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Emission factors for methane engines on vehicles and ships

with a focus on methane emissions

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SMED (Swedish Environmental Emissions Data), is a collaboration between IVL Swedish Environmental Research Institute, Statistics Sweden (SCB), Swedish University of Agricultural Sciences (SLU) and the Swedish Meteorological and Hydrological Institute (SMHI). The collaboration commenced in 2001 with the long-term aim of gathering and developing the competence in Sweden within emission statistics. SMED is, on behalf of the Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management, heavily involved in the work related to Sweden's international reporting obligations on emissions within six subject areas (air, water, waste, hazardous substances, noise and measures). A central objective of the SMED collaboration is to develop and operate national emission databases. SMED data also supports national, regional and local governmental authorities for decision making. For more information visit the SMED website www.smed.se (in Swedish).

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Sammanfattning

SMED utgör en förkortning för Svenska MiljöEmissionsData, som är ett samarbete mellan IVL, SCB, SLU och SMHI.

Den här rapporten beskriver emissioner från metanmotorer på vägfordon och fartyg. Syftet är att ta fram relevanta emissionsfaktorer för olika motortyper och fordonstyper, alternativt fartyg. Fokuset är att presentera emissionsfaktorer för metanutsläpp och uppskattningarna omfattar både emissioner från motorer och från bränslesystemen ombord. Metan passerar genom motorerna i olika grad beroende på förbränningsteknik vilket utgör den främsta källan till metanutsläpp från metandrivna land- och sjötransporter.

Som en bakgrund till emissionsberäkningarna beskriver vi de olika typerna av metanbränsle, de olika motortyperna, och hur kombinationer av dessa används på fordonstyper respektive fartyg. De transportslag som ingår är ”Heavy duty vehicles” där emissionsfaktorer presenteras för kategorierna ”Heavy Goods Vehicles” (HGV, tunga lastbilar) och ”Bus” (bussar), “Light duty vehicles” med emissionsfaktorer för kategorierna ”Passenger car” och "Light Commercial Vehicle” (passagerarbilar och lätta kommersiella fordon), och “Ships” (fartyg).

Endast få emissionsmätningar finns tillgängliga vilket gör att många av de emissionsfaktorer som vi presenterar bedöms ha stor osäkerhet.

Emissionsfaktorer för 2019 summeras i tabellen nedan. En viktig anledning till skillnaderna i emissionsfaktorer mellan olika landbaserade fordonsslag och fartyg är att utsläppsregleringarna skiljer sig mycket åt.

Sammanfattande tabell. Emissionsfaktorer 2019 för de i studien inkluderade bränslena och fordonsslagen.

		CH_4	CO_2	N_2O	SO_2	NO_X	CO	NH_3	NMVOC	$PM_{2,5}$	BC
		g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ
CNG	Pass, car	0,0046	56*	0,00016	0,00056	0,039	0,24	0,011	0,0041	0,00033	0,000049
CNG	LCV	0,0051	56*	0,00012	0,00056	0,015	0,69	0,0092	0,0055	0,0018	0,000272
CNG	HGV	0,018	56*	0,0050	0,00056	0,065	0,055	N/A	0,0016	0,00046	0,000070
CNG	Bus	0,016	56*	N/A	0,00056	0,25	0,050	N/A	0,0014	0,0038	0,00057
LNG	HGV	0,022	56*	0,0014	0,00012	0,030	0,20	N/A	0,00096	0,00041	0,000061
LNG	Ships	0,68	55	N/A	0,00012	0,30	0,23	N/A	0,042	0,0026	0,00077

*56,54 g/MJ används vilket motsvarar emissionsfaktorer för naturgasförbränning i den svenska nationella rapporteringen till UNFCCC

Summary

SMED is short for Swedish Environmental Emissions Data, which is a collaboration between IVL Swedish Environmental Research Institute, SCB Statistics Sweden, SLU Swedish University of Agricultural Sciences, and SMHI Swedish Meteorological and Hydrological Institute.

This report covers emissions from methane engines on road vehicles and ships, and aims at presenting relevant emission factors for different engines and vehicle types and ships. A focus is placed on methane emissions, and both engine emissions and non-engine emissions are included. Methane fuel passes through the engine to varying degrees in different engine types causing a main part of the methane emissions from methane fueled road vehicles and ships.

As introduction to the emission calculations we describe the use of different types of methane fuel, the use of different engine types, and typical properties of vehicles/vessels with different types of methane engines. The report presents emission factors for heavy duty vehicles in the categories “Heavy Goods Vehicle” (HGV) and “Bus”, emission factors for light duty vehicles are presented for the categories “Passenger car” and “Light Commercial Vehicle” (LCV), while emission factors for ships do not contain any subcategories.

There is generally a shortage of measurement data that cause high uncertainties for many emissions factors.

Emission factors for 2019 are summarized in the Summary Table below. Different regulations apply which a.o. cause the large difference seen for some emissions between land-based vehicles and ships.

Summary Table. Emission factors 2019 by fuel and vehicle types included in the study.

