of natural gas drivetrains used in UK road freighting and impacts to UK emission targets

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Abstract
Using natural gas as a fuel in the road freight sector instead of diesel could cut greenhouse gas and air quality emissions but the switch alone is not enough to meet UK climate targets. A life cycle assessment (LCA) has been conducted comparing natural gas trucks to diesel, biodiesel, dimethyl ether and electric trucks on impacts to climate change, land use change, air quality, human health and resource depletion. This is the first LCA to consider a full suite of environmental impacts and is the first study to estimate what impact natural gas could have on reducing emissions form the UK freight sector. If LNG is used, climate change impacts could be up to 33% lower per km and up to 12% lower per kWh engine output. However, methane emissions will eliminate any benefits if they exceed 1.5-3.5% of throughput for typical fuel consumption. For non-climate impacts, natural gas exhibits lower emissions (11-66%) than diesel for all indicators. Thus, for natural gas climate benefits are modest. However, emissions of CO, methane and particulate matter are over air quality limits set for UK trucks. Of the other options, electric and biodiesel trucks perform best in climate change, but are the worst with respect to land use change (which could have significant impacts on overall climate change benefits), air quality, human toxicity and metals depletion indicators. Natural gas could help reduce the sector's emissions but deeper decarbonisation options are required to meet 2030 climate targets, thus the window for beneficial utilisation is short.

Keywords: natural gas; life cycle assessment; heavy duty trucks; road freight; methane emissions; climate change

1. Introduction

Road transport is a major source of emissions, accounting for 22% of UK greenhouse gas emissions (GHG) in 2015, of which 18% is from the road freight sector. The road freight sector carries out the transportation of cargo in heavy good vehicles (HGVs), which are vehicles with a tractor unit weighing ≥3,500 kg. Globally the sector contributed 8% towards GHG emissions and 26% of all vehicles in use in 2015 (IEA, 2017a, IEA, 2017b, Statista, 2018). The sector's primary fuel is diesel but the introduction of strict regulations to curb tailpipe emissions (CO_2, nitrogen oxides (NO_x) and particulates amongst others (icct, 2016)), as well as diesel price volatility (EIA, 2018a, World Bank, 2018) have led to companies and operators to look for alternative fuels, such as biodiesel, and alternative technologies such as batteries (electric vehicles) (IEA, 2017b). Biodiesel has issues related to its feedstock (e.g. crop competition, water use and land use) (Hassan and Kalam, 2013). Electric trucks currently have low travel range and there is limited charging infrastructure available (Bonges and Lusk, 2016). Natural gas is another alternative to diesel and could offer emissions reductions relative to it.

Natural gas produces 75% the CO_2 of diesel or petrol/gasoline upon combustion, and generally low quantities of air pollutants (EIA, 2018b, IGU, 2017). It has been used as a transport fuel since the 1930s (Yedla, 2015) and is usually cheaper (per unit energy) than crude oil derived fuels (FT, 2018). Natural gas powered engines are similar in design to diesel and many diesel vehicles can be retrofitted to use natural gas (AFDC, 2018a, AFDC, 2018b, NGV Global, 2018b). Since 2008, the number of natural gas vehicles (NGVs) in the world has increased by 2.6-fold, with over 26 million registered in 2018. Most NGVs are found in China (5.4 million), Iran (4.5 million) and India (3.1 million) (NGV Global, 2018a). The increasing uptake of NGVs could play an important role in countries meeting emissions targets. The UK must reduce its greenhouse gas emissions to ≤20% of 1990 level by 2050, according to the Climate Change Act 2008 (UK Parliament, 2008), while also keeping emissions of air pollutants within the limits set in the national Air Quality Objectives (DEFRA, 2005). Other countries have also set ambitious climate targets following the Paris Agreement: Australia 72-74% of 2005 levels by 2030 (Australian Government, 2015); Canada 20% of 2005 levels by 2050 (Government of Canada, 2016); China 35-40% of 2005 levels by 2030 (IEA, 2016).

Despite this, current local air quality limits are often exceeded (Carrington, 2018, Shotter and Huber, 2018, Wilkes et al., 2018). For example, the annual allowance for NO_x in London was exceeded within the first 30 days in 2018 (which is an improvement on the previous 10 years) (Carrington, 2018). These failures have prompted governments to be called on to do more and take emission targets more seriously (Griffin and Gabbatiss, 2018, McGrath, 2018). This has led to governments to look for cost-effective means for rapid emissions reductions, such as natural gas. However, whilst NGVs may produce air quality improvements compared to traditional fuels, there is uncertainty of the climate mitigation potential given the impact of methane emissions. Furthermore, methane emissions also have a strong human health and ecosystem impact via photochemical ozone creation. Emissions of methane may arise from various points in the natural gas supply chain, as well as methane slip from the engine (unburnt methane passing through the engine). The DfT estimates that if methane slip exceeds 2.6 g CH_4/km, any climate benefit in converting from diesel is negated (assuming CO_2 emissions to be 800 g/km and 9% CO_2 savings over diesel for retrofitted dual fuel trucks) (Bates et al., 2014). Further studies commissioned by the DfT have found that methane slip from dual fuel trucks are indeed high enough to negate carbon savings over diesel (John Norris, 2015, Robinson, 2017). For dedicated gas trucks, studies to measure slip in existing models have been carried out but the estimation of the amount of slip needed to negate climate benefits has not been conducted (John Norris, 2015, Robinson, 2017).

Most environmental studies of NGVs have focused on personal transportation vehicles rather than HGVs. These studies typically compare natural gas (either as compressed natural gas (CNG) or liquefied natural gas (LNG)) with diesel or gasoline (Arteconi et al., 2010, Bates et al., 2014, Beer et al., 2002, Bicer and Dincer, 2018, Cai et al., 2017, Curran et al., 2014, Dai and Lastoskie, 2014, Elgowainy et al., 2018, Hackney and de Neufville, 2001, Hekkert et al., 2005, Huo et al., 2013, John Norris, 2015, Lave et al., 2000, Luk et al., 2015, Robinson, 2017, Rose et al., 2013, Shahraeeni et al., 2015, Sharma and Strezov, 2017, Strømman et al., 2006, Tong et al., 2015). The studies all consider climate change impacts, whilst some also consider other impacts, such as cost effectiveness and air quality. In terms of HGV specific studies, to the authors' knowledge there are only three peer reviewed life cycle studies: Arteconi et al. (2010), Beer et al. (2002) and Cai et al. (2017), which compare natural gas powered HGVs to diesel based on GWP.

This study is novel because it conducts a life cycle assessment (LCA) of CNG and LNG as a HGV fuel, including a full suite of environmental impacts and comparing against diesel and alternative fuels. The aim of this work is to assess the environmental impacts associated with switching from diesel to natural gas versus other fuels. The study estimates the maximum allowable methane emissions to ensure climate impacts are maintained below those from diesel trucks, as well as investigating the potential role in NGVs toward decarbonising transport and meeting UK emission targets. This work is of interest to fleet operators and transport policy makers as well as HGV manufacturers. The methodology, data and assumptions used to conduct this research are presented in the next section, followed by the presentation and discussion of the results leading to the conclusions drawn.

2. Methodology

An LCA is conducted to assess the environmental impacts of natural gas drivetrain HGVs in the UK, following the steps outlined in ISO 14040/14044 (ISO, 2006a, ISO, 2006b). A system boundary from 'cradle to grave' is considered, considering the whole fuel cycle, from fuel production/extraction to use in the vehicle (Figure 1). The impacts have been calculated based on literature fuel economy/consumption values and impacts to climate change, land use change, air quality, human toxicity and resource depletion are considered. The study does not consider variations in driving regime, the impact of varying loads or the impact of different road type. However, the percentage of urban driving is considered.

Spark ignition (dedicated fuel) and dual fuel engines are considered for the natural options, as sufficient data on fuel consumption and tailpipe emissions were only available for these two engine types. Two methods for delivering LNG are considered; transport of LNG to the fuel station in a cryogenic trailer and onsite liquefaction (at the fuel station) (Figure 1). For CNG, only onsite compression is considered (Figure 1). To assess the impacts, two functional units have been used; 1 km distance travelled by a HGV and 1 kWh engine output. These two functional units have been selected to allow comparisons with the HGV LCA literature, other vehicles and other uses of natural gas (marine shipping, electricity generation etc.).

In total, seven fuel options are considered:

- compressed natural gas (CNG; compressed at fuel station);
- liquefied natural gas (LNG; liquefied on site and delivered by trailer);
- dual fuel (diesel and LNG; LNG liquefied on site and delivered by trailer);
- diesel (baseline);
- biodiesel (from soybean);
- dimethyl ether (from natural gas); and
- electricity (battery; 2016 UK electric mix).

