Environmental and economic analysis of liquefied natural gas (LNG) for heavy goods vehicles in the UK: a Well-to-Wheel and total cost of ownership evaluation

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N.B.: This is the ACCEPTED MANUSCRIPT version of this article. The final, published version of the article can be found at: https://doi.org/10.1016/j.enpol.2019.111161

Abstract

This paper evaluates the environmental and economic performance of liquefied natural gas (LNG) as a transition fuel to replace diesel in heavy goods vehicles (HGVs). A Well-to-Wheel (WTW) assessment based on real-world HGV drive cycles is performed to determine the life-cycle greenhouse gas (GHG) emissions associated with LNG relative to diesel. The analysis is complemented with a probabilistic approach to determine the total cost of ownership (TCO) across a range of scenarios. The methodologies are validated via a case study of vehicles operating in the UK, using data provided by a large food retailer. The spark-ignited LNG vehicles under study were observed to be 18% less energy efficient than their diesel counterparts, leading to a 7% increase in WTW GHG emissions. However, a reduction of up

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to 13% is feasible if LNG vehicles reach parity efficiency with diesel. Refuelling at publicly available stations enabled a 7% TCO saving in the nominal case, while development of private infrastructure incurred net costs. The findings of this study highlight that GHG emission reductions from LNG HGVs will only be realised if there are vehicle efficiency improvements, while the financial case for operators is positive only if a publicly accessible refuelling network is available.

Key Words:

Alternative fuels

Greenhouse gas emissions

Heavy goods vehicles

Liquefied natural gas

Total cost of ownership

1 Introduction

Transport is responsible for a quarter of greenhouse gas (GHG) emissions in Europe and remains the only major sector in which they continue to rise (European Environment Agency, 2018). Heavy goods vehicles (HGVs), predominantly large trucks, account for a quarter of these emissions (European Commission, 2018) and without action, the increasing demand for road freight will lead to further growth in emissions (DfT, 2018a; IEA, 2017). In order to limit global warming to 2°C and deliver the commitments defined by the Paris Agreement, it will be necessary to decarbonise HGVs.

Currently, almost all HGVs are fuelled by diesel (Andress et al., 2011; BEIS, 2018a). Alongside improvements in the optimisation of road freight logistics, switching from petroleum-based fuels to a cleaner alternative could reduce operational emissions and lower dependence on imported oil (Osorio-Tejada et al., 2017). While electrification offers a pathway to decarbonise light-duty vehicles, payload capacity and range requirements prevent the implementation of such technologies in HGVs in the short- to mid-term (DfT, 2017). Biofuels have the potential to significantly reduce GHG emissions from road freight, but uncertainty surrounds the availability of appropriate feedstocks and their wider sustainability, particularly in terms of indirect land use change (ILUC) (Kollamthodi, 2016). While there is growing attention towards the potential for renewable methane in transport, for example, the available resource is severely restricted due to competition from other sectors, such as heating and power (Baldino et al., 2018; Speirs et al., 2018). At present, natural gas represents one of the few available options to displace diesel from HGVs, with liquefied natural gas (LNG) in particular being favoured for long-haul distribution due to its greater energy density relative to compressed natural gas (CNG) (Kumar et al., 2011).

In addition to technical constraints, commercial requirements also limit the use of alternative fuel and vehicle technologies to those that can achieve greater economic payback over the vehicle lifetime. Road freight can form a significant component of the economic output of a country, contributing approximately £12 billion to the UK economy in 2017 (ONS, 2017), for example. As such, it is essential that an alternative technology does not jeopardise economic activity from existing operations. The total cost of ownership (TCO) associated with a vehicle is widely perceived as the most important purchasing tool for HGV buyers in Europe (Bain & Company, 2018) and any commercially-viable alternative should therefore exhibit TCO savings relative to its diesel counterpart. While largely specific to the North American market, the literature highlights payback on incremental LNG vehicle costs to be achievable through fuel cost savings, owing to the lower price of natural gas relative to diesel (Deal, 2012; Jaffe et al., 2015; Johnson, 2010). Given the high distances covered annually and large amounts of fuel consumed, long-haul distribution represents the sector with greatest potential for reduced running costs. Considering these factors, the use of LNG is evaluated as a fuel to displace diesel from HGVs and potentially reduce GHG emissions associated with road freight in the short- to mid-term.

The lower carbon content of natural gas relative to diesel has been shown to enable reductions in GHG emissions in HGVs due to the lower levels of carbon dioxide (CO_2) from combustion (Argonne National Laboratory, 2012; Osorio-Tejada et al., 2017). However, despite being cited as a ‘clean fuel’ by the EU in their Clean Fuel Strategy (European Commission, 2014), some studies have found that GHG emissions from the LNG supply chain can exceed those associated with the supply of coal (PACE, 2009). In particular, the lower carbon content of natural gas can be offset by small amounts of methane (CH_4) leakage during both the supply and use of LNG, owing to its greater potency relative to CO_2 (IPCC, 2009). To comprehensively assess the environmental impact associated with a transition from diesel to an alternative fuel source such as LNG, the emissions produced over the life cycle of each fuel must be quantified.

The aim of this paper is to assess the economic and environmental performance of long-haul HGVs fuelled by LNG relative to their diesel counterparts in the United Kingdom. The UK has long been a pioneer of gas vehicle testing, funding the Low Carbon Truck Trial (LCTT) in 2012 (CENEX, 2016), and subsequently has one of the most developed LNG refuelling networks in Europe (DfT, 2017). The LNG vehicles implemented throughout the LCTT, however, were entirely dual-fuel (fuelled by both natural gas and diesel) and suffered from significant levels of non-combusted methane leakage, known as 'methane slip' (Stettler et al., 2016). By contrast, dedicated LNG vehicles with spark-ignited (SI) engines are studied here, which have been observed to emit low levels of non-combusted methane (Ricardo-AEA, 2015). This can be attributed to the use of three-way catalysts in SI vehicles, as well as developments in engine technology and the recirculation of crankcase gases in modern designs (Souto, 2015). While important to consider in the study of densely populated environments, where they are known to have most severe impacts (DEFRA, 2014), air pollutants such as particulate matter (PM) and nitrogen oxides (NOx) were outside the scope of this analysis, since the HGVs under study travelled predominantly on long-haul routes made up of motorways and trunk roads.

While GHG emissions from natural gas HGVs have been quantified for the North American market (Cai et al., 2017), there has been no transparent life-cycle analysis conducted for the UK market to date. Here, a Well-to-Wheel (WTW) assessment is performed to analyse the environmental burden associated with LNG and diesel HGVs in the UK from a life-cycle perspective. Publicly available economic comparisons of the two fuels have often been similarly specific to a certain time or region, with the TCO being reported as a single value rather than indicating the levels of sensitivity to volatile parameters such as fuel price. As such, this study also defines a Monte-Carlo based approach to determine the TCO for LNG HGVs relative to their diesel counterparts, using probability distributions to capture the uncertainty associated with key stochastic variables. This represents the first known application of such a method to calculate the TCO for HGVs in the literature and provides an insightful view to inform financial decision making under a range of economic conditions. Furthermore, the method proposed here is replicable and transferrable to other markets; thus, facilitating researchers in this field to undertake similar studies elsewhere.

In this paper, the methodology applied to determine the WTW emissions and TCO for each fuel type is described in detail in the following section. Next, the findings of the environmental and economic study for a hypothetical fleet operator in the UK are presented, alongside a discussion of the results in a wider context. Finally, the key findings of the study are summarised, referring to the future impacts associated with switching from diesel to LNG.

2 Methodology and Data

The methodology behind the environmental and economic assessments of LNG and diesel for a fleet operator in the UK are described herein. The vehicles compared were an SI LNG long haul HGV and a diesel HGV, with the fuel properties and vehicle specifications detailed in Table A.1 and A.2.

Two distinct models were employed to perform the assessments: a) for the environmental analysis, a WTW analysis of GHG emissions was undertaken using GREET (Argonne National Laboratory, 2012) and b) for the economic evaluation, a Monte-Carlo based framework was developed to make a probabilistic estimation of the TCO. In order to provide insight into LNG investments under uncertainty, probability distributions were assigned to key economic parameters to determine the range of TCO outcomes.

To characterise the costs and GHG emissions associated with each vehicle type, a Large UK Food Retailer operating both diesel and SI LNG HGVs was examined as a case study to validate the methodological framework. Vehicle energy efficiencies were measured over long-haul duty cycles and served as inputs to both the economic and environmental assessments. As such, these assessments provide a real-world estimation of the costs and GHG emissions incurred by a typical fleet operator in the UK, giving valuable insights into the trade-offs that shifting to LNG can bring to fleet operators. Naturally, changes in underlying assumptions on techno-economic and environmental parameters could result in very different findings depending on the context of the analysis.