		CH_4	CO_2	N_2O	SO_2	NO_X	CO	NH_3	NMVOC	$PM_{2.5}$	BC
		g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ
CNG	Pass. car	0.0046	56	0.00016	0.00056	0.039	0.24	0.011	0.0041	0.00033	0.000049
CNG	LCV	0.0051	56	0.00012	0.00056	0.015	0.69	0.0092	0.0055	0.0018	0.000272
CNG	HGV	0.018	56	0.0050	0.00056	0.065	0.055	N/A	0.0016	0.00046	0.000070
CNG	Bus	0.016	56	N/A	0.00056	0.25	0.050	N/A	0.0014	0.0038	0.00057
LNG	HGV	0.022	56	0.0014	0.00012	0.030	0.20	N/A	0.00096	0.00041	0.000061
LNG	Ships	0.68	55	N/A	0.00012	0.30	0.23	N/A	0.042	0.0026	0.00077

*56.54 g/MJ is used which corresponds to the emission factor for natural gas combustion in the Swedish national reporting to the UNFCCC.

Keywords: natural gas, LNG, CNG, methane, emission factors, trucks, buses, ships

Introduction

Emissions from methane engines differ in many aspects from those from combustion of fuel oils in gasoline and diesel engines. An important issue is to quantify the methane emissions from the vehicles and vessels that use methane as a fuel. These are very specific to gas driven vehicles and ships. The methane emissions consist of both slip of uncombusted methane through the engine and emissions from the fuel supply systems including e.g. crankcase emissions and vents. The methane emissions are important to characterize due to their global warming potential. This report focusses on describing emissions of methane and other greenhouse gas (GHG) emissions. The slip from the engine depends to a great extent on the combustion characteristics of the engine and is little described in existing literature for certain engine types. The uncertainties on the emitted quantities from fuel tanks and fuel supply systems on vehicles and ships are also large.

Further, methane fuels are often and correctly described as clean fuels in the sense that emissions of particles and sulphur dioxide are low. Depending on engine type, a transition from diesel and fuel oils to methane could also reduce the NO_X emissions from the land based and marine fleet.

For this study, emission factors are compiled from a literature study on methane driven vehicles and ships. The source of methane is either natural gas or biogas, and the fuel gas contains also minor amounts of energy containing hydrocarbons in gas form. The emissions covered include CO_2, CH_4, CO, N_2O, SO_2, NOx, NH_3, NMVOC, $PM_{2.5}$, BC and when available also: TSP, PM_{10}, Pb, Cd, Hg, As, Cr, Cu, Ni, Se, Zn, PCB, Dioxin, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Indenopyrene, PAH 1-4, and HCB.

The methane fuel used in the transport sector is of both fossil and renewable origin; Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG) are common forms of fossil methane fuels while non-fossil alternatives originate from biogas and substitute methane (SNG). Different methane fuels dominate in different segments of the transport market.

The report is divided in six chapters of which this introduction is the first. The second chapter provides a brief description to the different methane fuels used in the transport sector, their current use and general technical requirements on the supply system and engine. The third chapter treats methane emissions from gas engines in a generic context. Of the following three sections, the chapter 4 covers emission from land-based methane driven heavy vehicles, the chapter 5 treats other land-based methane driven vehicles, and chapter 6 is on methane driven ships. All three are further divided into the following subsections:

- Use of different types of methane fuel
- Use of different engine types and typical properties of vehicles/vessels with different types of methane engines.

- Emissions from the storing and supply of methane from a tank to wheel/propeller perspective. Emissions are specified for the relevant combinations of fuel type and engine type as far as possible.
- Overview of emission factors
- Presentation of emission factor weighting procedure and recommendation of single emission factors for further use in emission inventories and scenarios.

Aim

The primary aim of this work is to present emission factors of methane and other greenhouse gases from vehicles and ships that use liquefied or compressed methane as fuel. The emission factors are described and presented so that they can be used by the Swedish Environmental Protection Agency in the calculation of national emissions of GHGs. Emission factors are presented as mass unit per unit of energy content of the fuel (e.g. g/MJ). Emission factors for other gaseous compounds and particles mentioned in the introduction will be provided if they are judged to be reasonably reliable. There is a low availability of published material and measurements which is a cause for gaps in this reporting.

The expected development of emission factors from present state till 2030 are described for the species included in SMED scenarios: CH_4, N_2O, SO_2, NOx, NH_3, NMVOC, $PM_{2.5}$ and BC. Emission factors representative for combinations of gas fuels and engines for the fleets used historically are presented for 2015, 2016, 2017, and 2018.

Method

The data collection is done through literature reviews and complemented with communication with engine manufacturers. Uncertainties are estimated and motivated in the presentation of emission factors.

Calculations used for weighting are described and motivated in the respective sections on emissions for different transport modes.

Methane as a fuel

Methane is seldom used in pure form as a fuel. Most often the methane is one among many constituents of a gas mix including a variety of light hydrocarbon compounds. From an engine perspective it is important to know the methane content of the fuel in relation to the other gases in order to avoid uncontrollable combustion in the engine, so called knocking. Natural gas and biogas are both to a majority consisting of methane gas and these are both referred to as methane fuels in this report, although also other hydrocarbons and other gases are part of these fuels. Methane fuel can also be industrially produced. This is often referred to as synthetic or substitute natural gas (SNG). The origins to the carbon in the SNG can however be of either fossil or renewable origin. The composition of the gases used as fuels are also important from an emission perspective.