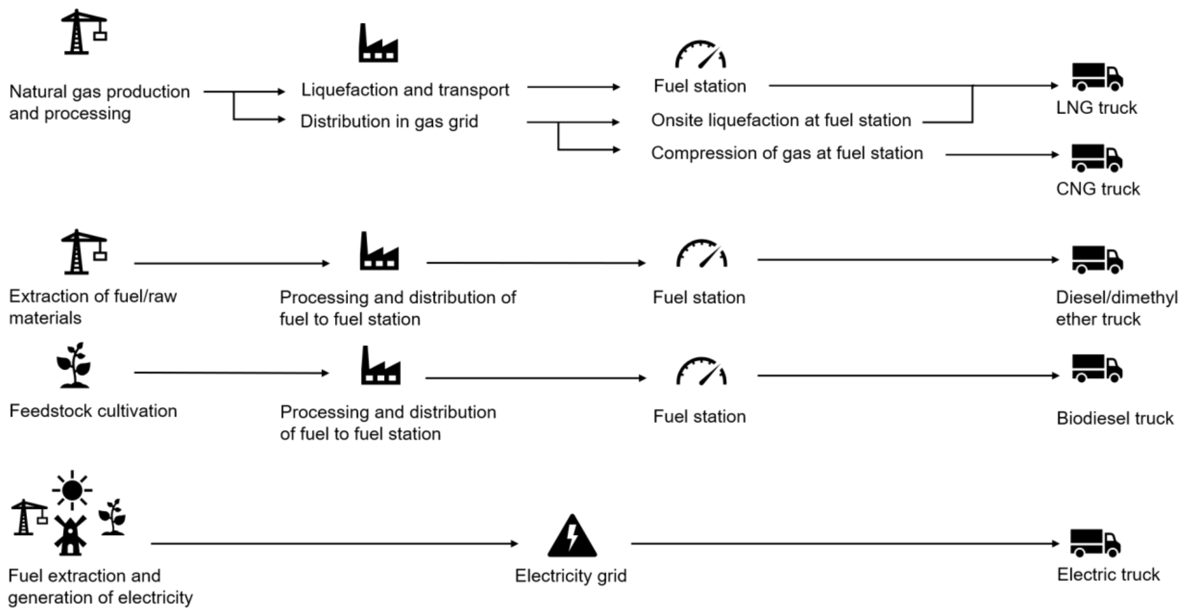

Figure 1: Life cycle system boundaries of fuels considered in this work. System boundaries are from 'cradle to grave'. The construction of the HGV body is also considered. [Liquefied natural gas: LNG; compressed natural gas: CNG]

2.1. LCA modelling

The LCA was modelled using GaBi v8 software (thinkstep, 2018), using data from the ecoinvent 3.3 dataset (ecoinvent, 2018a), GREET (Argonne National Laboratory, 2017) and various literature sources as described in the following section. The IPCC AR5 LCIA methodology (IPCC, 2014) was used to calculate the impacts to climate change using up-to-date GWP CO_2 equivalences, while the ReCiPe LCIA methodology was used to calculate the impacts to land use change, air quality, human health and resource depletion (abiotic and fossil) (Huijbregts et al., 2016). To assess the effect of methane emissions, the amount of methane slip needed for the GWP to equal diesel was calculated, as well as the sensitivity of total climate impact to changes in emissions.

2.2. Data and assumptions

The inventory data for fuel consumption and urban share is shown in Table 1. To model the emissions from the truck, literature data on fuel consumption and share of urban travel (based on UK conditions) (Table 1) were used with tailpipe emissions data from GREET to build the models in GaBi. A range of fuel consumptions, as shown in Table 1, are used to produce upper and lower emissions estimates, as well as calculate an average. It should be noted that it was not possible to compare like-for-like engines on a power output basis. Each engine option has a different capacity and performance range, as shown in Table 1. In particular the electric truck, which uses four motors and is based on a prototype vehicle which will become commercially available in 2019 (no field test data available). As the electric truck has much lower fuel consumption than the other fuels, the results per kWh engine output will be skewed in favour of the other trucks. However, as two functional units are used, this allows for a balanced comparison of the impacts. The truck body is not considered in the LCA models as the average annual mileage of HGVs in the UK is high and their operating lifespan can be up to or over 13 years (DfT, 2017). Process models were also built for the fuel stations and LNG trailer transport, as well as the upstream stages of the fuel supply chain, using literature data (Table 2), and data from the ecoinvent 3.3 dataset. The LNG trailer is assumed to be driven by a diesel-powered tractor unit and travels 728 km (roundtrip) from LNG import terminals in the UK to the fuel stations. This was estimated by calculating the transport distances between all UK LNG terminals and all LNG fuel stations as per NGV Network (2018). Details on the calculation can be found in Table A3 in the supporting information (SI).

Table 1: Fuel consumption, engine size and urban share of trucks considered. Sources: (Burke and Zhao, 2017, Cryogas M&T Poland, 2016, Cryogas M&T Poland, 2017, Iveco, 2018b, Iveco, 2018a, Tesla, 2018).

Fuel	**Fuel consumption (MJ/km)[a, b]**	**Engine/motor size (kW)**	**Urban share**
CNG	21.4 (13.3-26.1)	150-294	0.36
LNG	14.4 (13.0-18.7)	264-294	0.36
Dual fuel (LNG and diesel)[c]	18.1 *(*18.1-18.5)	313-343	0.36
Diesel	12.3 (10.0-17.4)	313-403	0.36
Biodiesel[e]	11.2 (10.5-20.2)	246-400	0.36
Dimethyl ether	6.5 (6.5-11.8)	246-400	0.36
Electric	4.5	820[d]	0.36

[a]Based on HHV for liquid fuels. (…) is range in fuel consumption.
[b]Values given are the average fuel consumptions of various on road tests. Some tests consider mostly urban driving with others consider a mix of urban, rural and motorway/highway driving. It was not possible to disaggregate the data to obtain fuel consumption for different driving regimes for all the fuels considered.
[c]3:2 LNG to diesel ratio based on energy content (HHV).
[d]Four 205 kW motors are used (one per wheel)- total motor size is 820 kW. Lithium ion battery is used.
[e]Soybeans imported to the UK from a mix of countries; RoW ecoinvent dataset was used (Efeca, 2018).

Methane emissions for the different life cycle stages are taken into account and are presented in Table 3, based on ecoinvent data as the central estimate. It should be noted that the emissions from the supply chain are low, especially in comparison to the target set by the OGCI in 2018; to achieve 0.2% methane emissions in upstage supply chain stages by 2025 (OGCI, 2018). However, the supply chain emissions are within range of emissions reported in previous studies (Balcombe et al., 2018). The impact of higher supply chain emissions is considered in the sensitivity analysis. To model the fuel stations and LNG trailer, literature data was collected on fuel station energy consumption and fugitive emissions. It was assumed that the biodiesel and dimethyl ether fuel stations have the same energy consumption as diesel and the fuel is delivered to the fuel station in the same manner. The electric truck uses lithium-ion batteries and is assumed to be charged from a charging point connected directly to the electric grid. The fuel station energy considers electricity for running the fuel dispensing equipment, as well as energy for compressing (for CNG) or liquefying (LNG) gas onsite. Energy used by convenience stores and other services were not included. As fuel stations dispense large quantities of fuel over their lifetime, the impacts of infrastructure and equipment were not considered in the LCA model. The UK 2016 electricity mix was used to charge the electric HGV and to meet energy demands at the fuel stations (Table A1 in the SI). The UK 2016 natural gas mix (Table A2 in SI) was used as the feed stream for CNG and LNG liquefied onsite, while the UK LNG import mix was used for LNG delivered by trailer. For the upstream stages, ecoinvent datasets were used. The datasets were used as is but were modified where necessary to use UK electricity (to make as UK specific as possible).

Table 2: CNG, LNG and diesel fuel station energy and emissions specifications. Sources: (Arteconi et al., 2010, Bates et al., 2014, John Norris, 2015, Robinson, 2017).

	CNG	**LNG**	**Diesel**
Fuel station energy demand (MJ/GJ fuel)	231	192	7.9×10^{-3}
Liquefaction energy (kWh/kg)	-	0.15	-
LNG cooling (kWh/kg)	-	0.1	-
Fuel station fugitive emissions (kg/MJ)	1.86×10^{-7}	1.12×10^{-7}	-
Fuel station boil-off	0%	0%	-
LNG trailer boil-off	-	0%	-

Table 3: Methane emissions in each life cycle stage, expressed as percentage of throughput of each stage. Sources: (Argonne National Laboratory, 2017, Arteconi et al., 2010, ecoinvent, 2018b, ecoinvent, 2018c, ecoinvent, 2018d).

	Supply chain	**Fuel station**	**Truck**
CNG	0.06%	0.0004%	0.5-0.6%
LNG T	0.0001%	0.00007%	0.4-0.7%
LNG OSL	0.06%	0.00007%	0.4-0.7%

LNG boil-off at the fuel station and in the trailer are assumed to be zero, because it has been assumed that the throughput of the fuel station is such that there is no time for boil-off to initiate. Similarly, the transit of the LNG trailer is assumed to take less than the time needed for boil-off to initiate (estimated to be 5 days) (Gunnarsson and Helander, 2015). In reality there may be boil-off at the fuel station and trailer and the rate of boil-off is affected by external conditions (e.g. outside air temperature and equipment condition and maintenance) and is further investigated in the sensitivity analysis.

It is important to note that while driving regime and road type are not directly considered in this study, the impacts of both are reflected in the wide range in fuel consumptions considered. The impact of cargo load is also not considered. The study is also limited to emission data from GREET, which is US-specific, does not consider newer vehicles (2015 onwards) and has fixed values for non-CO_2 emissions. As literature data was used, it was also not possible to compare like-for-like trucks (same manufacturer, similar engine design, same load and drive regime) for all the fuels considered. Future work could consider the impact of driving regime and load for multiple HGV fuels/technologies. The use of field data on tailpipe emissions would reduce the uncertainty in emissions and could be another topic of future work.

2.3. Impact on UK emission targets

To assess the potential impact of natural gas HGVs on UK emissions, the results of the LCA were used to calculate total annual emissions of CO_2, CO, CH_4, non-methane hydrocarbons (NMHC), particulate matter (PM) and NO_x assuming the conversion of the entire fleet. The calculations are based on 2015 fleet number and mileage (26.8 billion vehicle km in total) (DfT, 2017). Natural gas is compared to diesel to determine the emissions benefits that could be achieved and whether fuel switching could help the UK achieve its emissions targets. The tailpipe emissions are also compared to the Euro VI HGV standards for CO, CH_4, NMHC, NO_x and PM, to assess what impact natural gas trucks could have on meeting air quality limits.