2.1 Vehicle energy efficiency data

The vehicles under study operated from a distribution centre in West England with a fleet of 45 diesel and 2 LNG tractor units. Measurements of the fuel consumed and distance travelled by one vehicle of each fuel type were compiled from delivery records, which were recorded by the driver at the end of each journey. These were obtained from the Large Food Retailer over a two-month period, between June and July 2018, and were supported by similar measurements recorded across the whole fleet by the fleet telematics provider. The journeys selected were specifically long-haul duty cycles; individual journeys shorter than 50 km were removed from the data set, which had negligible (< 0.5%) impact on the weighted-average fuel efficiency. In total, 41 journey records were measured for the diesel vehicle and 42 for the LNG vehicle. Using the energy density of each fuel, specified in Table A.1, the efficiency of each vehicle was calculated in terms of energy consumed per kilometre travelled. The vehicle energy efficiency values were used as key inputs in the environmental and economic assessments to determine the fuel consumed over the life of each vehicle.

2.2 Well-to-Wheel GHG analysis

The WTW system boundary is shown in Figure 1, representing the key stages in the life cycle of each fuel. The WTW system is comprised of two stages: a) the Well-to-Tank (WTT) phase that includes the recovery, processing, liquefaction (LNG only), distribution, and storage of the fuel, as well as the refuelling of vehicles, and b) the Tank-to-Wheel (TTW) phase that accounts for the final use of the fuel in vehicles. Since diesel and LNG vehicles mainly differ in the type of tank used for fuel storage, they were assumed to have the same embodied energy. Furthermore, it has been shown that the fuel itself is responsible for more than 80% of total emissions associated with the transport system (Nahlik et al., 2016), so it was decided that the construction and decommissioning of vehicles and infrastructure should be neglected.

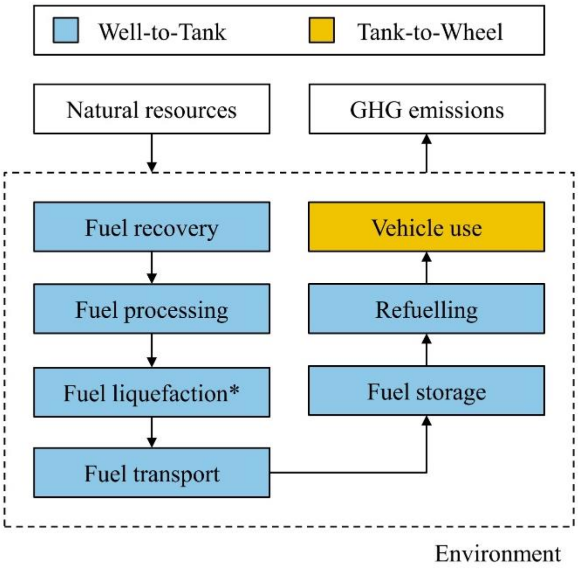

Figure 1 – System boundary for the life cycle of diesel and LNG (* indicates LNG only process).

The GHG emissions, CO_2, CH_4, and nitrous oxide (N_2O) associated with each WTW stage were calculated per vehicle-kilometre using the GREET software (Argonne National Laboratory, 2012). As GREET was specifically designed for the assessment of transport fuels and vehicle technologies, it contains an extensive set of relevant pre-defined process parameters. The software calculates the CO_2 produced by combustion on a carbon mass balance basis for each relevant technology, while non-combustion emissions were specified using values from the literature; non-combustion emissions from the literature are detailed for each life-cycle stage in the following sub-sections. Since the GREET inventory data is largely specific to North America, pathway-specific parameters and associated emissions were updated to reflect the appropriate pathways for the UK. Two distinct LNG supply pathways were considered (Qatar-to-UK and US-to-UK), and the diesel supply line was modelled to reflect the current mix of imported and domestically produced diesel in the UK.

To provide a comparative evaluation, the global warming potential (GWP) was used to characterise the impact associated with all GHG emissions relative to CO_2. The GWP values used to calculate the CO_2 equivalent (CO_2e) over a 100-year time horizon were adopted from the Fifth Assessment Report (AR5) published by the IPCC; CO_2, CH_4, and N_2O were considered to have GWP values of 1, 34, and 298, respectively (IPCC, 2009).

2.2.1 Well-to-Tank emissions

The supply lines for each fuel were evaluated according to the key stages in each WTT pathway. For diesel, this included the production of crude oil, the refining process, and the transportation of products from the initial point of production to the final storage site. Meanwhile, the LNG WTT pathways incorporated the recovery and processing of natural gas, the liquefaction process, the transportation of products from the initial point of recovery to the final storage site, and the refuelling of vehicles. The carbon intensity of electricity from the grid was modified by country, as shown in Table A.3. These values were calculated by combining the electricity mix for each country (detailed in Table A.4) with the CO_2 intensity of each generation technology in GREET (Argonne National Laboratory, 2016).

2.2.1.1 LNG Well-to-Tank pathways

With no liquefaction facilities of its own, the UK is reliant on imports for its supply of LNG. The Isle of Grain terminal in South East England is the only terminal in the UK that is currently capable of receiving LNG to unload onto road tankers for distribution to refuelling stations. As such, all imports are modelled as being shipped to the Isle of Grain.

Over the last five years, Qatar has provided over 90% of LNG to the UK and is the most representative source of imports for the current supply pathway (DUKES, 2017a). Natural gas was considered to be recovered from the North Dome field and transported 80 km by pipeline to the Ras Laffan liquefaction facility (Korre et al., 2012). Given the potency of CH_4 as a GHG, even small amounts of leakage could have a significant impact on the WTT emissions associated with LNG. CH_4 leakage levels from recovery and processing were assumed to be 0.77% and 0.13% of volumetric natural gas throughput, respectively, based on findings by Kollamthodi (2016) and Cai et al. (2017). These represent the central estimates of the values reported for methane leakage in the literature. Natural gas was liquefied with a liquefaction train efficiency of 91%. This is consistent with findings by Vink and Nagelvoort (1998) for C3/MR refrigeration cycles, which are employed in over 80% of large-scale liquefaction facilities globally (Brendeng and Hetland, 2004). The process parameters for natural gas recovery, processing and liquefaction are detailed in Table A.5 to A.7.

Liquefied gas is shipped 11,604 km to the UK by Q-max tankers (Sea-distances.org, 2018). The tankers are powered by diesel (Qatargas, 2018) and, assuming their storage capacity is fully utilised, carry a payload of 121,000 tonnes of LNG, based on the tanker specifications in Table 1 and fuel properties in Table A.1. Unlike conventional tankers, which utilise boil-off gases for propulsion, Q-max vessels are equipped with an on-board system to re-liquefy gaseous methane. An additional 6 MW demand was included to account for the diesel-powered re-liquefaction system, assuming 0.14% of storage capacity boils off per day (Anderson et al., 2009; Tagliaferri et al., 2017). The return journey was made under ballast conditions, meaning re-liquefaction requirements were only considered for the outward journey. Since indirect GHG emissions were outside the scope of this study, emissions of sulphur dioxide (SO_2) from ships were not considered. Once LNG reaches the import terminal, it is unloaded into cryogenic storage vessels before being distributed to refuelling stations.

Nominal levels of CH_4 vented during refuelling were assumed to be 0.2% of LNG throughput, based on a recent bottom-up study of methane leakage from refuelling stations by Clark et al. (2017). Boil-off gas is also produced in the fuel tank as the LNG warms, causing the pressure in the vessel to rise. At pressures greater than 16 bar, boil-off gases will be automatically vented to the atmosphere to maintain safe conditions within the tank (Souto, 2015). To minimise vented methane, completely filled fuel tanks are designed to keep pressures below 16 bar for at least five days of inactivity (following UNECE Regulation No. 110) (TNO, 2017). Since frequently used vehicles are unlikely to experience pressure release venting, automatic venting was neglected in the nominal case. The driver can also vent boil-off gases manually. Manual venting was assumed to be equivalent to 0.1% of LNG throughput based on observations by Clark et al. (2017).

The US is soon likely to emerge as a significant source of LNG imports to the UK. Being closer than the majority of Asian markets and keen to diversify its supply sources, the UK represents an attractive market, with several US cargos being delivered last year (Shiryaevskaya, 2018). The US pathway mainly differs from the Qatar pathway in terms of the distance that gas is transported by pipeline, the type of tanker used to transport LNG, and the distance that it is shipped. Natural gas was assumed to be recovered from the Barnett shale gas play and transported 500 km by pipeline to the Sabine Pass liquefaction facility. Ocean tankers ship the liquefied gas a distance of 9,069 km from the Sabine Pass facility to the UK (Sea-distances.org, 2018). The tankers were modelled on a typical Atlantic-max vessel which operates from the Sabine Pass facility (MarineTraffic, 2018; VesselFinder, 2018). Powered by heavy fuel oil (Safaei et al., 2015), these tankers were found to have a maximum capacity of approximately 70,000 tonnes of LNG, based on the tanker specifications in Table 1 and fuel properties in Table A.1. Levels of CH_4 leakage from recovery, processing, and refuelling, as well as the liquefaction train efficiency, were assumed to be the same as in the Qatar pathway.