A European Standard, EN 16723-2:2017, specifies requirements on contents of natural gas, biomethane and their blends for use as automotive fuels. The standard applies to both compressed and liquefied gas.

Natural gas

Composition

The distributed natural gas often contains >90 mole-% methane. The remainder, often between 4 and 10%, are primarily other hydrocarbon gases, of which ethane and propane are most abundant (see e.g. Uniongas, 2020; Kimpton & Brown, 2010). Minor amounts of non-hydrocarbon species such as CO_2, nitrogen, water and dihydrogen sulphide (H_2S) can also occur in the gas. Heating values depend on the composition of the gas. The lower heating value expressed per mass unit varies accordingly and a typical range is between 48.5 MJ/kg to 52.5 MJ/kg and a relatively high content of ethane, propane, and butane gives a higher heating value (American Petroleum Institute, 2015).

Table 1 presents typical compositions, heating values, at atmospheric conditions of lean natural gas after removing unwanted contaminants and non-gas liquids in the raw extracted gas.

Countries apply different standards to the composition of marketed natural gas and accordingly the compositions of natural gas vary between countries. Some countries also add nitrogen to the distributed gas. The differences between nations are reported by Kimpton and Brown (2010), and the span for individual components vary considerably, see Table 1. Different gas mixes are sometimes referred to as low, or rich, gas (low in methane content with higher shares of heavier hydrocarbons) and high, or lean, gas (high in methane content and lower shares of the heavier hydrocarbons).

Table 1. Typical composition of natural gas (Uniongas, 2020; Kimpton & Brown, 2010; IEA-AMF, 2020b; Tractebel Engineering S.A., 2015).

		Union gas, 2020	IEA-AMF, 2020b	Tractebel, 2015 (lean)	Tractebel, 2015 (rich)	API, 2015	Kimpton & Brown, 2010
Component							
Methane	% mole	94.7 (87-98)	82-93	92.32	81.62	87.66-99.8	71-99.6
Ethane	% mole	4.2 (1.5-9)	5.5-13	3.25	8.17	0.1-11.41	0.06-12.2
Propane	% mole	0.2 (0.1-1.5)	2-5.5 (C_3+)	1.80	4.49	0.91-2.98	0.01-6.4
Iso-butane	% mole	0.02 (trace – 0.3)		0.43	1.44	0-0.70	0.01-1.3
Normal-Butane	% mole	0.02 (trace – 0.3)		0.62	1.54	0-1.3	0.01-2.2
Iso Pentane	% mole	0.01 (trace – 0.04)		0	0.28	0-0.01	
Normal pentane	% mole	0.01 (trace – 0.04)			0.45	0-0.01	0.01-3.3
Hexane +	% mole	0.01 (trace – 0.06)			0.20		0.01-0.13
Nitrogen	% mole	0.5 (0.2-5.5)	0.5-13	0.69	0.94		0.24-27.6
Carbon dioxide	% mole	0.3 (0.05-1.0)		0.89	0.86		0.03-13.3
Oxygen	% mole	0.01 (trace – 0.1)					
Hydrogen	% mole	0.02 (trace – 0.05)					
Specific gravity		0.58 (0.57-0.62)					
Gross Heating Value dry	MJ/m^3	38.8 (36-40.2)					27.5-48.7
Sulphur	mg/m^3		3-10				
Molecular weight	g/mole			17.78	20.62		

The sulphur content of natural gas is naturally low. It is however common to add odorants to the gas in order to make leakages detectable by the human nose. Many of these compounds contain sulphur, e.g. mercaptan.

Liquefied natural gas (LNG)

At minus 162°C the natural gas becomes liquid at atmospheric pressure. The liquefaction reduces the volume by a factor of more than 600 and the gas can be stored in so called cryogenic tanks, that are insulated and pressurized to keep the LNG in a liquid state. The density of LNG varies between 0.41 and 0.51 kg/dm^3, depending on the storing conditions temperature and pressure, and the composition of the gas (American Petroleum Institute, 2015).

The non-hydrocarbon content and hydrocarbon compounds that could freeze during the liquefaction is removed prior to liquefaction. A small amount of nitrogen may remain. The processed gas has a typical methane content of 95 mole-% and approximately 5 mole-% ethane, propane and butane. No more than 0.5% heavier hydrocarbons remain in the processed gas (American Petroleum Institute, 2015).

Compressed natural gas (CNG)

CNG is natural gas compressed to approximately 200-248 bars to around 1% of its volume at atmospheric pressure in room temperature. The compressed gas is kept in pressurized containers without cooling (Tractebel, 2015).

CNG production includes gas pre-treatment and compression. During the pre-treatment process heavy hydrocarbons are removed to avoid condensation when storing as CNG. Further the gas is dehydrated, and contaminants, such as hydrogen sulphide and carbon dioxide, are removed. The amount of compression required depends on the delivery pressure of the source gas reservoir and gas quality (Tractebel, 2015).

Biogas

Biogas is formed at anaerobic break down of biologic material, e.g. agricultural waste, manure, municipal waste, sewage, and food waste. Raw biogas primarily contains methane and carbon dioxide, and minor amounts of nitrogen, hydrogen, water and sulphur containing compounds. Depending on source, methane content can be anything from below 40% to 80%, and CO_2 content between 20% and 50% (IEA-AMF, 2020b). The raw gas is treated to increase level of methane and remove impurities like CO_2, water and hydrogen sulphides and any particulate matter. The upgrade results in biogas with a high methane content, often >95% (IEA-AMF, 2020b). In its purified state it can be used interchangeably and in mixes with CNG and LNG, in compressed or liquefied form, respectively.