3. Results

3.1. Climate change

Out of all the natural gas options considered, only LNG (trailer; T and onsite liquefaction; OSL) exhibits a lower global warming potential (GWP) (17-21%) than diesel on a km basis, as shown in Figure 2. When the lowest LNG fuel consumption is considered, the GWP is 33% lower. However, the higher fuel consumption scenarios eliminate the GWP benefit, as shown by the error bars in Figure 2. CNG and dual fuel have a higher GWP than diesel (11-52%), with CNG only comparable to diesel under the lowest fuel consumption scenario. The higher GWP of dual fuel is due to the increased overall fuel consumption. In comparison to the other alternative fuels and technologies, only LNG (T and OSL) has lower GWP than dimethyl ether and is comparable to the electric truck (UK electricity mix). The option with lowest GWP is biodiesel and is six times lower than diesel and five times lower than LNG. Note that the climate benefit for GWP20 between LNG and diesel is smaller than for GWP100. This is because over a shorter time frame, methane emissions have a stronger effect on global warming.

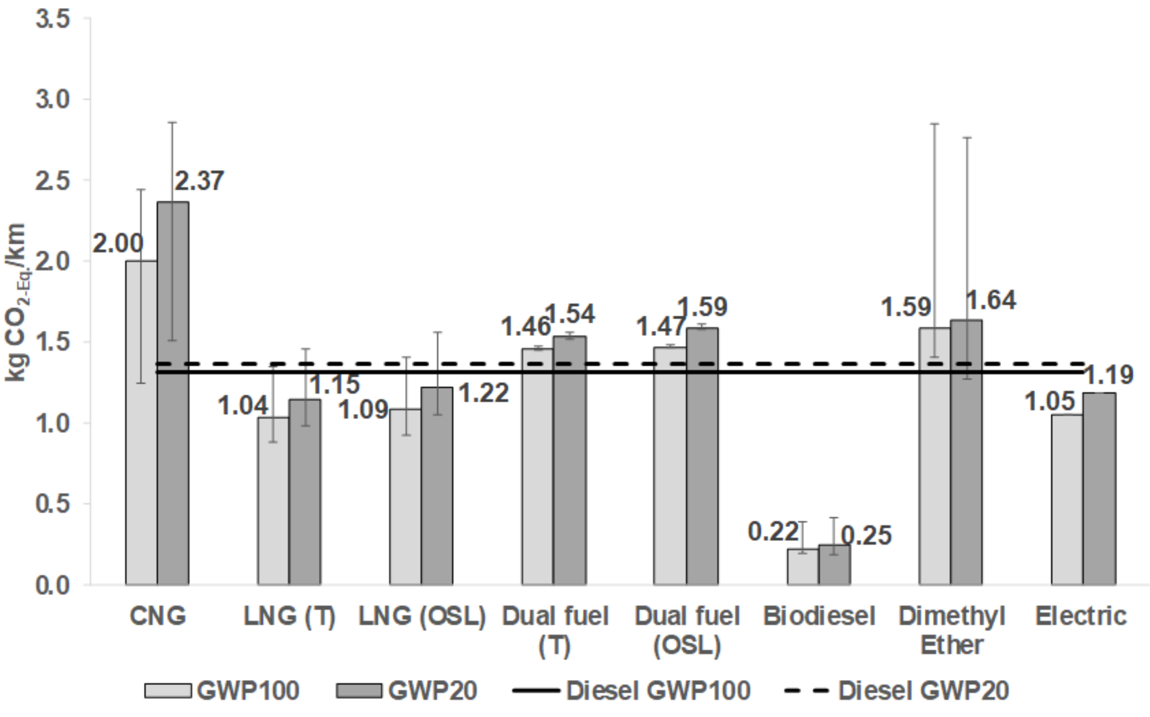

Figure 2: Global warming potential (GWP) over 100-year time horizon of natural gas and other diesel alternatives per km distance travel. The bars show the average GWP and the error bars the range in GWP. The GWP is proportional to fuel consumption; the lower limit represents the lowest fuel consumption while the upper limit represents the highest fuel consumption.

The average GWP of diesel is displayed in the figure. The maximum GWP of diesel is 1.51 kg $CO_{2\text{-Eq.}}$/km and the minimum is 0.87 kg $CO_{2\text{-Eq.}}$/km.

When the functional unit of 1 kWh engine output is considered, the results are similar except CNG has an even higher GWP; the climate benefits of LNG become marginal (4-7% for GWP100, 12% when lowest fuel consumption is considered but no benefit for GWP20); electric has GWP comparable to dimethyl ether and has GWP 46-77% higher than LNG (Figure 3). This difference in the results between the two functional units is due to the assumed efficiency of the different trucks. The electric truck has the largest power output but the highest fuel efficiency. Thus, when impacts are converted to kWh motor output, its impacts are larger than the other options. The motor and fuel consumptions considered for the electric truck, 2 kWh input/km output (Tesla, 2018), are based on a prototype, which goes into commercial production in 2019. On-road tests carried out using this truck may yield a different fuel consumption and the results of this work should be interpreted with caution.

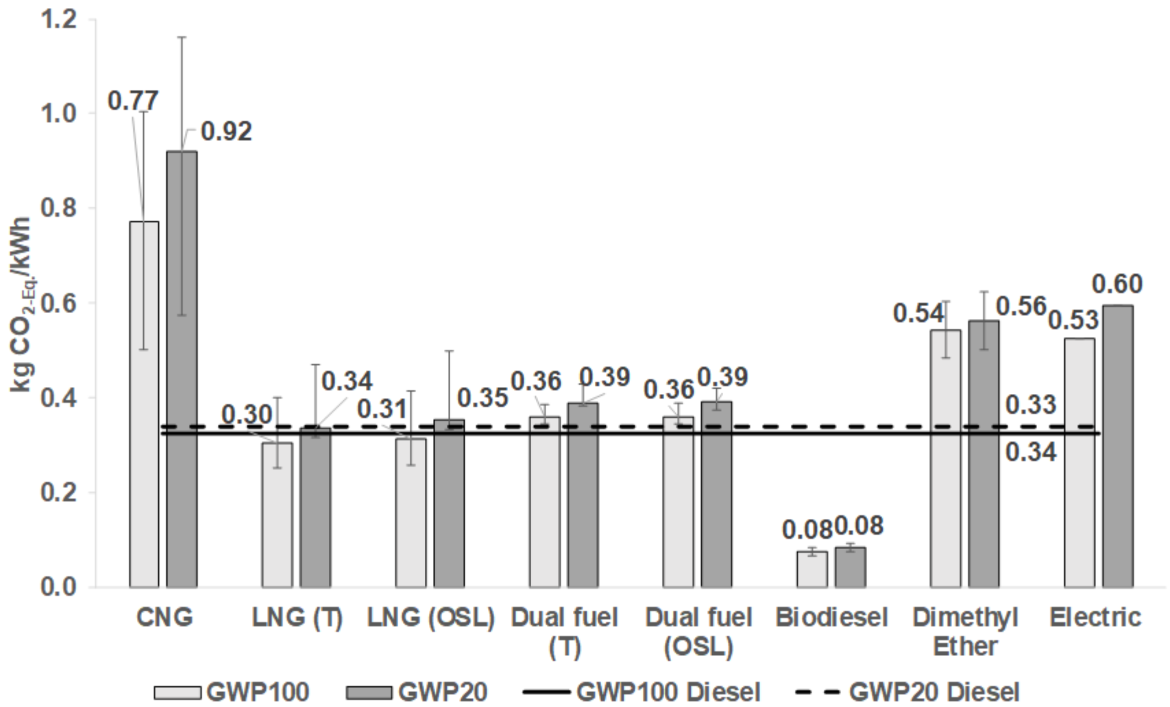

Figure 3: Global warming potential (GWP) over 100-year time horizon of natural gas and other diesel alternatives per kWh engine output. The bars show the average GWP and the error bars the range in GWP. The GWP is proportional to fuel consumption; the lower limit represents the lowest fuel consumption while the upper limit represents the highest fuel consumption. The average GWP of diesel is displayed in the figure. The maximum GWP of diesel is 0.37 kg $CO_{2\text{-Eq.}}$/kWh and the minimum is 0.21 kg $CO_{2\text{-Eq.}}$/kWh.

The life cycle stage which contributes the most towards the GWP is, in general, the combustion of fuel in the truck (61-88% for all options besides biodiesel and electric, Figure 4). The second most impactful stage is the electricity used by the fuel stations for the natural gas trucks. This includes energy for compressing and liquefying natural gas at the fuel station, as well as electricity to run the fuel dispensing system. The third most impactful stage for the natural gas trucks is fuel production. These stages contribute 14-35% to the GWP of CNG and LNG due to the use of fossil fuels in the UK electric mix, as well as fossil fuels used in producing the fuel. For biodiesel, the production of fuel is the main source of greenhouse gas emissions (85%) because of the need to produce a feedstock and then convert the biomass into a liquid fuel (Figure 4). For the electric truck, electricity to charge the truck contributes the most (67%, Figure 4) due to the UK electric mix containing fossil fuels.