Table 1 – Key specifications of representative ocean tankers.

Tanker type	**Parameter**	**Value**	**Source**
Q-max	Volumetric storage capacity (m^3)	260,000	(MAN, 2013)
	Brake-specific fuel consumption (g/kWh)	165	(MAN, 2014)
	Average design ship speed (m/s)	10.3	(MAN, 2013)
	Specified Maximum Continuous Rating power (kW)	45,000	(MAN, 2013)
Atlantic-max	Volumetric storage capacity (m^3)	163,000	(MAN, 2013)
	Brake-specific fuel consumption (g/kWh)	185	(Theotokatos, n.d.)
	Average design ship speed (m/s)	10.3	(MAN, 2013)
	Specified Maximum Continuous Rating power (kW)	32,500	(MAN, 2013)

2.2.1.2 Diesel Well-to-Tank pathway

The diesel WTT pathway was modelled according to the current UK supply mix, with 55% produced domestically and 45% imported (DUKES, 2017b). The process parameters for crude oil recovery and refining are detailed in Table A.8 and A.9, respectively.

Crude oil for domestic refining was assumed to originate from the North Sea and Africa which, together, account for 75% of crude oil imports in the UK (UKPIA, 2017). North Sea crude oil was considered to be transported 354 km by pipeline from the Ekofisk oil field (Offshore Technology, 2014). African crude oil was assumed to be shipped 6,241 km, a weighted-average distance for the major oil exporting countries: Nigeria, Angola, and Algeria

(CIA, 2016; Sea-distances.org, 2018). The Atlantic-max vessel detailed in Table 1 was assumed to transport crude oil.

Pathways for imported diesel were constructed for the three major sources of diesel in the UK and blended according to their relative contribution to total imports: the US (24%), Russia (21%) and the Netherlands (19%) (DUKES, 2017b). Since the process parameters for crude oil recovery and refining were largely the same between countries, differing only by electricity mix, these pathways were made distinct by varying the distances and modes used to transport crude oil and refined diesel. Transport modes and associated distances are detailed in Table 2 for each diesel exporting country. Since the Netherlands acts as a major trading hub, diesel could have been produced in the Netherlands, elsewhere in Europe, or beyond (IEA, 2014). As such, it was approximated as being transported 2,500 km by a mix of rail (80%), river (10%) and road (10%). This is representative of the distance from other key diesel exporters such as Russia, Belgium, and countries in the Middle East.

In the UK, the Renewable Transport Fuel Obligation (RTFO) requires that a proportion of the fuel provided by large suppliers (defined as those producing more than 450,000 litres annually) is composed of biofuel (DfT, 2018b). Biodiesel was assumed to make up 2.3% of diesel at the pump, in line with recent government reporting (BEIS, 2018b). The associated WTT emissions factor of 14 gCO_2e/MJ was based on biodiesel produced from used cooking oil (DfT, 2018c) since this feedstock represented approximately 80% of UK biodiesel in 2018 (DfT, 2018d).

Table 2 – Transport modes and distances for diesel exporting countries.

Exporting Country	**Product**	**Mode**	**Distance (km)**	**Source**
US	Crude oil	Barge	1,200	(Dunn et al., 2013)

		Pipeline	672	(Dunn et al., 2013)
	Diesel	Ocean tanker (Atlantic-max)	8,286	(Sea-distances.org, 2018)
Russia	Crude oil	Pipeline	850	(Irkutsk Oil Company, 2009; Lukoil, 2014)
	Diesel	Rail	520	(Irkutsk Oil Company, 2009)
		Road tanker	130	(Irkutsk Oil Company, 2009)
		Ocean tanker (Atlantic-max)	6,460	(Sea-distances.org, 2018)
Netherlands	Crude oil	Pipeline	850	(Irkutsk Oil Company, 2009; Lukoil, 2014)
	Diesel	Rail	2,000	(OEC, 2016)
		Barge	250	(OEC, 2016)
		Road tanker	250	(OEC, 2016)
		Ocean tanker (Atlantic-max)	391	(Sea-distances.org, 2018)

2.2.2 Tank-to-Wheel emissions

Combustion emissions were assumed to be 74.75 gCO_2e/MJ for diesel with no biodiesel content and 56.77 gCO_2e/MJ for LNG, based on conversion factors recently published by BEIS (2018b). Since biodiesel was assumed to be produced from used cooking oil, the associated TTW emissions were considered to be biogenic and therefore did not contribute to global warming (RSB, 2017). In turn, the TTW emissions factor for diesel vehicles was modelled as

73.03 gCO_2e/MJ, based on a biodiesel blending level of 2.3% (BEIS, 2018b). Tailpipe CH_4 emissions were found to contribute 0.21 gCO_2e/MJ during a typical long-haul drive cycle (15% urban, 25% rural, and 60% motorway driving) for the LNG HGV, while taken to be negligible for the diesel HGV. These values were based on recent real-world tests on HGVs comparable to those operated by the Large Food Retailer under study, carrying average payloads of 31 tonnes (TNO, 2017).

2.2.3 Well-to-Wheel GHG sensitivity analysis

To understand the impact of uncertainty surrounding stages in the life cycle of each fuel, key parameters were varied about their nominal values in a sensitivity analysis. The upper and lower bounds for these parameters are detailed in Table A.10. CH_4 leakage during NG recovery and refuelling, shipping distance, and vehicle efficiency were modified according to estimates from the literature. Levels of biodiesel content were varied to quantify the impact of reaching blending restrictions, known as the ‘blend wall’, which limits the proportion of biodiesel in diesel purchased at the pump to 7% (IPU, 2007). While not accounted for in the nominal case, owing to significant uncertainty surrounding its value, the impact of CH_4 leakage throughout the natural gas pipeline was also explored.

2.3 Total Cost of Ownership

A net present value (NPV) analysis was carried out to determine the TCO incurred by the fleet operator over the lifetime of a HGV fuelled by diesel and LNG. A four-year vehicle lifetime and a discount rate of 8% were chosen to represent typical values for diesel and LNG HGVs in the UK, based on information obtained by surveying HGV industry experts and validated using figures reported by Joss (2017). The discount rate is the same for both assets as decision-makers suggest using the same financial criteria to compare technologies on a “like for like” basis. Otherwise, evaluations run the risk of being unfairly prejudiced towards a certain technology.

Monte-Carlo simulations enabled the uncertainty associated with volatile parameters such as fuel price to be captured in the estimation of the TCO. Assumptions underlying the average values for key parameters (summarised in Table 3) are described in the sub-sections below and the associated probability distributions are detailed in Table A.11. These distributions were assumed to cover the range of feasible values for uncertain parameters throughout the vehicle lifetime and were derived through consultations with industry stakeholders and by understanding the changing dynamics of these parameters. All costing values are given in terms of pricing conditions of the 2018 market.

The TCO was calculated according to the following formula,

$$TCO = \frac{I}{n} + \sum_{t=0}^{3} \frac{l + \left(f + \frac{k * a}{c}\right) * d * e + m + x}{(1+r)^t}$$

where I = private infrastructure investment (£), n = number of vehicles served by private infrastructure, l = annual vehicle lease costs (£), f = fuel price (£/MJ), k = ratio of AdBlue consumption to diesel consumption by volume (L_{AdBlue}/L_{Diesel}), a = AdBlue price (diesel only, £/L), c = energy density of diesel (MJ/L), d = annual distance travelled (km), e = vehicle energy efficiency (MJ/km), m = annual vehicle maintenance costs (£), x = annual vehicle tax (£), r = discount rate (%), and t = time (year of vehicle ownership).

The availability of refuelling infrastructure and stem mileage associated with refuelling at public stations are not captured in this cost, since fleet operators are assumed to only invest in LNG technology when a refuelling station is within a practical distance from their depot, on a main distribution route, or on-site. Furthermore, vehicles are leased rather than being purchased outright by the fleet operator; meaning residual value and resale were also neglected.

2.3.1 Vehicle costs

Costs associated with leasing and operating each vehicle type were obtained through interviews with the Large Food Retailer under study and from the literature. These are detailed in Table 3. In addition to covering the use of the vehicle, lease costs also included the additional training required by drivers using the LNG vehicles. The value for vehicle tax was based on the cost to tax an articulated tractive unit and its trailer in the UK, which depends on the vehicle size and weight (Vehicle Certification Agency, 2018).

Annual fuel costs were calculated using the energy consumption values (described in Section 2.1.1) that were measured for each vehicle over long-haul duty cycles. The annual average distance travelled by each vehicle was assumed to be 180,000 km, based on figures provided by the Large Food Retailer. Diesel fuel prices were sourced from recent government publications (BEIS, 2018c). Since the gas vehicle market is not fully established, typical LNG fuel prices were set according to an indicative range (Cluzel, 2016). An additional £0.03/kg was included for LNG that was acquired from a public refuelling station, based on discussions with a Refuelling Infrastructure Provider. This represents a retail component of the overall fuel price that is required by the third-party provider to payback the initial capital investment and maintenance costs associated with the refuelling station.