SNG

A natural gas substitute can be produced from hydrocarbon sources of fossil (e.g. coal) or renewable (e.g. biomass) origin via processes including gasification and methanation. The extent of this fuel on the market is not known and not considered further in this report.

Methane emissions

Methane emissions occur both as a slip through the engine, and as leakages from the tank and fuel supply system. We treat the two types of sources separately throughout this report.

Methane slip through the engine

Combustion characteristics determine the slip through the engine and thereby also the specific emission. Differences can be large between old and new engines, and the working principle of the engine is crucial. As explained in the following also the operational profile of the engine is very important. An engine operating at high engine loads results in a more complete combustion with small slips, while at low engine loads the lower temperatures in the engine causes higher amounts of methane to remain uncombusted. Methane in the exhaust gases are mainly from the following three sources:

- **Overlap of open valves.** For certain engines it can be beneficial to have a short period of overlap in the opening of the exhaust valve and the intake valve. This ensures that all the gas in the combustion chamber is exchanged as the next one starts and is a rather common characteristic of diesel engines. In engines where air and methane are mixed prior to the intake, this overlap causes a slip of methane through the exhaust valve. This is primarily a concern for older diesel engines that have been rebuilt to LNG dual fuel engines (Pavlenko et al., 2020; IEA-AMF, 2020b).
- **Gas in enclosed spaces.** Minor parts of the combustion chamber are not reached by the combustion. In a low-pressure engine, there is a mix of methane and air present in the cylinder through parts or the full compression stroke, and in some engines also during the intake stroke. Small volumes of the gas mix enter crevices and other available spaces that are sheltered from the combustion in one way or another. During the expansion stroke the gas escapes the hidden spaces and becomes part of the exhausts. Locations of importance for these mechanisms are mainly at the piston head gaskets and the rings between the piston head and the cylinder lining. This slip is minimized through design changes and it is a potentially bigger problem in rebuilt diesel engines than in new gas- and dual fuel-engines. Another way to avoid this slip is to use direct injection ignition as is done in the high-pressure gas engines (Pavlenko et al., 2020; IEA-AMF, 2020b).
- **Incomplete and inefficient combustion.** The flame propagates from the ignition source through the cylinder in the presence of a combustible gas in sufficient concentrations. In certain conditions the mixture is too lean for a

complete combustion close to the walls of the combustion chamber. A too lean mixture can also result from a too strong mixing of the gases in the cylinder. A related phenomenon that occurs close to the cylinder linings is a drop of temperature close to the cylinder linings. Heat is conducted away from the chamber by the walls. This results in so called "quench zones" which are spaces close to the cylinder walls that where the temperature is too low for an efficient combustion (Pavlenko et al., 2020; IEA-AMF, 2020b).

Methane leakage from tank and fuel supply system

Methane emissions through the tank and fuel supply system are difficult to measure and quantify. Known emissions occur through the crank case during combustion, leakages and intentional emissions from the fuel supply system.

Crank case slip exists in four-stroke engines and the leakage occurs between the piston rings and the cylinder walls during the compression stroke. Approximately 1% of the intake gas has been measured to leak to the crank case, and it is thereby reasonable to assume that methane leaks accordingly. There are technical solutions that involve an enclosed crank case and where the crank case gases are redirected to the engine intake air. This is however technically challenging for turbo charged engines since oily residues in these gases may harm the turbo charger. For engines without this feature, it is believed that methane that passes through the crank case is accountable for the highest share of the non-engine emissions (Pavlenko, 2020).

Unintentional leakages from the fuel supply system are unwanted since an accumulation of methane in enclosed spaces is a safety risk and the leakages also mean that fuel is lost. The extent of leakages is not possible to quantify in a generic way.

Occasionally, there are ventilations of the systems at preparations for repair and maintenance work. This is sometimes called blow-off. The term blow-off can also be used for other instances when gas in a tank needs to be changed if it is of poor quality.

During normal operations, LNG driven vehicles and vessels may need to release gas from tanks to lower the pressure in the tank. This is referred to as boil-off or boil-off gas (BOG).

Heavy duty road vehicles

Heavy duty road vehicles are all vehicles with a maximum permissible weight >3.5 tonnes registered to drive on public roads. The two main categories are heavy trucks and buses.

Methane fuel for heavy duty vehicles

Both CNG and LNG are used as fuels for heavy duty road vehicles. Vehicles registered before 8 December 2019 are only registered as “methane fuelled”, and it is not possible to say with certainty how many of the approximately 1,000 trucks and 2,600 buses (Trafikanalys, 2020) fuelled by methane that are fuelled by CNG or LNG. Vehicles registered after December 8th 2019 are registered as either “CNG” or “LNG” fuelled. The majority is most likely CNG fuelled today, but LNG fuelled trucks are expected to increase in coming years. 70% of registered trucks 2019 were Euro VI and 30% were older (Euro V or EEV).