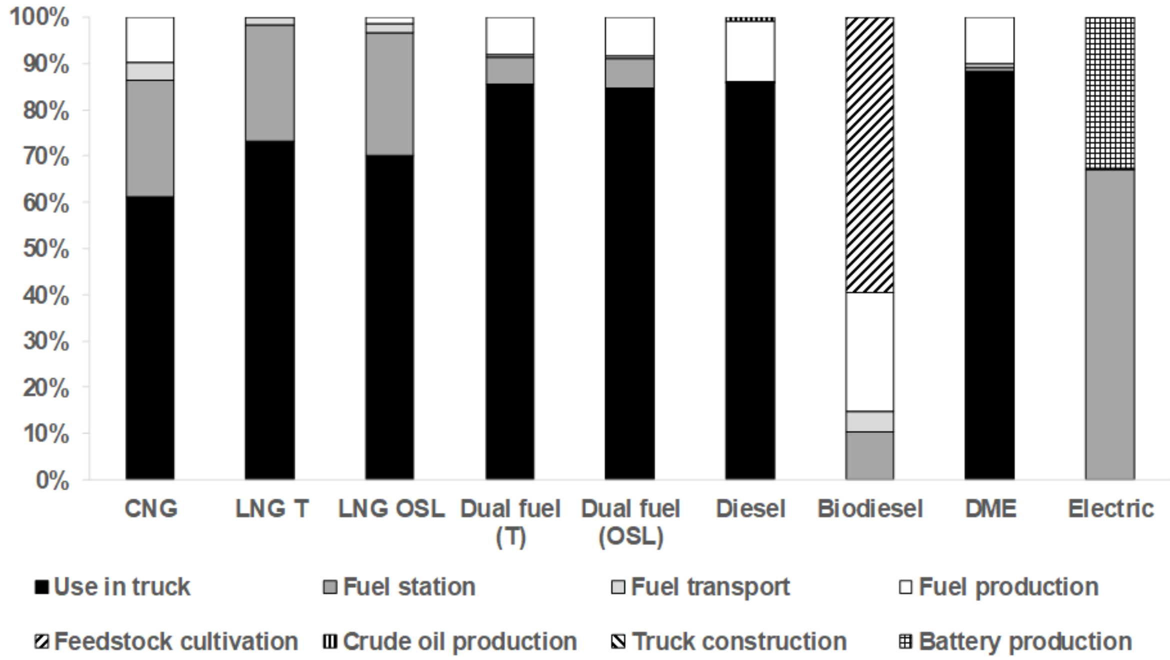

Figure 4: 'Hot spot' analysis of GWP, showing which stages contribute what towards the GWP for natural gas, diesel and other diesel alternatives. For both km and kWh basis.

3.2. Comparison to the literature

The results of this work are comparable with other literature estimates for LNG, dual fuel and diesel but is approximately double for CNG (Figure 5). This is due to the higher CNG fuel consumptions considered in this work. The higher fuel consumption represents fuel consumptions based on road tests which were mostly urban driving cycles, which have higher fuel consumption, while the lower fuel consumptions used in this work reflect mostly highway/motorway drive cycles, which have the lowest fuel consumption. The CNG literature did not consider urban drive cycle. Taking this into account, the GWP calculated for the lower fuel consumptions are on par with the literature. For the other fuels, there is good agreement, as can be seen in Figure 5 between the average GWPs and the values calculated in this work are within range what has been reported in the literature.

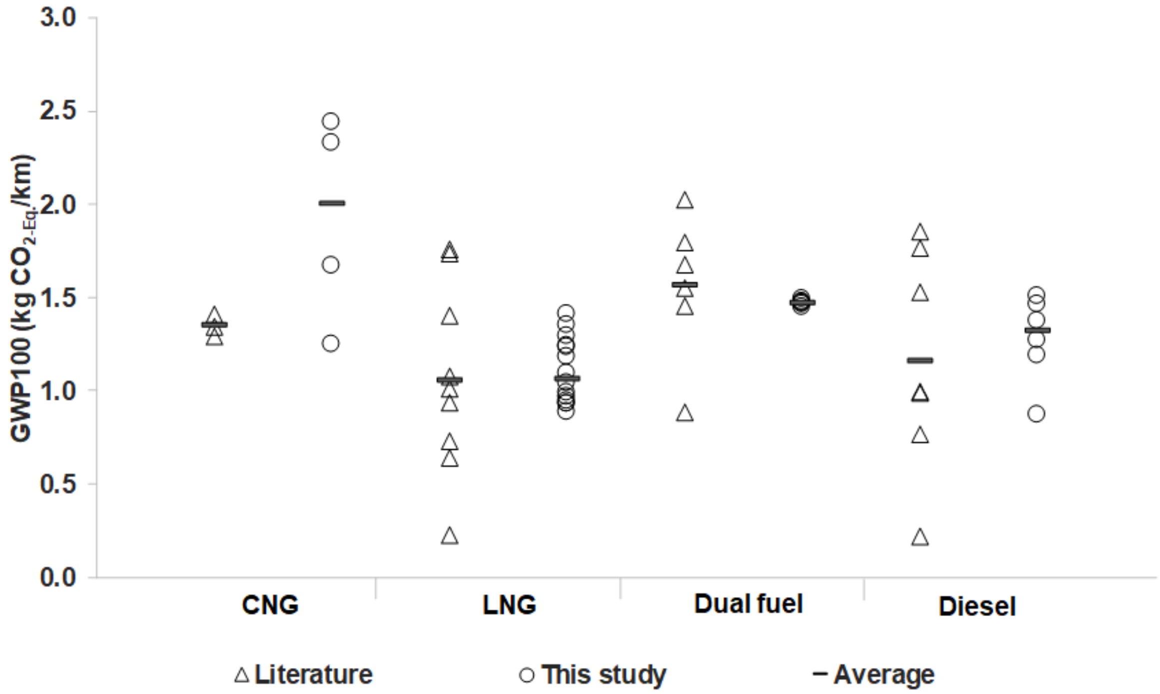

Figure 5: Comparison of GWP100 calculated in this work to GWP reported in the literature for CNG, LNG, dual fuel and diesel (Arteconi et al., 2010, Bates et al., 2014, Beer et al., 2002, Cai et al., 2017, John Norris, 2015, Robinson, 2017). The data points (triangles and circles) represent a GWP value calculated in this work or one reported in the literature.

3.3. Methane sensitivity

The impact of methane emissions on the GWP of CNG and LNG (dedicated) is presented, considering the effect of methane/engine slip and emissions in the supply chain and fuel station. For CNG and LNG, most of the emissions come from the truck (57-74%, Figure 6) and therefore, this stage is more likely to have a larger effect on GWP sensitivity. The fuel station is the second largest source of emissions for CNG and LNG T, while the supply chain is the second largest source of emissions for LNG OSL. This is due to the different delivery routes to the fuel station. There are lower emissions from the LNG T supply chain as the fuel is transported mostly in LNG ships and trailers with minimal pipeline transport. LNG ships and trailers are assumed to have minimal or zero methane emissions as boil-off gas is used to fuel the ship or transport duration is not long enough for boil-off to initiate. The difference in the volume of grid gas needed to produce CNG and LNG is the reason why the supply chain is a larger source of emissions for LNG OSL, as CNG has 1/100th the volume of natural gas (atmospheric conditions), while LNG has 1/600th the volume. Note that upstream supply chain emissions are very low as estimated in ecoinvent, but have been shown to vary widely in more recent studies (Balcombe et al., 2018). Indeed, a global estimate of methane emissions from natural gas is 1.7% of production (IEA, 2017c), although this includes low pressure distribution and end-use which is not accounted for here. Even so, higher methane emissions are a risk, which is assessed in the sensitivity analysis in the proceeding section.

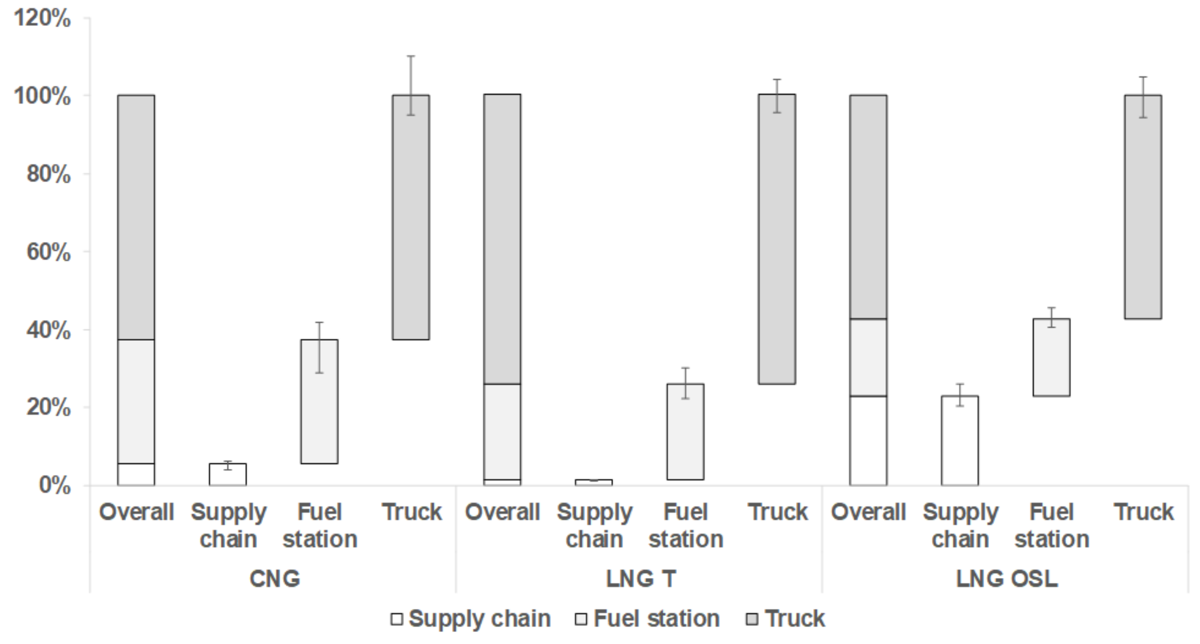

Figure 6: Sources of methane emissions in CNG and LNG truck life cycle per MJ fuel consumed. Emissions include direct contributions and indirect from electricity and fuel production.