Additional costs for AdBlue, a urea solution required in SCR aftertreatment technologies to reduce nitrogen oxides in tailpipe emissions, were included for diesel vehicles. The ratio of AdBlue consumption to diesel consumption by volume, k, was assumed to be 0.04 L_{AdBlue}/L_{Diesel}, based on figures provided by the Large Food Retailer. The LNG vehicle did not incur costs associated with AdBlue, since dedicated LNG vehicles do not require SCR aftertreatment to meet Euro VI air quality standards.

2.3.2 Infrastructure costs

The diesel vehicles were assumed to be refuelled off-site due to the abundance of refuelling stations, while two refuelling scenarios were considered for LNG vehicles: a) on-site (private), and b) off-site (public) refuelling stations. In addition to influencing the level of driver acceptance towards alternative fuels, the type of refuelling station also impacts the TCO. Public refuelling stations, constructed by third-party providers, do not incur any additional infrastructure costs to the fleet operator. Currently, 11 of the 23 LNG refuelling stations in the UK have public access (Gas Vehicle Hub, 2018). There is, however, a trade off associated with private refuelling stations: the fleet operator can dispense fuel at a lower LNG price compared to a public station but must bear the capital costs for infrastructure investment.

Since refuelling station costs were found to vary widely throughout the literature, a single source (Mariani, 2016) was chosen as they provided a breakdown of the refuelling infrastructure costs by component. Mariani (2016) presented the costs for modular storage tanks that constrain the refuelling stations to specific configurations. The capital costs were calculated to be £500,000 for a station that serves 20 vehicles and £750,000 for a station serving up to 40 vehicles (Mariani, 2016). The authors also conducted interviews with refuelling infrastructure providers who confirmed these costs to be representative of similarly sized stations.

Table 3 – Average costs associated with operating each vehicle type.

Parameter	**Vehicle**	**Value**	**Source**
Annual lease (£)	Diesel	14,500	Large Food Retailer
	LNG	26,500	Large Food Retailer
Annual maintenance (£)	Diesel	4,500	Large Food Retailer
	LNG	5,500	Large Food Retailer

Annual tax (£)	Diesel/LNG	650	(Vehicle Certification Agency, 2018)
Fuel price (£/L)	Diesel	1.03	(BEIS, 2018c)
AdBlue price (£/L)	Diesel	0.16	Large Food Retailer
Fuel price (£/kg)	LNG on-site	0.68	(Cluzel, 2016)
	LNG off-site	0.71	Refuelling Infrastructure Provider

2.3.3 Fuel duty and investment risk

The literature review highlighted that payback on greater upfront vehicle costs is driven largely by fuel cost savings, which are enabled by the lower fuel price of LNG relative to diesel. While the commodity price of natural gas is lower than for diesel, the lower level of duty on LNG in the UK contributes most to the fuel price gap (GOV.UK, 2018). Fuel duty is a critical source of revenue for most governments, contributing £28 billion to the UK budget in 2016, and a transition away from diesel would result in a loss of revenue (OBR, 2018). Wider uptake of LNG vehicles could lead to an increase in the level of duty on LNG, causing the fuel price gap to narrow and potentially remove the economic benefits associated with fuel switching. In the 2018 Autumn Budget, the UK government announced that the fuel duty differential between alternative and main road fuels would be fixed until 2032 (EUA, 2018). This, however, could change in the future, with a review scheduled for 2024. In the event of a widespread transition from diesel to LNG, the government could take action to raise the duty on LNG to minimise losses in fuel duty revenue. Given that this has potential to remove any economics benefits associated with fuel switching, such heavy dependence on the duty gap poses a significant risk to an investor.

A scenario was investigated whereby fuels are taxed on a carbon basis to simulate a potential change to LNG fuel duty. The carbon content of diesel and LNG was assumed to be

73.71 gCO2/MJ and 56.66 gCO2/MJ, respectively, based on recent values published for carbon reporting by BEIS (2018b). Assuming diesel duty would remain fixed at £0.58/L (£0.016/MJ), the duty on LNG would rise from £0.25/kg (£0.005/MJ) to £0.60/kg (£0.012/MJ).

Variance-based sensitivity analyses were also conducted following the method of Sobol (Homma and Saltelli, 1996; Sobol', 1993), enabling the overall variance in the TCO to be decomposed and attributed to single input parameters. Indicators of variance, known as Sobol indices, were used quantify the relative influence of uncertain parameters. The key parameters considered were fuel prices, vehicle energy consumption, vehicle lease costs and, in the case of private refuelling, the number of vehicles served by the station.

2.4 Cost-benefit analysis

GHG emissions were monetised to evaluate climate change costs and assess the environmental burden associated with fuel switching. Emissions were priced to match CO_2 abatement costs, reflecting the value which society currently places on mitigating climate change. Low, central, and high carbon prices were adopted (£30/tCO_2e, £60/tCO_2e, and £110/tCO_2e) to capture varying levels of 'willingness-to-pay'. These values are in close agreement with the prices suggested by Kuik et al. (2009), who compiled the results of 26 models from the literature to provide an estimate of the abatement cost required to limit global warming to 2ºC above pre-industrial levels.

Monetised GHG emissions were combined with the TCO to calculate the total costs incurred to society for each fuel type. The total cost to society (TCS) associated with a particular fuel type was calculated according to the following formula,

$$TCS = TCO + p * \sum_{t=0}^{3} \frac{WTW * d * e}{(1+r)^t}$$

where *p* = carbon price (£/tCO$_2$e) and *WTW* = well-to-wheel GHG emissions measured on an energy basis (tCO$_2$e/MJ). As previously defined, *TCO* = total cost of ownership incurred by the fleet operator (£), *d* = annual distance travelled (km), *e* = vehicle energy efficiency (MJ/km), *r* = discount rate (%), and *t* = time (year of vehicle ownership). The ratio of the total TCS of an LNG HGV to the total TCS of its diesel counterpart indicates whether there are overall costs or benefits incurred by society. Values below 1 indicate that net benefits are generated for society from fuel switching while values greater than 1 represent net costs.

It is important to note that external effects aside from climate change were not included in the TCS. While natural gas engines have been shown to offer air quality benefits relative to their Euro VI diesel counterparts (Joss, 2017; LowCVP, 2017), criteria air pollutants such as particulate matter (PM) and nitrogen oxides (NOx) are known to have most severe impact in densely populated areas (DEFRA, 2014). Since the HGVs under study travelled predominantly on long-haul routes between distribution centres, made up of motorways and trunk roads rather than densely populated urban areas, the external costs associated with air pollution were neglected in the TCS calculation. Furthermore, the financing of public infrastructure was beyond the scope of this study, meaning investment costs per vehicle were not included in the TCS calculation for publicly available refuelling stations.

3 Results and discussion

3.1 Vehicle energy consumption

The mean energy consumption, μ, and the associated standard deviation, σ, observed for diesel and LNG HGVs are given in Table 4. The mean energy efficiency of the LNG vehicle measured in this study was 82% of the value exhibited by the diesel vehicle, in agreement with values assumed in the literature (Cai et al., 2017; ICCT, 2017). This is later found to significantly constrain the potential benefits delivered by switching to LNG from an environmental and economic perspective.

Table 4 – Measured energy consumption for diesel and LNG trucks.

Fuel type	**Energy consumption, μ ± σ (MJ/km)**
Diesel	10.7 ± 1.33
LNG	13.0 ± 0.96

The efficiency penalty incurred by the LNG vehicle relative to its diesel counterpart is due to the inherently lower efficiency of SI engines compared to the compression-ignition engines in diesel vehicles. Although opportunities exist to improve the efficiency of SI LNG vehicles, they are likely to continue to have a lower energy efficiency than their diesel counterpart in coming years (ICCT, 2017). In particular, the mandatory EU targets to reduce 15% of GHG emissions from large trucks by 2025 (relative to 2019 levels) is likely to drive innovation in diesel engine technology (European Commission, 2018). Without clear commitment from the market, further development of LNG vehicles from manufacturers could be limited.

At present, there are no policies in the UK that incentivise improvements in the energy efficiency of LNG vehicles. It may be argued instead that the development of LNG vehicle efficiency is inhibited by existing measures to fix the fuel duty differential (discussed in Section 3.3.1). As a large proportion of fuel savings arise from this differential, fixing the fuel duty gap would enable lower efficiency LNG vehicles to remain competitive with diesel.

In the results that follow, the relative vehicle energy efficiency has been varied between 60% and 100%, with the latter bound representing efficiency parity. This range enables the impacts associated with improvements in either technology to be explored and allows the threshold relative vehicle efficiency required to see benefits from fuel switching to be determined.

3.2 Well-to-Wheel GHG analysis

The WTT GHG emissions associated with the diesel and LNG pathways are detailed in Table 5 on an energy basis. While diesel emissions are expected to rise in coming years, owing to the poor state of the UK refining industry and declines in domestic production (Vandervell, 2015), the findings below suggest that supply chain emissions for diesel will remain lower than those associated with LNG in the near future. Even in the upper limit of complete dependence on imports, diesel WTT emissions were lower than those from either LNG supply scenario.