CNG buses have been in use since the 90s (Norrman et al., 2005) and operate mainly within public transport. CNG trucks were introduced in the 00s. A common use of CNG-fuelled trucks is as garbage trucks, but there are also truck models for distribution and regional transport. Both garbage trucks and public transport operate in urban areas, in low speeds and with multiple stops. Operational conditions affect emissions, with a particular impact on NO_X emissions.

LNG trucks have become more popular in recent years. Both Scania and Volvo, which together make up 85% of the vehicle market (BIL Sweden, 2020), have LNG models in their lineup. Iveco, which have a smaller market share in Sweden but larger abroad, also sells LNG trucks. The Swedish Transport Agency states that there is most likely no LNG buses (Transportstyrelsen, 2019). LNG trucks tend to be used for medium range or long haul transports due to multiple reasons: i) the high energy content of LNG enables a longer range than other alternative fuels, ii) LNG and CNG tanks demands more space than conventional diesel tanks, which is a challenge for smaller trucks, and iii) the risk of methane release from tanks (i.e. boil-off) if the truck is at stand-still for a longer period of time is low.

Compressed gas is either sold as a mix of natural gas and biogas or compressed biogas only. The share of renewable energy in compressed gas has increased over the years and was 93% in 2018 (Swedish Energy Agency, 2019). Table 2 shows typical values for vehicle gas sold in Sweden, although the European Standard EN 16723-2:2017 allows for both higher sulfur content (30 mg/Nm^3) and lower methane number (65). The former Swedish standard for gas as a vehicle fuel, SS 155438, which predates the European standard, stipulates a methane content of 97% +/- 1-2 % and a sulfur content of <23 mg/Nm^3.

Table 2: Typical range of fuel properties of compressed gas. Circle K (2020), Biogas Gotland (2016), Gasnätet Stockholm (2016), ST1 Sverige (2019).

Property	Typical value	Unit
Density	0.77-0.78	kg/ Nm^3
Lower heating value	46.8	MJ/kg
Methane content	95-98%	vol-%
Sulphur	8-30	mg/kg

In Sweden, liquefied gas is sold as either natural gas or liquefied biogas. The share of renewable energy for all gas sold is lower than for compressed gas, 29% in 2018 (SCB, 2019). The main distributors of liquefied gas for road vehicles are Gasum and Fordonsgas. There are currently 19 tank stations where LNG or LBG is available (Energigas, 2020).

Table 3: Typical range of fuel properties of liquefied gas. Fordonsgas (2011), Scangas (2017), Verbeek & Verbeek (2014).

Property	Typical value	Unit
Density	450	kg/m3
Lower heating value	49.3	MJ/kg
Methane content	98-99%	Vol-%
Sulfur	<1-5	ppm

For all emissions except CO_2, it is assumed that natural gas and biogas have the same emission factors. Very few of the reports have details on the share of natural gas and biogas of fuel used in test.

Methane engines in heavy duty vehicles

There are two main types of engines used in Swedish heavy-duty road vehicles, spark ignition (SI) and high-pressure direct ignition (HDPI). Overall, CNG trucks and buses use spark ignition engines and runs only on CNG. LNG trucks use either spark ignition engines which run only on LNG, or HPDI engines, which use diesel oil as a pilot fuel for ignition and LNG as main fuel. Stoichiometric combustion is the dominant technology for Euro VI SI engines, while lean-burn combustion was more common for Euro IV and Euro V engines. The stoichiometric engine produces less methane than lean-burn engines, resulting in significantly lower methane emissions for Euro VI vehicles than older Euro IV and Euro V vehicles (Speirs et al, 2019).

Scania currently market SI engines with stoichiometric combustion and Volvo market models with HDPI engines. The Volvo engine is approved as a Type 1A engine (Volvo Trucks, 2018), according to Regulation (EU) 133/2014 on dual fuel engines. This means that there is no diesel mode for operation and the energy ratio of gas to diesel during a hot cycle is at least 90%. A typical gas-to-diesel proportion is 95-98% (Speirs, 2019). Diesel is used for ignition and as “back-up” fuel in service mode. Since the dual fuel engine is a Type 1A engine, the same Euro VI emission standards applies to both SI and HDPI engines.

The Scania LNG emissions treatment use EGR and a 3-way catalyst (Scania, 2017), whereas the Volvo LNG emission treatment use SCR and particulate filters (Volvo, 2017). Different engine technologies will have an impact on non-methane emissions such a NO_X, N_2O and NH_3. HPDI engines operates on a diesel cycle, resulting in higher NO_X emissions from combustion.

Table 4: Euro VI Emission standards for positive ignition engines (apply to SI and HPDI type 1A engines). All units are g/kWh except particle number (PN) for which the unit is #/kWh.

Stage	CO	NMHC	CH_4	NO_X	PM	PN
Euro VI	4.0	0.16	0.5	0.46	0.01	6.0×10^{11}

Emissions from methane driven heavy duty vehicles

Methane emissions

Tank and supply system

There is a limited number of studies that quantify methane emissions from tank and supply systems. There is one study on leakage from heavy duty CNG vehicles, and a few studies on emissions from LNG vehicles' tank and supply systems.