3.3.1. Engine slip

Figure 7 shows the impact of total methane emissions on the GWP of LNG. As depicted by the large 'grey area', there is a broad variation in the impact of emissions governed by the truck fuel efficiency. Methane emissions must be kept below 3.1-3.5% of throughput (7.8-9.0 g CH_4/km) to ensure climate parity with a diesel equivalent. Interestingly, when considered on a kWh basis, methane emissions must be kept below 1.00-1.39% (0.8-1 g CH_4/kWh, Figure B2 in SI) to ensure a climate benefit over diesel. This lower baseline is due to the marginal difference between LNG and diesel options when expressed on a per kWh engine output basis, highlighting the care that must be taken when selecting the functional unit, as well as the interpretation of the result. With high LNG fuel consumption, methane slip must be effectively zero to reach parity, whilst with low fuel consumption slip must be kept below 5.5-6.0% (12.4-13.3 g CH_4/km) or 1.89-2.26% (1.3-1.5 g CH_4/kWh) on a kWh basis. For CNG, only under the lowest fuel consumption and low methane slip (2.2% of engine throughput) does this option become comparable to diesel (Figure B1 in SI).

Thus, the acceptable levels of methane emissions are governed by the highly varied fuel consumption. The maximum allowable methane emissions range from zero to 6%, whereas our central assumption is 0.6%, or 1.4 gCH_4/km. Work commissioned by the DfT found that slip from a dedicated truck is relatively low with maximum of 0.2-0.5 g CH_4/km recorded (John Norris, 2015), which is much lower than our central assumption. However, the same report also found that slip reported for other natural gas trucks can range from very low to up to 1.65 g CH_4/km (John Norris, 2015) and stated that slip is dependent on the age of the vehicle (technology changes with introduction of emission standards) and engine temperature. These values suggest that LNG trucks offer a climate benefit over diesel fuels in all but the highest fuel consumption scenarios. However, poorly maintained engines or defects may cause engines and onboard fuel systems to be less efficient and emit higher amount of methane.

When supply chain and fuel station emissions were considered, the impacts to the GWP are similar to engine slip for both CNG and LNG but less impactful. The maximum allowable emissions are similar to engine slip but marginally lower. This is because tailpipe emissions are the largest source of methane, as shown in Figure 6.

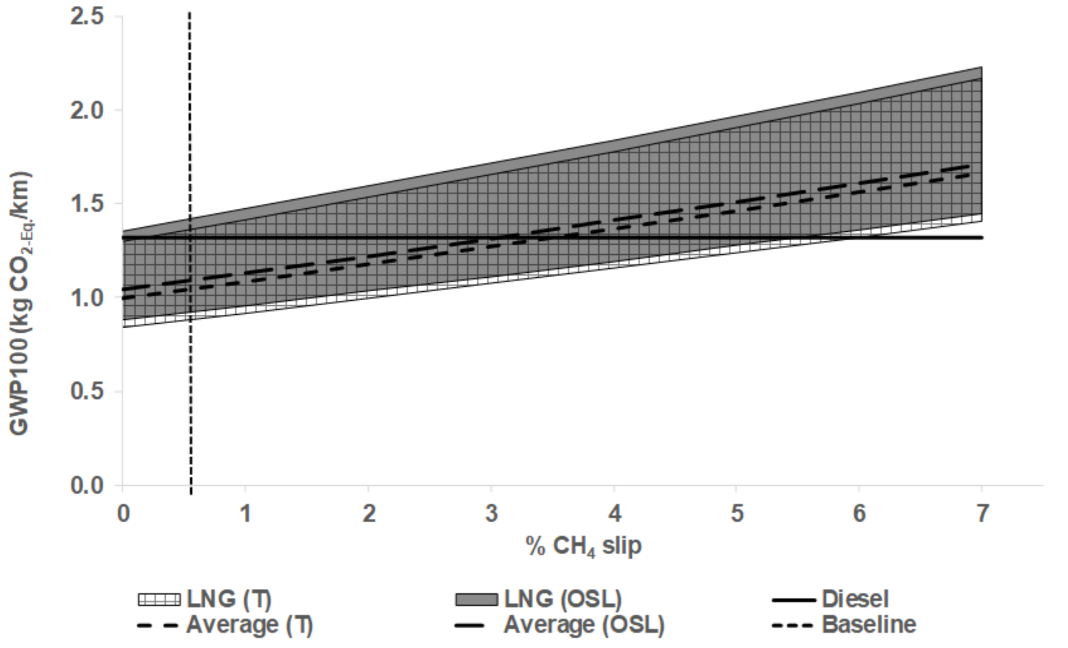

Figure 7: Variation in GWP with methane slip for dedicated LNG truck for LNG delivered via trailer or liquefied on site (per km). The dashed lines running across the shaded area is the GWP100 for average fuel consumption and the dashed line running vertical is the baseline engine slip considered in the LCA models. The solid line running across is the GWP100 of diesel.

3.4. Land use change

The impacts to land use change are measured through the land use change (LUC) indicator, which measures impacts to habitat and species loss due to land transformation, occupation and relaxation. The results show that all the natural gas options, bar LNG (OSL), have higher impact than diesel. CNG is 1.8-times higher than diesel while the LNG trucks have impacts comparable to diesel (Figure 8). Only LNG (OSL) has lower impacts than diesel while LNG (T) has lower impacts under low fuel consumption scenarios (indicated by the error bars). The non-natural gas options also have higher impacts for LUC than diesel, with biodiesel having the highest impact (400-times higher than diesel), followed by the electric truck (6-times higher) and dimethyl ether (1.5-times higher). The life cycle stages which contribute the most towards impacts to LUC are the fuel station, fuel transportation and fuel production for the natural gas trucks (Figure B3 in the SI). For the dedicated natural gas trucks, the fuel station and fuel transportation are more impactful than fuel production. For the dual fuel trucks, the fuel production is much more impactful. The reasons why these stages have impacts for land use change is due to the need for land transformation and occupation during mining (oil, natural gas, coal, minerals for making solar panels and wind turbines) and fuel cultivation. The fuel production stage contributes more for dual fuel and diesel because diesel is produced from crude oil in refineries and requires more processing (more materials and energy needed). The stages which contribute towards the impacts for dimethyl ether is similar to dual fuel and diesel, while for the electric truck the battery and electricity are the main hot spots. This is because of mining for materials to make the battery, as well as the UK electricity mix containing biomass, coal, natural gas, wind and solar PV. For biodiesel, the feedstock cultivation stage is the primary cause of LUC impacts.

In addition to impacts to habitat and species loss, LUC will also have an impact on climate change due to the loss of carbon sinks from vegetation removal and the release of greenhouse gases stored in soil/earth. These have not been explicitly included within this study, but based on the results presented in Figure 8, biodiesel would have a much greater impact than the other options, followed by the electric truck with the fossil fuel trucks having the lowest impact.

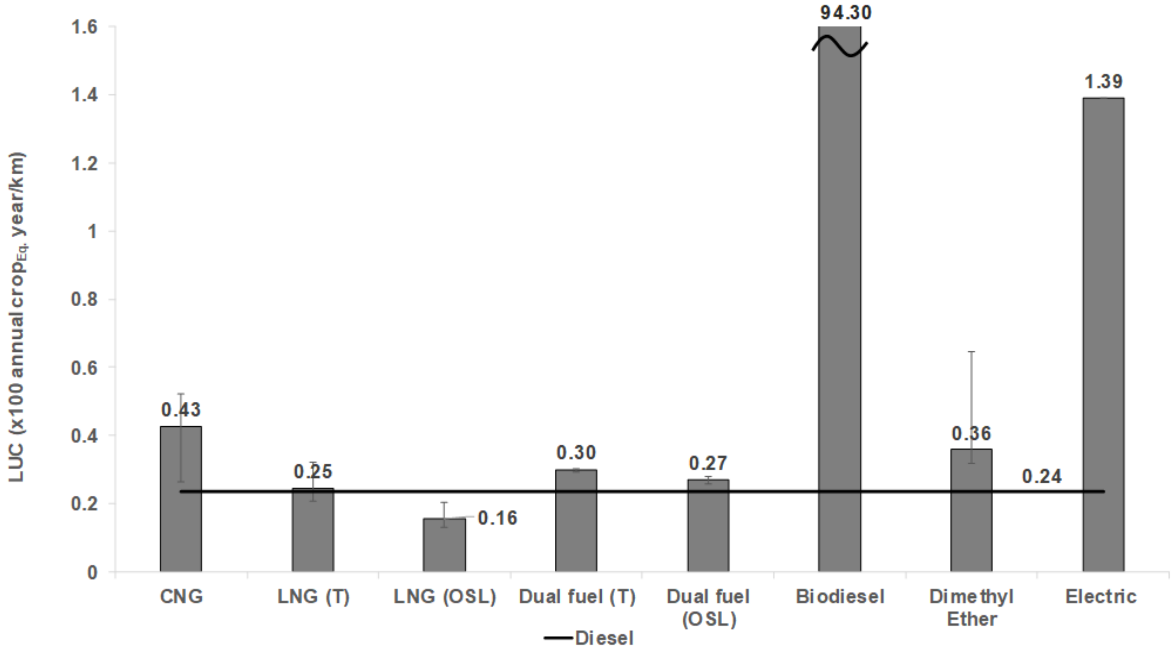

Figure 8: Impacts per km to land use change (LUC) for natural gas and other diesel alternatives, in comparison to diesel. The average impacts of diesel are displayed in the figure. The maximum impact to PM of diesel is 0.0027 annual crop$_{-Eq.}$year/km and the minimum is 0.0015 annual crop$_{-Eq.}$year/km. The impacts per kWh engine output are similar (Table B1 in the SI).