Table 5 – Well-to-Tank GHG emission factors associated with diesel and LNG.

Fuel Source	**WTT GHG emissions (gCO_2e/MJ-fuel supplied)**
Diesel (100% domestic)	15.84
Diesel (100% imports)	18.60
Diesel (current supply mix)	17.08
LNG (Qatar)	22.76
LNG (US)	23.82

The GHG emissions associated with each LNG WTT pathway are presented in Figure 2, showing the proportion of CO_2 and CH_4 produced in key life-cycle stages. Natural gas recovery, processing, and liquefaction were found to account for more than 80% of WTT emissions associated with LNG supply in both scenarios. Notably, the emissions associated with natural gas recovery were dominated by CH_4 leakage in both supply pathways. For both supply pathways, the total level of CH_4 leakage amounted to 1.2% of natural gas volumetric throughout. In contrast, the GHG emissions produced during the liquefaction stage were mainly CO_2, reflecting the high-energy intensity of the process.

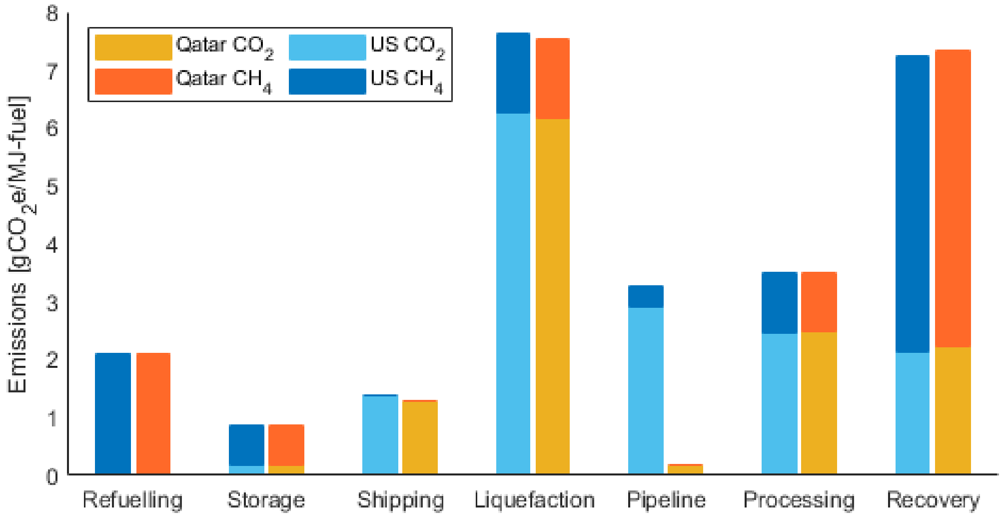

Figure 2 – GHG emissions associated with key stages in the LNG Well-to-Tank phase.

The GHG emissions associated with individual WTT stages were comparable between the two LNG supply pathways, with the only major difference arising in the transport of natural gas from the point of recovery to the liquefaction plant by pipeline. The greater distance required to transport the natural gas by pipeline, coupled with the high energy intensity associated with pipeline transport (Argonne National Laboratory, 2012), led to greater GHG emissions in the US pathway.

In contrast to pipeline transport, the relatively low energy intensity of transport by ocean tanker resulted in a minor contribution to emissions from shipping. The vessel type was found to influence these associated emissions. Despite travelling an additional 2,535 km from Qatar, emissions associated with shipping were lower than those for the US pathway, owing to the advantages afforded by modern Q-max tankers. Equipped with efficient slow-speed diesel engines and a greater payload capacity, Q-max tankers were found to reduce GHG emissions per tonne-kilometre by approximately 30% relative to the conventional Atlantic-max vessel.

Overall, WTT emissions are a minor component of the life cycle emissions associated with each fuel. TTW emissions, namely CO_2 produced during combustion, make up the vast majority of emissions on a WTW basis. The TTW emissions factor associated with LNG (56.98 gCO_2e/MJ) is significantly lower than that of diesel at the pump (73.03 gCO_2e/MJ), reflecting the lower carbon content of natural gas. From a life-cycle perspective, it was found that LNG could reduce WTW GHG emissions by up to 13% per unit of energy consumed; the WTW GHG emissions factors were calculated to be 90.11 gCO_2e/MJ for diesel and 79.74 gCO_2e/MJ for LNG.

Combining the WTT and TTW emissions factors with vehicle energy efficiency gives the GHG emissions produced per vehicle-kilometre. These are shown in Figure 3 for both fuel types over a range of relative vehicle efficiencies. The efficiency penalty suffered by the SI LNG HGV can be seen to reduce or, in some cases, nullify the potential for environmental benefits from fuel switching. At a relative efficiency of 82%, equivalent to the mean value measured in this study, LNG was observed to increase WTW GHG emissions by almost 7%. More broadly, even with efficiency parity, LNG vehicles fail to meet the mandatory targets outlined by the European Commission to reduce CO_2 from HGVs by 15% in 2025 (relative to 2019 levels) (European Commission, 2018).

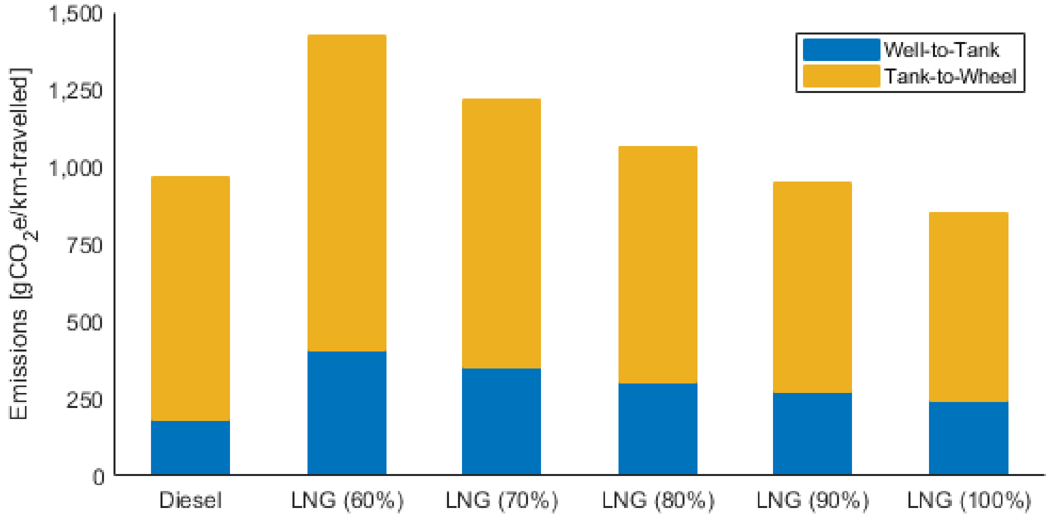

Figure 3 – GHG emissions per vehicle-kilometre travelled for relative vehicle efficiencies ranging from 60% to 100%.

The results of the WTW GHG sensitivity analysis are shown in Figure 4. The relative vehicle efficiency was found to have the most significant influence on GHG emissions, determining whether switching to LNG increases or decreases life-cycle emissions compared to diesel. A significant variation in emissions was also observed between the range of estimates for CH_4 leakage during recovery and pipeline transport. An additional 1% of natural gas volumetric throughput vented to the atmosphere was found to increase overall WTW emissions associated with LNG by 10% relative to the nominal case. Though less influential than CH_4 leakage during pipeline transport, venting from the refuelling station and vehicle tank was found to have a significant impact on the WTW emissions associated with LNG. These latter sources of CH_4 leakage highlight the importance of boil-off gas management during refuelling and vehicle use. Interestingly, variation in the distance that LNG is shipped by ocean tanker was found to be small for either of the two tanker types considered. Similarly, the level of biodiesel blending had only a minor impact on overall emissions.