Leakage: Trafikverket commissioned a study on leakage from CNG driven busses in 2016. The scope was leakage from gas tanks, fuel filling fittings, pipe and engine room. The study found that 15% of the investigated fleet of 60 vehicles had no leakage from tank and supply systems, 50% had a leakage from fuel fittings and 3% had some leakage from the engine room (AVL MTC, 2016). The total methane leakage from tank and supply was small compared to methane slip through the engine, where older EEV vehicles had an average methane leakage of 5.1 micrograms per day and Euro VI vehicles had an average methane leakage of 0.75 micrograms per day. The average exhaust pipe emissions were 28 mg per day, which means that the methane leakage added 0.02% and 0.003%, to tailpipe emissions for EEV and for Euro VI, respectively.

Boil-off: Boil-off gas (BOG) occurs when gas is released from tanks to lower the pressure. LNG trucks are legally required to have a minimum hold time of five days after being filled net full (Gunnarson & Helander, 2015). However, Vermeulen (2019) describes that boil-off started after two days of stand-still when a vehicle was prepared for measurements. A possible explanation according to the author is that the truck is fitted with a low-pressure system and most Dutch fueling station provide LNG with higher pressure (8 bars).

BOG will normally not occur during transport from factory, although this is a common case for which trucks can remain unused for longer than five days, since the tank is not filled net full during transport. After factory transport, BOG emissions depend on how the trucks is used. Both Gunnarsson & Helander (2015) and Nylund & Wenstedt (2019) mean that contractors seldom let their fleet be stationary for long. Gunnarsson & Helander points out that when LNG trucks become more common, there will most likely be an increase in trucks that are not used for five days due to vacations, maintenance or additional capacity. Estimation by Vermulen et al (2017) is that boil-off occurs 1-5 days per year and truck, which would equal emissions of 0.006-0.028 g/MJ. Nylund &

Wenstedt (2019) gives an example of boil-off for 3 days in a year. There is no known research on how common BOG is in an existing, commercial LNG fleet. If or when there is a release of BOG, about 2-5% of fuel mass is released per day (Nylund & Wenstedt, 2019; Vermeulen et al., 2017).

Blow-off: Blow-off gas is when gas in tanks is partly or fully released during certain maintenance work, or if a tank is filled with a bad batch of gas and needs to be exchanged. Vermulen et al. (2017) exemplifies that one full release of tank during a vehicle's lifetime could equal a yearly average emission of 61 kg of methane. Recalculating the methane emissions with the truck described in Vermeulen et al. (130 000 km/year, lifetime of 6.2 years, tank capacity of 378 kg and energy consumption of 15 MJ/km) this would equal methane emission of 0.03 g/MJ.

Nylund & Wenstedt estimate that maintenance that require blow-off will not occur if the tank is not at least half-empty. The report estimates that 25% of the remaining 50% of gas will escape during depressurization. There are little or no data on how frequently this maintenance is done, but Nylund & Wenstedt together with Scania use an estimation of 30 minutes maintenance once a year. Calculating methane emissions as g/MJ from the report figures (total CO_2-e emissions of 90 kg/100 km, blow-off is 0.007%, energy consumption 13 MJ/km and CO_2-e 28 for methane) this results in approximate methane emissions of 0.01 g/MJ.

Crank case slip is reventilated to tank in modern truck LNG engine according to Vermeulen et al. (2017). Hence, there is no contribution to methane emissions from crank case slip in trucks.

Engine emissions

Methane slip through engines are on average lower for heavy duty road vehicles than for marine engines. Methane has been a regulated pollutant since 2000 and Euro III, with sharpened regulations put in place for Euro VI. Overall, Euro VI engines has lower methane emissions than older vehicles. There are a limited number of studies of dual-fuel engines, but the existing studies indicate that methane emissions from HPDI engines are slightly higher than from SI engines. However, it should be noted that a limited number of trucks have been tested, usually one or two vehicles per test report, and it cannot be made certain that HPDI engines in general have higher methane emissions. Emission standards of the vehicle, and subsequently the average fleet age, is most likely more important for the weighted emission factors.

Table 5 shows the CH_4 emission limit and how it has changed over time.

Table 5: Emission standards for CH_4 emissions and heavy-duty gas vehicles, values in unit g/kWh.

Pollutant	EEV	Euro III	Euro IV	Euro V	Euro VI
CH_4	0.65	1.6	1.1	1.1	0.5

Nijenhuis (2019) performed an “in-service conformity test” with a portable emission measurement system (PEMS) on a Euro VI HPDI tractor truck with a maximum permissible weight of 46 tonnes. Test were performed in the Netherlands, were LNG has a slightly lower methane content than Swedish methane (fuel sample 94%-vol). All three test rounds showed emission values within the legal limits (which includes a conformity factor of 1.5 for on-road tests). Vermeulen (2019) tested the same truck as in Nijenhuis (2019), but on additional test tracks. The truck was also equipped to measure boil-off and the test procedure is described in Vermeulen (2019), but results have not yet been released. van Schaijk (2018) tested an Euro VI with a SI engine. The test was a follow-up from a previous test (Vermeulen et al., 2017), where the focus was on emissions in urban operation, hence not fully representative for LNG truck operational conditions in general. Vermulen et al (2017) tested two Euro VI SI tractor trucks with a total weight of 32 tonnes. On-road tests were carried out with both a reference track, aiming to mirror real usage and a track mirroring a supermarket delivery with mainly urban operations. Finally, the AVL 2016 and 2015 test are made on Swedish CNG trucks within the Swedish in-service conformity test program. SGC 2014 test are made on a Swedish CNG-fueled garbage truck.