3.5. Air quality

The impacts to air quality are measured through two indicators: particulate matter formation potential and photochemical ozone formation potential, as shown in Figure 9. The LNG (dedicated and dual fuel) trucks have lower impacts than diesel for both indicators (37-61%) with LNG T having the lowest impact out of all the options. CNG has higher impact than diesel for particulate matter (21%) but photochemical ozone formation potential is 15% lower (Figure 9). When a kWh engine output basis is considered, the results are similar but CNG is higher for both indicators and diesel now has the lowest impact for particulate matter (Table B1 in SI). The stages which contribute the most towards these two indicators is different between the two. For particulate matter, electricity used at the fuel station and emissions from fuel production are the main impact hotspots for the natural gas trucks (Figure B4 in SI). This is because of emissions from coal in the electricity mix and raw gas being used to fuel upstream fuel equipment. When photochemical ozone formation is considered the combustion of fuel in the truck, along with the fuel station and fuel production are the main impact hotspots (Figure B5 in SI). This is because of emissions of methane and NMHC from the tailpipe and power plants. However, air quality standards consider individual pollutants rather than LCA indicators. When emissions of air pollutants are considered, all the dedicated natural gas trucks have lower emissions than diesel for NOx, SO_2 and SO_x (Table B2 in SI). Therefore, natural gas trucks offer air quality benefits both in the LCA indicators and individual pollutants.

When the non-natural gas options are considered, the electric truck has higher impacts than both diesel and CNG. This is because of the battery, as the raw materials required to make it need to be mined and processed, as well as the electricity mix as coal has high impacts for air quality (Cooper et al., 2014) (Figures B4 and B5 in SI). Dimethyl ether has impacts on par with LNG, while the biodiesel truck has the highest impact for photochemical ozone, but its impact is similar to LNG dual fuel for particulate matter on a km basis. This is because of fuel processing, feedstock cultivating and producing a crude oil from the feedstock (Figures B4 and B5 in SI).

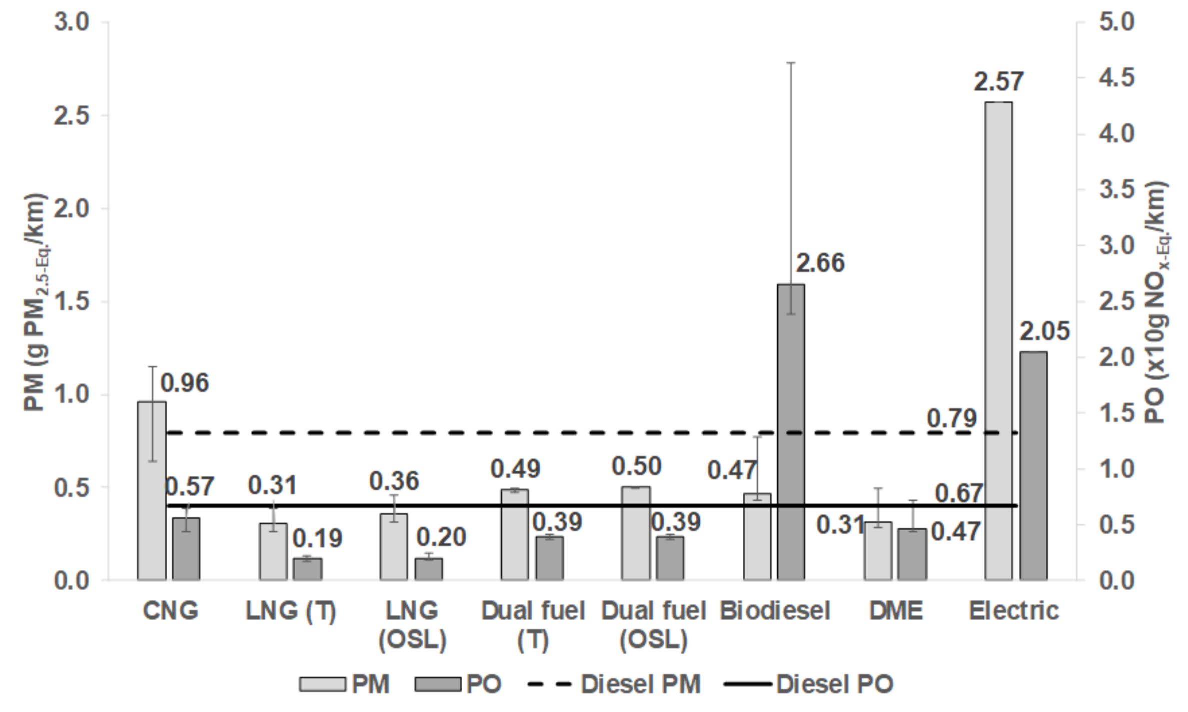

Figure 9: Impacts per km to air quality for natural gas and other diesel alternatives, in comparison to diesel. Particulate matter (PM) and photochemical ozone (PO) formation potential is considered. The average impacts of diesel are displayed in the figure. The maximum impact to PM of diesel is 0.92 g $PM_{2.5\text{-}Eq.}$/km and the minimum is 0.63 g $PM_{2.5\text{-}Eq.}$/km. The maximum impact to PO of diesel is 7 g $NO_{x\text{-}Eq.}$/km and the minimum is 5.9 g $NO_{x\text{-}Eq.}$/km.

3.6. Human toxicity

The impact to human health is measured through the human toxicity potential indicator, considering both potential to cause cancerous and non-cancerous ailments. In comparison to diesel, all the LNG (dedicated and dual fuel) trucks have similar impacts (Figure 10; 5% higher to 26% lower). CNG, on the other hand has three times higher impact than diesel but is lower than biodiesel, dimethyl ether and electric (Figure 10). The option with the highest impact for human toxicity is the electric truck. This is because of the metals and other minerals needed to make the battery (Figure B6 in SI). On a kWh basis, the results are similar, except both dedicated LNG trucks are worse than diesel (12-25%, Table B1 in SI) and the impacts of diesel are lower in relation to the other options. The stages which contribute the most towards human health impacts are the fuel station and fuel production stages for the natural gas trucks (Figure B6 in SI). This is because of coal and nuclear in the electric mix, as well as mining waste and waste produced from natural gas production. The biodiesel truck has the second highest impacts for human toxicity. This is because of the fertilizers and pesticides used for cultivating the feedstock and the chemicals used and produced when producing the biodiesel (Figure B6 in SI).

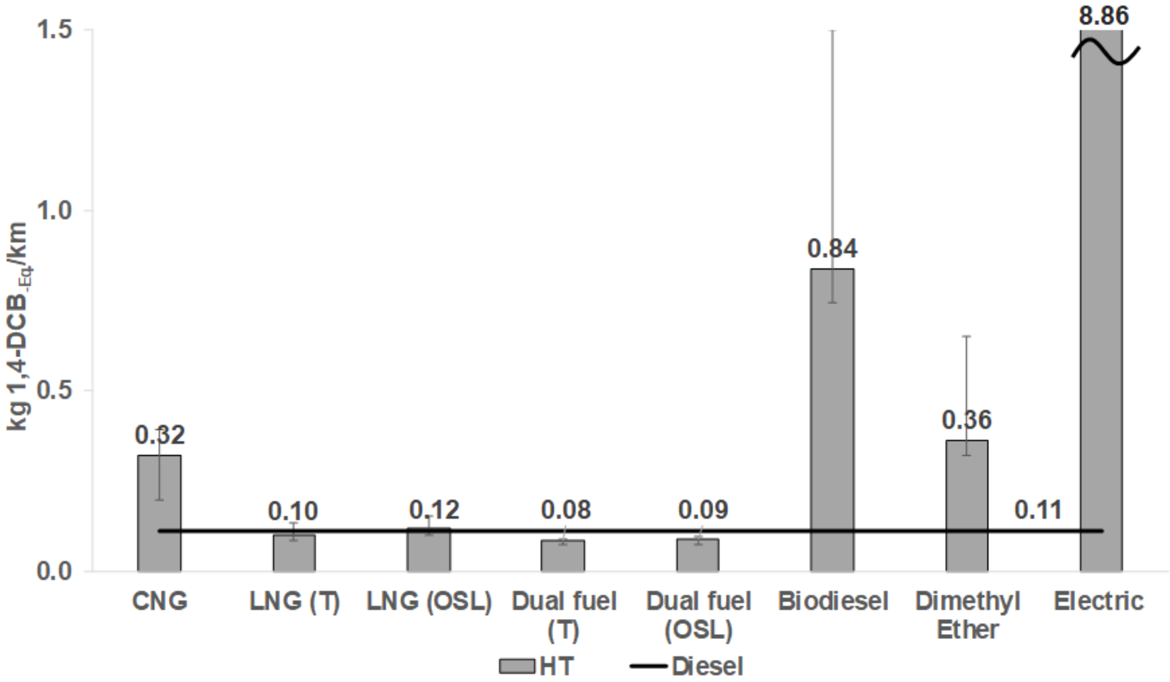

Figure 10: Impacts to human toxicity (HT) per km for natural gas and other diesel alternatives, in comparison to diesel measured in kg 1,4-dichlorobenzene (1,4-DCB) equivalent. Impacts considers both cancer and non-cancer impacts to human health. The average impact of diesel is displayed in the figure. The maximum impact of diesel is 0.13 kg 1,4-DCB$_{-Eq.}$/km and the minimum is 0.07 kg 1,4-DCB$_{-Eq.}$/km.