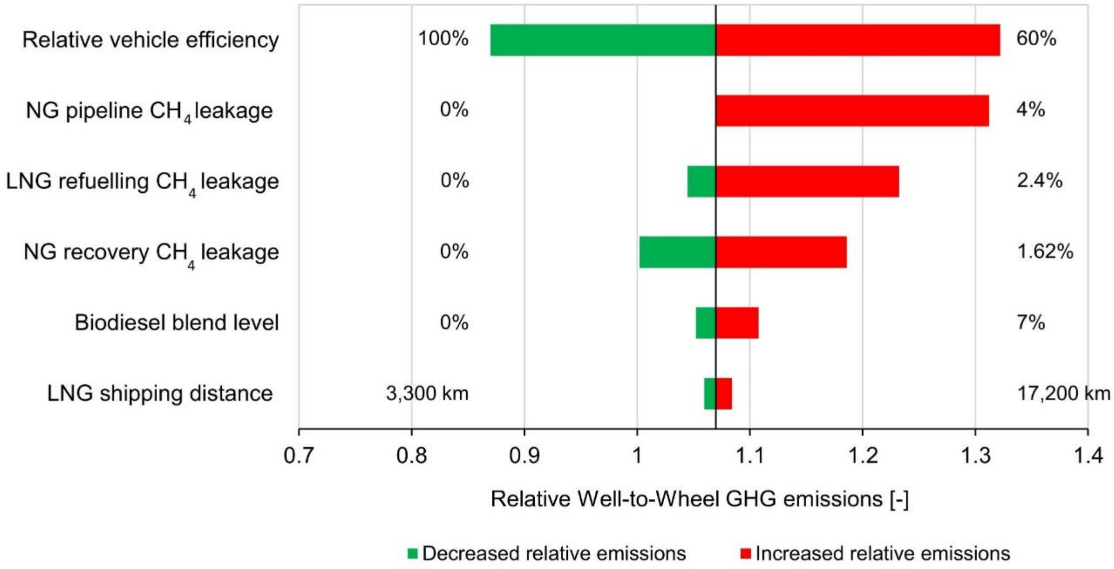

Figure 4 – Sensitivity analysis for WTW GHG emissions of the LNG HGV relative to diesel, where the values alongside each bar denote the corresponding lower and upper limits of the parameter.

3.3 Economic analysis

The lower fuel price of LNG was found to deliver significant operational cost savings relative to diesel, which enabled economic payback on the higher lease and maintenance costs associated with LNG over the lifetime of the vehicle. Consequently, the journeys that benefit most from fuel switching are those with high diesel consumption and a high relative vehicle efficiency. This can be explained by the fact that these journeys enable the greatest amount of diesel to be replaced by LNG, which, in turn, generates maximal fuel cost savings. AdBlue costs and vehicle tax had a negligible impact on the TCO for either fuel type.

Figure 5 shows the outcomes of Monte-Carlo simulations for the relative TCO (i.e. the TCO of the LNG HGV relative to the diesel TCO) in each refuelling scenario, where a relative TCO equal to 1 represents the breakeven point. As the primary determinant of fuel costs, ranges of relative vehicle efficiencies were analysed. The probability of achieving a relative TCO below 1 or, equivalently, generating an overall saving over the vehicle lifetime by fuel switching, can be seen to increase as the vehicle efficiency penalty suffered by the LNG HGV is reduced. Note that this has greater impact when moving between fixed intervals at lower relative vehicle efficiencies. This can be observed from Figure 5 as the gradient of relative TCO curves increases at higher relative vehicle efficiencies.

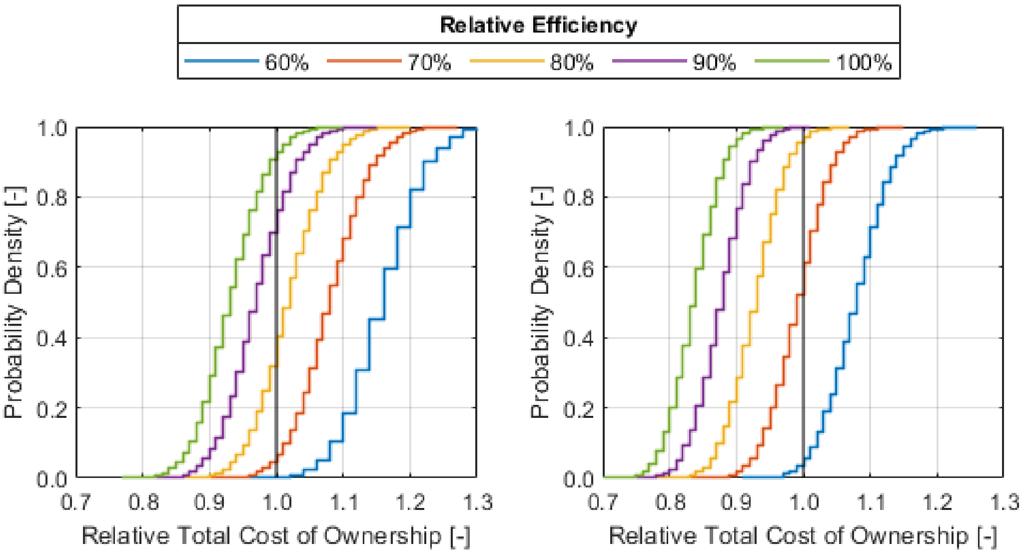

Figure 5 – Monte-Carlo distributions of the relative TCO of LNG at various relative vehicle efficiencies to diesel for private (left) and public (right) refuelling stations.

Despite paying a marginally lower fuel price at a private refuelling station, the choice to invest in private infrastructure is less economic than utilising public stations. This can be attributed to the fact that the differential between on-site and off-site fuel prices is insufficient to justify the development of private infrastructure. The use of public refuelling stations also avoids the introduction of constraints surrounding fleet size, since there are no capital costs that would benefit from being shared across a large number of vehicles. Smaller fleets, for instance, would otherwise be severely exposed to high infrastructure investment costs per vehicle.

The vehicle lifetime was shown to have a similar impact on the relative TCO for private refuelling through a sensitivity analysis, shown in Figure A.1. The most severe impacts were observed as the vehicle lifetime was reduced from the nominal four years, since fuel cost savings were increasingly insufficient to repay the capital costs associated with private infrastructure. The impact of varying the discount rate was also evaluated, as illustrated in Figure A.2, but had negligible impact on the relative TCO for private refuelling. As was the case for fleet size, the vehicle lifetime and discount rate had no impact on the relative TCO for public refuelling, since there are no capital costs incurred for the construction of infrastructure.

While the use of public refuelling stations has been demonstrated to achieve the greatest economic benefits over the vehicle lifetime, these stations are not accessible within a practical range of most depots. Although initiatives are in place to develop a pan-European network of refuelling stations, such as the EU Blue Corridors project (NGVA, 2018), the fleet operator may be required to develop refuelling stations in order to implement LNG vehicle technologies in the near future. Larger fleets benefit most from investment in private infrastructure for several reasons. Firstly, refuelling stations benefit from economies of scale. LNG storage vessels, which represent the most significant cost component of a refuelling station (Mariani, 2016), dramatically reduce in cost per unit of stored fuel as their capacity increases. Secondly, a refuelling station that serves a larger fleet is likely to experience greater throughput. Interviews with refuelling infrastructure providers found that this enables distribution costs and, consequently, the overall procurement cost of the fuel to be reduced.

As the technology matures with wider uptake and benefits from economies of scale, costs associated with LNG vehicles are expected to reduce (ICCT, 2017). By contrast, the upfront costs associated with diesel HGVs are likely to increase in the future, owing to the increasing complexity of the aftertreatment technologies required to meet stringent air quality standards.

Combined, these effects would narrow the gap between upfront vehicle costs, reducing the fuel price differential required to generate economic payback by transitioning to LNG.

3.3.1 Fuel duty and investment risk

The variance-based Sobol analysis determined that the energy efficiency of the diesel HGV, the diesel fuel price and the energy efficiency of the LNG HGV had greatest influence on the relative TCO. This can be attributed to the fact that these parameters directly influence fuel costs, which represents the largest component of the TCO for either fuel type. The LNG fuel price also has an impact on the relative TCO, but to a lesser extent. Since fuel expenditure associated with LNG is much lower than for diesel, varying the LNG fuel price between £0.60/kg and £0.80/kg had a relatively minor impact on the relative TCO. Vehicle lease costs and, in the case of private infrastructure, the number of LNG vehicles served by the refuelling station were found to have a minor impact on the relative TCO.

Based on the measured vehicle efficiencies, shown in Table 4, diesel and LNG vehicles were found to currently incur fuel duty costs of £0.171/km and £0.065/km, respectively. Raising the level of duty on LNG according to the carbon content of the fuel was found to result in the duty on LNG rising to £0.60/kg (£0.012/MJ), which is equivalent to £0.156/km at present day vehicle efficiencies. While this increase in duty would still result in reduced government revenue from fuel switching, it would be sufficient to eliminate any economic benefits associated with LNG relative to diesel.

For the LNG vehicle market to become sufficiently developed, several authors have cited the importance of linking LNG and diesel fuel prices, while maintaining a fixed fuel duty ratio (Hao et al., 2016; Joss, 2017). As previously discussed, existing policy in the UK ensures that the fuel duty differential between diesel and LNG will remain fixed until 2032. However, it may be argued that this measure unfairly subsidises the cost of an LNG HGV relative to diesel, in light of the finding that present-day LNG vehicle technology performs worse than its diesel counterpart from an environmental and energy efficiency standpoint.

3.4 Cost-benefit analysis

The findings from the assessments of vehicle capital costs, running costs, refuelling infrastructure costs, and climate change costs can be combined to give the overall costs and benefits delivered by LNG HGVs relative to diesel. Figure 6 shows the TCS associated with LNG HGVs relative to the diesel equivalent over a range of relative vehicle efficiencies for three carbon price scenarios: the main bars represent the central carbon price scenario (£60/tCO_2e) and the error bars signify the lower and upper price scenarios (£30/tCO_2e and £110/tCO_2e, respectively). As mentioned in Section 2.3.4, values below 1 indicate that net benefits are generated for society from fuel switching while values greater than 1 represent net costs.