Verbeek and Verbeek, 2014, give a review of the (then) current state of knowledge.

The Handbook Emission Factors for Road Transport (HBEFA) provides emission factors for road traffic of all current vehicle categories and a wide variety of traffic situations. Emission factors for all regulated and a set of non-regulated pollutants are included. The HBEFA data presented here are combinations of national activity data of the Swedish fleet and operational conditions (for CNG) paired with a number of measurements on European trucks. For LNG trucks, there is currently no activity data on average vehicle age due to issues earlier described in this report.

Table 6 shows emission factors for methane in literature and from HBEFA.

Table 6: Methane emissions from literature.

Source	LNG SI	LNG HPDI	CNG
	Average CH4 g/MJ	**Average CH4 (g/MJ)**	**Average CH4 (g/MJ)**
Vermeulen 2019		0.029-0.037	
Nijenhuis 2019		0.030-0.045	
van Schaijk 2018	0.008-0.011		
Vermulen et al (2017)	0.001-0.023		
Verbeek and Verbeek 2014	0.03		
Willner and Danielsson 2014			0.02
AVL 2016			0.02
AVL 2015			0.03
HBEFA 4.1	0.011-0.026		0.016-0.018
Range of values	**0.001-0.026**	**0.029-0.045**	**0.016-0.03**

Other pollutants

Most available reports and published measurement studies describe the regulated pollutants CO, HC and NO_X. It is common that total hydrocarbon is the measured quantity and methane emissions are calculated by assuming that a weight percentage of methane in HC (between 92-100%).

There are some measurements on PM, but mainly on CNG vehicles and older vehicles. Ricardo-AEA (2014) measured PM on both a spark ignited and a HPDI methane truck. However, the HPDI truck is a Euro V aftermarket conversion and it is questionable if the results are representative for Swedish LNG vehicles.

There are only a few reports on N_2O emissions (Willner 2013; Willner and Danielsson, 2014), and although there are measurement results the report authors consider the results to be inconclusive. Vermeulen (2019) also measures N_2O concentrations above zero, but does not draw any conclusions on total emissions. Table 7 shows a summary of emissions factors for these pollutants in literature and HBEFA.

Table 7: Emission factors from HBEFA for 2019, and emission factors from literature review (g/MJ). When multiple measurements are included in a report, an average value of representative driving is chosen for Table 7. Empty cells mean there is no emission factor for the pollutant in the report. Emission factors in g/MJ.

Source	Fuel	Tech-nology	CO	NMHC	NOx	PM2.5	BC	N2O
			g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ
HBEFA	CNG	SI BUS	0.050	0.0014	0.25	0.0038	0.0006	
HBEFA	CNG	SI TRUCK	0.055	0.0016	0.065	0.00041	0.00007	
HBEFA	LNG	SI	0.05	0.00096	0.030	0.00041	0.00006	
Nijenhuis, 2019	LNG	HPDI	0.31		0.030			
Vermeulen, 2019	LNG	HPDI	0.26		0.015			
van Schaijk, 2018	LNG	SI	0.10		0.040			
Vermulen et al., 2017	LNG	SI			0.039			
SGC, 2014	CNG	SI	0.13		0.035	0.00043		
SGC, 2013	LNG	HPDI	0.02			0.0044		0.0018
SGC, 2013	CNG	SI	0.17		0.084	0.0003		
Nylund & Wenstedt, 2019	LNG	SI						0.0008
AVL, 2016	CNG	SI	0.068		0.038	0.0001		
AVL, 2015	CNG	SI	0.049		0.047	0.0002		
Hedegaard Gravesen, 2015	CNG	SI						0.001
Range of values	**CNG**	**SI**	**0.01-0.32**		**0.016 -0.25**	**0.00008 - 0.00043**		**0.001**
Range of values	**LNG**	**SI**	**0.08-0.13**		**0.013 - 0.053**			**0.0008**
Range of values	**LNG**	**HPDI**	**0.02-0.33**		**0.011 - 0.040**	**0.0044**		**0.0018**

NO_X emissions before aftertreatment will differ between the two engine types (SI and HPDI), but HPDI engines will be required to use SCR to meet Euro VI emission standards. Hence, Euro VI trucks show similar NO_X emissions ranging from 0.01-0.04 g/MJ during average operations for both engine types. van Schaijk (2018) and Vermeulen et al. (2017) show that NO_X emissions are higher during operation in urban traffic, indicating that weighted emission factors should also depend on operations.

N_2O emissions stems from the SCR system in HPDI trucks and cold starts in vehicles with a 3-way catalyst (SI engines). Heavy vehicles, contrary to passenger cars, generally operates for longer periods and with less stand-still. Hence, cold starts are less common than with passenger cars. Willner (2013) and Willner and Danielsson (2014), are the only measurements found on European trucks. Quiros et al. (2017) found that N_2O emissions from an SI CNG truck with a three-way catalyst were 35-98% lower compared to a diesel truck, depending on operational conditions. An alternative approach could be to compare N_2O emission factors for HPDI trucks to diesel trucks, and SI trucks to petrol trucks. Hedegaard Gravesen (2015) performed measurements on a Danish CNG bus.