3.7. Resource depletion

Two indicators are used to measure impacts to resource depletion: metals depletion and fossil fuel depletion potential. Out of the natural gas trucks, all the LNG trucks have lower resource depletion potentials than diesel as shown in Figure 11 (11-66%). The impacts are similar to diesel for dual fuel while the dedicated trucks have a more noticeable benefit. LNG T has the lowest impact out of all the natural gas options for both indicators. The difference between the dedicated and dual fuel trucks is because of the diesel used in the dual fuel truck. CNG on the other hand, is 72% higher for metals depletion but is 13% lower for fossil depletion. On a kWh basis, the results are similar but CNG and the dual fuel trucks have higher impacts than diesel for fossil depletion (Table B1 in SI). The stages which contribute the most towards metals depletion is the electricity used at the fuel station and fuels and resources used in fuel production (Figure B7 in SI). These stages contribute towards metals depletion because of resources needed to drill gas wells, process and transport the gas, as well as coal, nuclear and renewables in the electric mix. The stages which contribute towards fossil depletion is fuel production stage (Figure B8 in SI). This is because this indicator considers the extraction of fossil fuels from the ground. Therefore, the upstream stages (for natural gas and diesel) contribute the most as this is where the resource is being extracted. Other stages contribute towards fossil fuel depletion if fossil fuel energy is used.

The other fuels have impacts higher than diesel for metal depletion, as shown in Figure 11 and Table B1, but lower impacts for fossil fuel depletion (except electric). This is because of the resources needed to produce the fuel and battery (Figures B7 and B8 in SI). The option with the highest impact for metal depletion is the electric truck. This is because of the rare earth metals and graphite needed to make the battery. The electric truck also has the highest impact for fossil depletion. This is because of fossil fuels used in the UK electric mix and the efficiency of fossil fuel power plants.

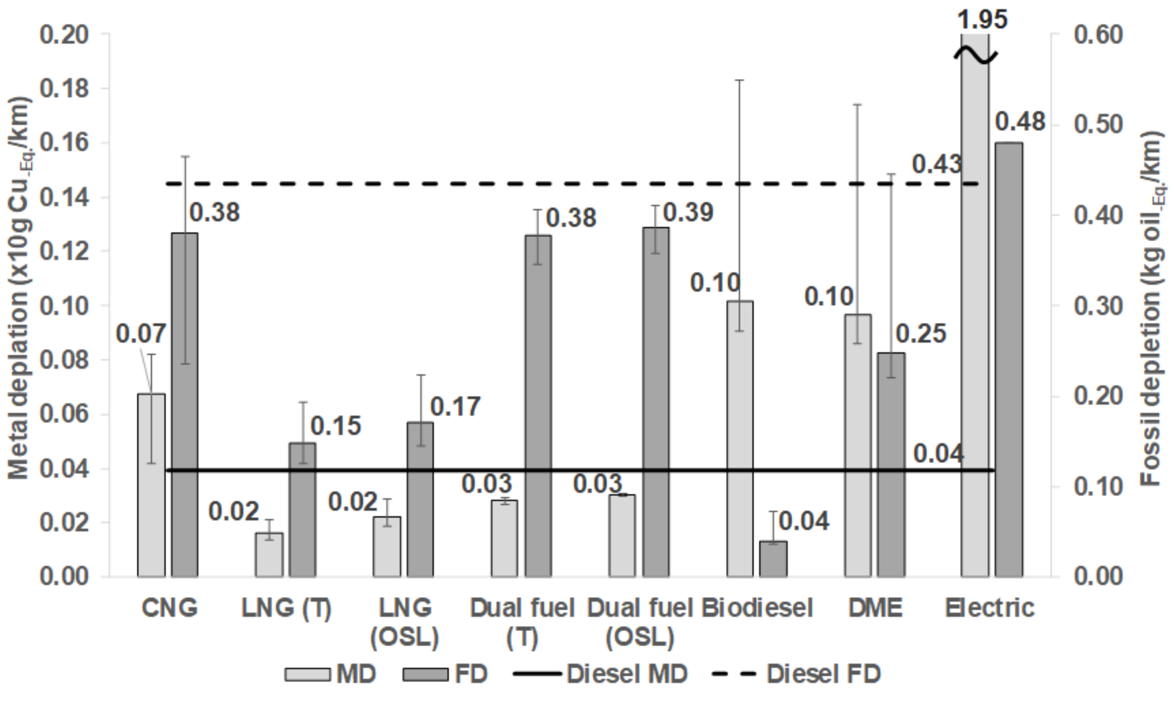

Figure 11: Impacts to resource depletion per km for natural gas and other diesel alternatives, in comparison to diesel. Metals (and other abiotic resources) depletion (MD) and fossil fuel resource depletion (FD) is considered. The average impacts of diesel are displayed in the figure. The maximum impact to MD of diesel is 0.45 g $Cu_{-Eq.}$/km and the minimum 0.26 g $Cu_{-Eq.}$/km. The maximum impact to FD of diesel is 0.50 kg $oil_{-Eq.}$/km and the minimum is 0.24 kg $oil_{-Eq.}$/km.

4. Uncertainty assessment

An uncertainty assessment is presented here in a mixture of quantitative and qualitative analysis, due primarily to the lack of data availability for some key parameters. Here key data sources used in the LCA have been identified, alongside the sources and types of uncertainty attributed to them. These data sources were identified to be key based on the hot spot analysis of each indicator (Figure 4 and Figures B3 to B8 in the SI). Based on this, fuel consumption, fuel station and emissions from the fuel supply chain were identified to be key parameters, as indicated in Table 4. The main sources of uncertainty for these data sources relate to data sample completeness and sample size, or whether current estimates are representative of the large variability (e.g. for methane emissions). The impact of varying emissions in the supply chain was assessed in Section 3.3. A quantitative assessment of uncertainty has been estimated for fuel consumption and supply chain fugitive emissions. However, the impact of fuel consumption uncertainty on GWP and ODP is relatively small.

Table 4: Key data sources and their uncertainty.

Data source	**Uncertainty**	**Quantitative uncertainty assessment**
Fuel consumption of trucks	The measurement technique used to estimate fuel consumption can vary depending on the method	Applying ±3% uncertainty, the fuel consumptions of the trucks would range from: CNG: 12.89-26.92 MJ/km

	used. Chassis dynamometer testing has an associated uncertainty of 3% (icct, 2018). The data used for the fuel consumptions of the CNG and electric truck are not based on road trials and are based on the vehicle manufacturer specification. A source of uncertainty specific to the electric truck is that there is only one data point and the truck model is currently a prototype not available (at the time of writing) for commercial purchase.	LNG: 11.79-19.29 MJ/km Dual fuel: 17.56-19.02 MJ/km Diesel: 9.7-17.34 MJ/km Biodiesel: 9.72-20.86 MJ/km DME: 5.66-12.16 MJ/km Electric: 4.33-4.61 MJ/km This would affect the GWP and ODP results. <u>GWP (kg $CO_{2Eq.}$/km)</u> CNG: 0.84-1.56 (average 1.94-2.06) LNG (T): 0.86-1.39 (average 1.01-1.07) LNG (OSL): 0.90-1.45 (average 1.06-1.12) Dual fuel (T): 1.41-1.52 (average 1.42-1.50) Dual fuel (OSL): 1.43-1.53 (average 1.43-1.51) Diesel: 0.84-1.56 (average 1.28-1.36) Biodiesel: n/a DME: 1.34-2.94 (average 1.54-1.64) Electric: n/a <u>ODP (x10g $NO_{xEq.}$/km)</u> CNG: 0.42-0.66 (average0.55-0.58) LNG (T): 1.01-1.07 (average 0.19-0.20) LNG (OSL): 0.18-0.25 (average 0.20-0.21) Dual fuel (T): 0.35-0.42 (average 0.38-0.40) Dual fuel (OSL): 0.35-0.42 (average 0.38-0.40) Diesel: 0.57-0.72 (average 0.65-0.69) Biodiesel: 2.31-4.78 (average 2.57-2.73) DME: 0.42-0.73 (average 0.45-0.48) Electric: n/a
Fugitive methane emissions • Methane slip • Supply chain emissions • Fuel station fugitives	The quantification of fugitive methane emissions has a high degree of uncertainty. This is because emissions are different for different supply chain and supply route. Also, different quantification techniques (top-down or bottom-up) will yield different results. While the impacts of varying	Uncertainty bounds for methane emissions from natural gas systems have been estimated to be -16% to +17% by EPA (EPA, 2018). Applying these to the supply chain emissions considered in this work, this would increase total supply chain emissions to 0.05-0.07% for CNG, 0.0001-

	methane emissions in the supply chain and from engine slip were analysed in a sensitivity analysis, emissions could be higher than those considered in the sensitivity analysis.	0.00012% for LNG (T) and 0.5-0.07% for LNG (OSL). However, this would have minimal impact on the GWP and ODP, as slip from the engine and emissions from the fuel station have a larger impact.
Fuel station energy consumption	The data used to estimate fuel station energy use was specific to a set throughput and truck capacity. Fuel stations vary in size and this was not considered in the data used, which introduces a source of uncertainty.	-
LNG trailer boil-off	As was mentioned in Section 2, LNG boil-off will be affected by external factors. In this work it was assumed that LNG boil-off does not initiate as the holding time is less than the time required for boil-off to initiate. However, this may not be the case due to external factors, introducing a source of uncertainty. While the impact of LNG boil-off was considered in the methane sensitivity analysis, emissions could be higher than those considered in the analysis.	-

5. Impact on UK emissions and comparison to Euro VI emission standards

Based on the results and data used in this work, emissions saving if the UK's HGV fleet were to switch from diesel to natural gas have been calculated. Based on this, fuel switching to natural gas offers reductions in life cycle greenhouse gases (17-21%, based on average fuel consumptions; 5-49% for lowest CNG and LNG fuel consumptions, respectively) and tailpipe emissions of NO_x (50-82%) and particulates (29%, LNG only) but not in CO (6-16 times higher) (Table 4). Note LNG offers bigger reductions than CNG. These emissions reductions could help the UK reduce the impacts to climate change and air quality from the road freight sector but may not be enough to meet climate targets.