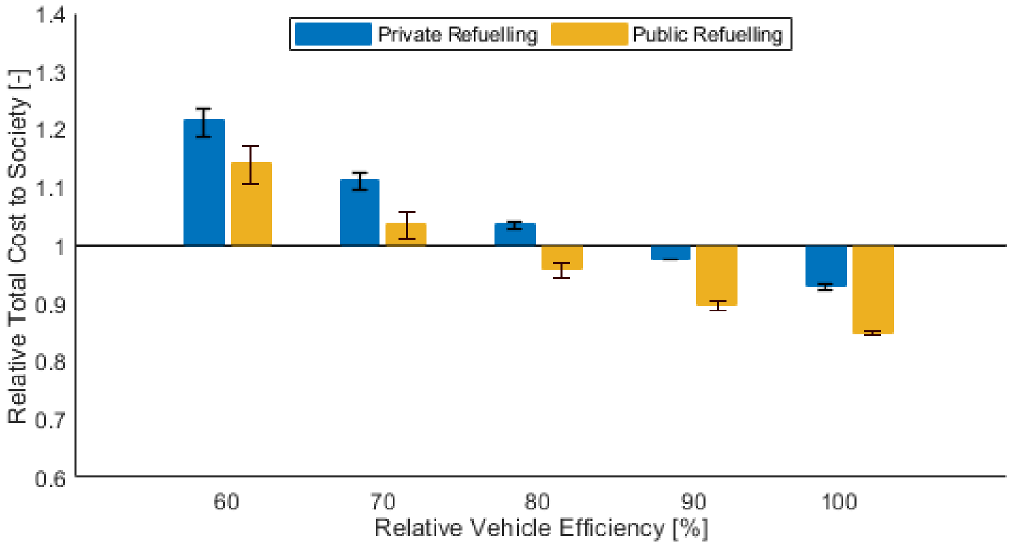

Figure 6 – The relative total cost to society (total cost of ownership and climate change costs) associated with LNG relative to diesel with private and public refuelling infrastructure under three carbon price scenarios.

As discussed in Section 3.3, the TCO associated with an LNG HGV refuelled at a public station is lower than if it had been refuelled privately, owing to the capital costs incurred by the fleet operator for private refuelling infrastructure. In turn, for a given relative vehicle efficiency, the TCS associated with an LNG HGV is always lower in the public refuelling scenario than in the private refuelling scenario.

Since the relative vehicle efficiency dictates the amount of fuel consumed in each vehicle type, it was found to be the most influential parameter in determining the costs incurred and emissions produced over the vehicle lifetime. With present-day LNG HGVs being 18% less energy efficient on average than their diesel counterparts, it was found that current LNG vehicles fail to deliver net benefits to society relative to diesel in the case of private refuelling, but produce benefits when refuelled at public stations. This reiterates the importance associated with developing a network of LNG refuelling stations across the UK if LNG is to play a significant role in road freight.

4 Conclusions and Policy Implications

A WTW environmental assessment was performed to quantify the life-cycle GHG emissions associated with LNG and diesel in heavy goods vehicles, incorporating both current and potential fuel supply pathways for the UK. To determine the whole cost borne by the fleet operator while also capturing potential uncertainty in stochastic variables, such as fuel price and vehicle efficiency, a probabilistic method to determine the TCO associated with each fuel type was defined. These methodologies were validated through a case study of a Large Food Retailer in the UK and provide fleet operators, consumers, and policy makers with valuable insights into the trade-offs associated with transitioning from diesel to LNG in road freight.

On average, LNG HGVs were observed to be 18% less energy efficient than their diesel counterparts. LNG was found to incur greater WTT emissions than diesel in both of the supply pathways modelled, mainly due to the CO_2 emissions produced from the energy-intensive liquefaction process. Despite natural gas having a significantly lower carbon content than diesel, the overall WTW GHG emissions associated with LNG were almost 7% greater than those from diesel at present day vehicle efficiencies. The greatest opportunity to maximise potential environmental benefits associated with switching to LNG was found to arise from improving the relative vehicle efficiency and, if efficiency parity were to be achieved, LNG vehicles could deliver a WTW GHG emissions reduction of up to 13% relative to diesel. However, while representing a significant contribution, this alone would be insufficient to meet European targets to reduce CO_2 emissions from HGVs by 15% by 2025.

In addition to being heavily influenced by the relative vehicle efficiency, the GHG emissions associated with LNG were observed to depend heavily on the level of CH_4 leakage throughout the life cycle of the fuel. Relative to the nominal case, an additional 1% of natural gas volumetric throughput vented to the atmosphere was determined to increase WTW emissions associated with LNG by 10%. Natural gas recovery and processing, as well as refuelling station venting, were found to be the primary sources of CH_4 leakage in the nominal case.

Economic payback on higher upfront vehicle costs was found to be driven by the lower fuel price of LNG relative to diesel. While the duty differential between diesel and LNG is set to remain fixed until 2032, any changes to the fuel price gap introduce a significant source of risk for an investor. With LNG taxed relative to diesel on a carbon basis, any opportunities to achieve financial savings from fuel switching are nullified. Monte-Carlo simulations also showed that financial benefits are possible in the majority of cases but only when vehicles were refuelled at public stations; investments in private refuelling infrastructure were typically found to negate the economic benefits associated with switching to LNG.

From a policy perspective, the provision of sufficient publicly accessible refuelling stations is critical to facilitate the wider uptake of LNG as an alternative fuel in road freight. Regulation surrounding these stations is important to ensure proper management of boil-off gases and minimise fugitive emissions. Above all, improvements in relative vehicle efficiency are necessary from academia and industry if the potential environmental and economic benefits associated with LNG are to be fully realised. In the absence of relative improvements to LNG vehicle efficiency by 2024, policy makers should reconsider the existing decision to fix the fuel duty gap and raise the level of duty on LNG to better reflect the external costs associated with the technology.

Given its influence on overall GHG emissions, future research is needed to better quantify the levels of methane vented to the atmosphere throughout the LNG life cycle, particularly during natural gas recovery and pipeline transport. Similarly, the impacts of air pollutants such as particulate matter (PM) and nitrogen oxides (NOx) from LNG vehicles need further investigation, particularly in densely populated areas to reassure social welfare impacts. An evaluation of the potential air quality benefits or drawbacks associated with LNG would contribute to a more holistic view of the trade-offs associated with fuel switching.

Acknowledgements

This research was supported by funds provided via the Imperial – Sainsbury's Supermarkets Ltd. partnership. This work was also supported by the Innovative UK grant "Kinetic energy recovery for urban logistics applications (KERS-URBAN)" [project reference 103253].

Nomenclature

I = Private infrastructure investment (£)

n = Number of vehicles served by private infrastructure

l = Annual vehicle lease costs (£)

k = Ratio of AdBlue consumption to diesel consumption by volume (L_{AdBlue}/L_{Diesel})

f = Fuel price (£/MJ)

a = AdBlue price (£/L)

c = Diesel energy density (MJ/L)

d = Annual distance travelled (km)

e = Vehicle energy consumption (MJ/km)

m = Annual vehicle maintenance costs (£)

x = Annual vehicle tax (£)

r = Discount rate (%)

t = Time (year of vehicle ownership)

μ = Mean of measured vehicle energy consumption (MJ/km)

σ = Standard deviation of measured vehicle energy consumption (MJ/km)

p = Carbon price (£/tCO2e)

Appendix

Figure A.1 – Impact of varying the vehicle lifetime on the relative total cost of ownership

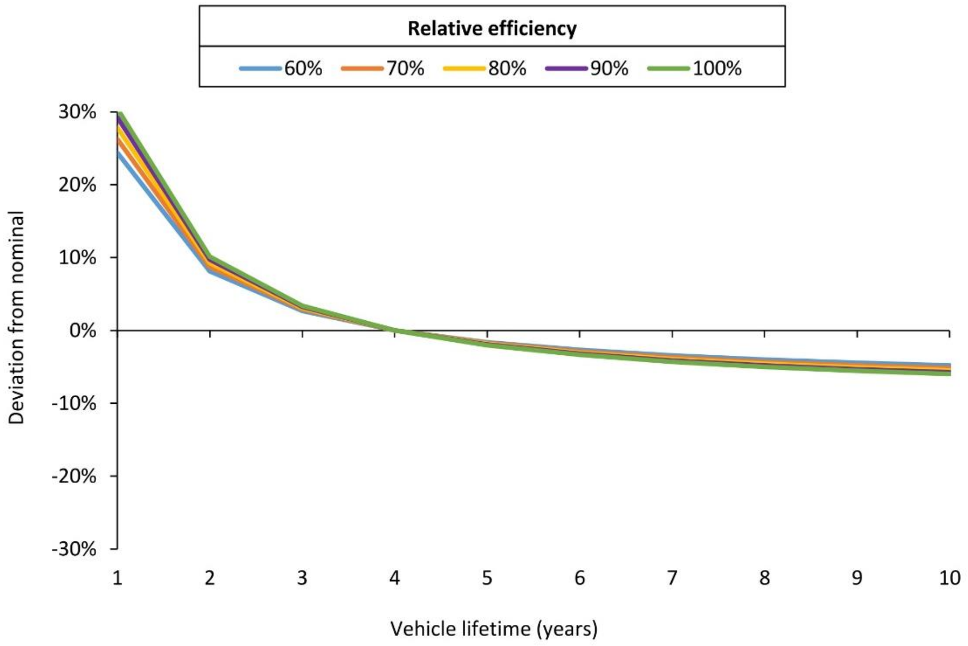

Figure A.2 – Impact of varying the discount rate on the relative total cost of ownership