The UK has a goal to cut greenhouse gas emissions to ≤20% of 1990 emissions (≤20% of 799 million tons $CO_{2\text{-Eq.}}$, ≤159.8 million tons $CO_{2\text{-Eq.}}$ (Mt $CO_{2\text{-Eq.}}$)) by 2050. To meet the fifth UK carbon budget, the Committee on Climate Change suggest that UK road transport must reduce emission by 46% by 2030 compared to 2010. If HGVs were to fairly contribute to this climate reduction, i.e. reduce its emissions by 46%, emissions would have to reduce from 19.6 Mt $CO_{2\text{-Eq.}}$/year (2015 emissions) to 10 Mt $CO_{2\text{-Eq.}}$/year by 2030.

Table 4 shows the extrapolated life cycle GHG emissions associated with different fleet conversions. Note that these emissions are on a life cycle basis and not necessarily in line with the CCC emissions estimates of total HGV emissions. However, this study also estimates the proportional reduction in emissions associated the fleet conversion to the different fuels. The only option that reduces GWP enough is the biodiesel option, offering an 83% reduction. Note that electric truck only gives a 20% reduction, but this is based on current UK electricity fuel mix, which is likely to reduce in carbon intensity over time. Importantly, LNG conversion reduces emissions by 21%, approximately half the way toward the 46% target. Thus, substantial efficiency measures in additional to an LNG changeover would be required to achieve the decarbonization target.

Table 5: Emissions of greenhouse gases, CO, NO_x and PM for UK HGV fleet if fuelled by different fuels, based on average fuel consumptions.

	GWP (Mt $CO_{2\text{-Eq.}}$)	**% Δ GWP from diesel**	**CO (kt)[a]**	**NO_x (kt)[a]**	**PM (kt)[a]**
Diesel	35.38	0%	23.80	58.09	1.31
CNG	53.60	51%	382.97	28.94	1.31
LNG T	27.87	-21%	133.20	10.72	0.92
LNG OSL	29.21	-17%	133.20	10.72	0.92
Biodiesel	5.90	-83%	8.84	21.44	0.92
Dimethyl ether	42.61	20%	8.77	21.43	-
Electric	28.14	-20%	-	-	-

[a]Tailpipe emissions.

Whilst whole fleet conversion would likely result in missing even near term climate targets, the natural gas options could assist with air quality targets whilst being a potential lower cost option than the deeper decarbonization measures. Current HGVs could be retrofitted to run on natural gas and there is already an infrastructure in place to support NGVs in the UK. Regarding air quality standards, the Euro VI emission standards apply for HGVs in the UK. As can be seen in Table 5, natural gas trucks are within the limits set for NMHC and NO_x but are over the limits set for CO, CH_4 and PM; LNG trucks are within the limit set for CO and CH4. The natural gas trucks also emit higher levels of CO and CH_4 than diesel (Table 4). Therefore, current natural gas truck technology offers emission reductions over diesel but only for NMHC and NO_x. The higher emissions of CO from natural gas trucks is in line with previous studies comparing tailpipe emissions from natural gas and diesel trucks (Miller et al., 2013, Quiros et al., 2016) and may be a result of differences in air to fuel ratios because of differences in engine design. If the uptake of natural gas trucks in the UK increases, it is important that emissions in CO, CH_4 and PM reduce, which could be achieved through improved engine design, three way catalysts (for CH_4) and particulate filters (for PM).

Table 6: Comparison on emissions from natural gas trucks to air pollutant limits set by Euro VI (icct, 2016).

		g/kWh	
	CNG	**LNG**	**Euro VI limit**
CO	4.1-8.1	1.5-1.6	1.5-4
CH_4	0.5-0.9	0.4-0.5	0.5
NMHC	0.06-0.12	0.01	0.13-0.16
NO_x	0.32-0.62	0.12	0.40-0.46
PM	0.01-0.02	0.01	0.01

The ability to reduce emissions of greenhouse gases and air pollutants is one factor which will affect the uptake of natural gas (and other diesel alternative) trucks in the future. Other factors which will affect uptake are cost (fuel and capital), fuel supply infrastructure and projected trends in demand for road freighting. While the cost of operating diesel alternative trucks is arguably the key factor which will determine their uptake in the future, the availability of alternative transport modes to trucks could also affect the level of uptake. An alternative to freight trucks is freight trains. The UK's current fleet of freight trains are powered by diesel engines but the UK Government has pledged to phase out diesel-only trains by 2040 (DfT, 2018). Alternative fuels to diesel include hydrogen fuel cells (Wiseman, 2019) and electricity (currently 5,374 km of 15,811 km of track is electrified) (ORR, 2017b), which could cut the sectors direct emissions to zero. Freight trains offers the benefit over trucks in that they have a higher load capacity and can carry more cargo per vehicle. However, they are limited to the availability of railway track. Freight trains are not suited for delivering cargo into city centres or other built-up urban areas. Freight trains are also not flexible in their delivery schedules as the UK's railway network is one of the busiest in Europe and the World (1.72 billion journeys made in 2016, fifth most used railway network in the world) (ORR, 2017a, UIC, 2015). Therefore, rail freight will not likely affect the role of freight trucks in the delivery and transport of good to and from the UK.

6. Conclusions

An environmental life cycle assessment has been conducted considering CNG, LNG (dedicated and dual fuel), diesel, biodiesel, dimethyl ether and electric battery as fuels for HGVs. The LCA considered impacts to climate change, land use change, air quality, human toxicity and resource depletion for two functional units: per km travelled and per kWh engine output. The effect of methane emissions on climate change impacts was assessed in a sensitivity analysis and found tailpipe emissions to be more impactful than supply chain and fuel station emissions. The implications of natural gas HGVs on meeting UK climate change and air quality targets was also considered.

The results of the LCA found that on a km basis, dedicated LNG trucks have benefits over diesel in all the indicators considered. Dual fuel LNG trucks have benefits over diesel in all indicators except climate change and land use change. CNG on the other hand, performs poorly in comparison to diesel for all indicators except fossil fuel depletion and photochemical ozone depletion. In comparison to the non-fossil fuel options, dedicated LNG trucks have lower impacts than biodiesel in land use change, air quality, human toxicity and metal depletion; lower than dimethyl ether in climate change, land use change, photochemical ozone formation, human toxicity and resource depletion; lower than the electric truck in all indicators bar climate change, where the impacts are similar. However, the climate change impacts of the electric truck are dependent on the electricity mix. For electricity mixes with high penetration of renewables and low contribution from fossil fuels, the climate change impacts of the electric truck would be much lower. The climate change impacts of land use change would also impact the electric and biodiesel trucks, with the latter having the highest impact out of all the options considered. On a kWh engine output basis, reductions relative to diesel in all indicators bar particulate matter are achievable for dedicated LNG trucks. CNG performs poorly for most indicators compared to diesel. Overall, of the options considered the electric and biodiesel trucks perform best in climate change, but are the worst with respect to air quality, human toxicity and metals depletion indicators. In these indicators, the option with the lowest impact is the dedicated LNG truck.

The sensitivity analysis analyzing the effect of methane emissions, considering engine slip, supply chain emissions and fuel station emissions found that for natural gas to be on par with diesel (for climate change), total methane emissions must be kept under 1.4-3.5% (up to 9 g CH4/km or up to 1 gCH4/kWh) of throughput for dedicated LNG truck. When higher fuel consumption rates are assumed, methane emissions must be zero. Measurements of engine slip are in the region of 0.2-1.65 g CH_4/km, which suggests that engine slip is not likely to have a significant impact on overall climate change impacts of natural gas trucks, except when fuel consumption is high.

When the impact to emissions from the UK road freight sector were considered, natural gas could reduce emissions by 21%, but only if dedicated LNG truck are used. However, this is not enough to meet ever more stringent climate targets. Also, the UK and several other countries have pledged to ban the sales of new build fossil fuel vehicles from 2025 onwards. Therefore, the role of natural gas in future transport systems is highly uncertain. However, recent riots in Paris because of a proposed increase in fuel duty (and other austerity issues) have highlighted other issues to decarbonizing the transport sector- fuel price and price in relation to wages (Chrisafis, 2018, Jolly, 2018). In addition to this, while natural gas trucks offer reductions in NO_x and NMHC, they exceed limits set for CO, CH_4 and particulate matter. Therefore, their role on reducing air pollution is also limited.

In conclusion, the results of this work suggest that while natural gas offers benefits over diesel in all environmental indicators considered, the magnitude of the reductions is not enough for the UK to meet medium-long term climate change targets and limits for some air pollutants are exceeded. Despite this, in the short-term it could be a viable transition fuel for moving the UK's HGV fleet towards zero tailpipe emissions technologies. However, other factors such as government emission reduction strategies, price of natural gas and improvements in natural gas truck and engine technology would influence the decision on whether or not to use natural gas as a HGV fuel.

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