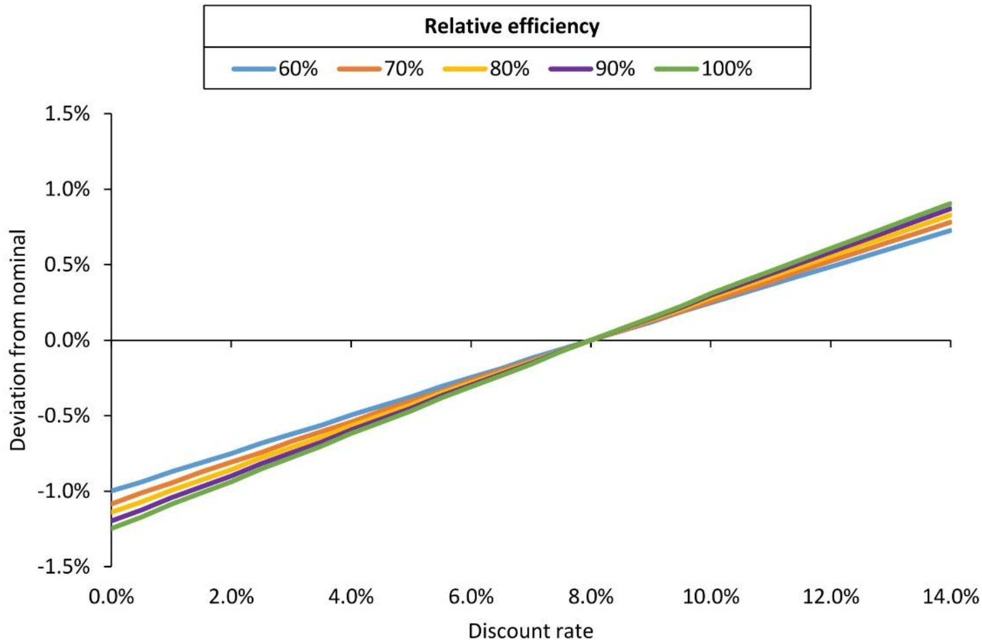

Table A.1 – Physical properties of diesel and LNG

Fuel type	Parameter	Value	Source
Diesel	Net CV (MJ/kg)	42.79	(BEIS, 2018b)
	Density (kg/m^3)	838.8	(BEIS, 2018b)
LNG	Net CV (MJ/kg)	48.38	(BEIS, 2018b)
	Density (kg/m^3) of Qatar LNG at -163°C and 1 atm	460	(International Gas Union, 2012)
	Density (kg/m^3) of US LNG at -163°C and 1 atm	423	(International Gas Union, 2012)

Table A.2 – Key specifications for the heavy goods vehicles under study

	Diesel HGV	LNG HGV
Axle configuration	6 x 2	4 x 2
Max. engine power (hp)	460	400
Fuel capacity (L)	450	1080
Euro class	VI	VI
Odometer at test start (km)	310,518	68,722

Table A.3 – Electricity generation mix by country

	Coal	Oil	Gas	Nuclear	Hydro	Wind	Solar	Bio	Other	Source
UK	7%	1%	43%	21%	2%	8%	4%	9%	7%	(BEIS, 2018d, 2017)
US	34%	1%	32%	20%	6%	5%	1%	1%	1%	(EIA, 2016)

Qatar	0%	0%	100%	0%	0%	0%	0%	0%	0%	(Wogan et al., 2017)
Russia	16%	3%	49%	19%	15%	0%	0%	0%	1%	(Benavides et al., 2015)

Table A.4 – Carbon intensity of grid electricity by country

	Electricity carbon intensity (gCO_2e/kWh)
UK	319
US	465
Qatar	500
Russia	408

Table A.5 – Process parameters for natural gas recovery (Clark et al., 2011; Lampert et al., 2014)

Group	Parameter	Value
Functional unit	Natural gas (mmBtu)	1
Input	Natural gas (mmBtu)	1
	Natural gas – boiler (Btu)	22,000
	Natural gas – flaring (Btu)	9,940
	Diesel (Btu)	2,820
	Residual oil (Btu)	256
	Gasoline (Btu)	256

	Electricty (Btu)	256
	Water (gal)	1.61

Table A.6 – Process parameters for natural gas processing (Clark et al., 2011; Lampert et al., 2014)

Group	Parameter	Value
Functional unit	Natural gas (mmBtu)	1
Input	Natural gas (mmBtu)	1
	Natural gas – boiler (Btu)	27,400
	Electricty (Btu)	816
	Diesel (Btu)	272
	Water (gal)	1.70

Table A.7 – Process parameters for natural gas liquefaction (Mintz et al., 2010)

Group	Parameter	Value
Functional unit	Liquefied natural gas (mmBtu)	1
Input	Natural gas (mmBtu)	1
	Natural gas – turbine (Btu)	96,900
	Electricty (Btu)	1,980

Table A.8 – Process parameters for crude oil recovery (Lampert et al., 2014)

Group	Parameter	Value
Functional unit	Crude oil (mmBtu)	1
Input	Crude oil (mmBtu)	1
	Natural gas – turbine (Btu)	7,330
	Natural gas – boiler (Btu)	7,330
	Electricity (Btu)	3,870
	Diesel (Btu)	3,100
	Gasoline (Btu)	408
	Water (gal)	19.5

Table A.9 – Process parameters for crude oil refining (Cai et al., 2013; Lampert et al., 2014; Paulo-Rivera et al., 2010)

Group	Parameter	Value
Functional unit	Diesel (mmBtu)	1
Input	Crude oil (mmBtu)	1
	Refinery still gas (Btu)	58,100
	Natural gas (Btu)	51,700
	Unfinished oil (Btu)	31,000
	Gaseous hydrogen (Btu)	12,900
	Refinery catalyst coke (Btu)	9,230
	Electricity (Btu)	3,200
	Water (gal)	2.56

Table A.10 – Upper and lower limits associated with key parameters in the WTW GHG sensitivity analysis

Parameter	Lower	Source	Upper	Source
NG recovery CH_4 leakage (% vol. throughput)	0	-	1.62	(Alvarez et al., 2018)
NG pipeline CH_4 leakage (% vol. throughput)	0	-	4	(Balcombe et al., 2015)
Shipping distance (km)	3,300	(Sea-distances.org, 2018)	17,200	(Sea-distances.org, 2018)
LNG refuelling CH_4 leakage (% vol. throughput)	0	-	2.4	(Clark et al., 2017)
Biodiesel content in diesel at the pump (%)	0	-	7	(IPU, 2007)
Relative vehicle efficiency (%)	60	-	100	-

Table A.11 – Probability distributions associated with key economic parameters. For a uniform distribution, *a* and *b* represent the lower and upper bounds; for a normal distribution, *a* and *b* represent the mean and standard deviation; for a triangular distribution, *a*, *b* and *c* represent the minimum, peak, and maximum.

Parameter	Vehicle	Distribution	Distribution parameters		
			a	*b*	*c*
Annual lease (£)	Diesel	Uniform	14,000	15,000	-
	LNG	Uniform	25,000	28,000	-
Annual maintenance (£)	Diesel	Uniform	4,000	5,000	-
	LNG	Uniform	4,500	5,500	-
Fuel price (£/L)	Diesel	Normal	1.03	0.04	-
Fuel price (£/kg)	LNG on-site	Triangular	0.60	0.70	0.80
	LNG off-site	Triangular	0.63	0.73	0.83
AdBlue price (£/L)	Diesel	Uniform	0.15	0.17	-

Table A.12 – Overview of interaction with key stakeholders

Research activity	Participants	Details	Timing
Interviews	Large Food Retailer currently engaged in gas vehicle testing	In-depth discussions following semi-structured interviews	May – August 2018
Interviews	Two leading gas vehicle refueling infrastructure providers	In-depth discussions following semi-structured interviews	June – August 2018

Surveys	11 drivers operating diesel and LNG HGVs at the depot of the Large Food Retailer	Multiple choice questionnaire to determine driver acceptance	July 2018

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