The HBEFA emission factors for SO_2 is currently set to “0”, although sulfur content of CNG/CBG is approximately 10 mg/Nm3. Recommended emission factors for SO_2 will be based on fuel sulfur content.

Emission factor overview – heavy duty vehicles

Methane emission factors

Overall, for Euro VI vehicles, and newer, the tailpipe emission is in the range of 0.01-0.04 g/MJ. The uncertainty in measurement data from the instruments is 5 % (Vermeulen et al, 2017). Fuel consumption varies somewhat depending on driving patterns and ambient conditions, but in large, tailpipe methane is proportional to the total fuel consumption.

There is little evidence that leakage from pipes and tanks is significant. The bus study showed a contribution of about 1-5 micrograms per day, which would equal about 0.8-3.8 ng/MJ for a vehicle with an energy usage of 12 MJ/km and annual mileage of 40 000 km.

Emissions from boil-off and blow-off are likely higher than leakage emissions. However, boil-off and blow off is not necessarily proportional to the fuel consumption of the vehicle. It should also be noted that there is little or no research into how often boil-off and blow-off occur during real usage, and only little research on size of emissions when boil-off and blow-off occur. Boil-off emission estimations in literature range from 0.006 to 0.03 g/MJ, and blow-off emission estimations range from 0.01 to 0.03 g/MJ.

In total, methane emissions could range from 0.01 g/MJ to 0.1 g/MJ depending on the size of methane contribution from boil-off and blow-off. The next section discusses recommendations for most likely values of emission factors.

Other pollutants

CO emissions vary from 0.01-0.3 g/MJ and seems to be higher for older vehicles (CNG vehicles) and HPDI engines.

NO_X emissions are higher for pre-Euro VI engines but seems to comparable for both SI and HPDI engines in Euro VI vehicles (including aftertreatment).

$PM_{2.5}$ emissions for Euro VI SI engines are low (0.0001-0.0004 g/MJ). There are only a few measurements of particulates from LNG HPDI engines and none on the latest technology.

Emission factor recommendation – heavy duty vehicles

Weighed emission factors must take the fleet composition into account. The most relevant aspects are emission standards, engine technology and vehicle size and weight. We assume that all LNG trucks fulfil Euro VI requirements, since, to our knowledge, no LNG fuelled HGVs were sold before the enter into force of these regulations. There is not yet any decision on further emission standards (“Euro VII”). Therefore, it is assumed that there is no changes in regulated emissions for future trucks.

With regards to engine and aftertreatment technology, we assume a 50/50 share of HPDI and SI engines based on the current market shares of the two engine types. The same aftertreatment technology as today is also assumed for future trucks, as there is no decision on stricter emission regulations.. For dual-fuel HPDI engines, 2-5% of the energy share is expected to be diesel and the remaining share is LNG (Speirs et al., 2019).

Regarding boil-off emissions, there is a possibility for further technical handling of BOG as discussed in Gunnarsson & Helander (2015). However, there are no legal requirements to equip trucks with such devices and this will add cost and weight to the vehicle. In addition, it is currently perceived that BOG is a minor part of total GHG-emissions. We therefore assume that there will be no BOG-abatement technology in place before 2030.

Finally, future LNG trucks are believed to be sold mainly in the same segments as today (medium range and long-haul transport.) with a maximum permissible weight of 16 tonnes or more (class N3 trucks). This means that HBEFA emission factors for tractor 34-40 tonnes are chosen to represent the expected future LNG fleet rather than the alternatives (Rigid trucks <12 tonnes).

Table 8 presents the recommended engine emission factors for heavy duty LNG vehicles 2019, and Table 9 presents recommended engine emission factors for heavy duty CNG vehicles in 2019.

Table 8. Engine emission factors for heavy duty LNG vehicles 2019. The uncertainty indicates the range in measured values. For full time series, see appended Excelfile "Weighted emission factors for methane fueled road vehicles".

Technology	Pollutant	EF 2019 (g/MJ)	Estimated lower limit*	Estimated upper limit*	Motivation
LNG HPDI	CH_4	0.033	0.028	0.038	Average of measurements in Vermeulen 2019 and Nijenhuis, 2019, excluding measurements with 0% and 100% load.
LNG SI	CH_4	0.010	0.0074	0.014	Average of HBEFA Euro VI LNG tractor and measurements in van Schaijk, 2018 and Vermulen et al., 2017, including only measurements on N_2 or reference track.
LNG	CO	0.10	0.077	0.13	Average measurements in van Schaijk, 2018 and Vermulen et al., 2017, including only measurements with normal load and operations
LNG HPDI	NO_X	0.024	0.018	0.031	Average of measurements in Vermeulen, 2019 and Nijenhuis, 2019 excluding measurements with 0% and 100% load.
LNG SI	NO_X	0.035	0.030	0.040	Average of HBEFA Euro VI LNG tractor and measurements in van Schaijk, 2018 and Vermulen et al., 2017, including only measurements on N_2 or reference track.
LNG	SO_2	0.00012	0.000040	0.00040	Based on range of S-content for fuel suppliers.
LNG HPDI	N_2O	0.0018	0.00060	0.0054	Measured by SGC, 2013.
LNG SI	N_2O	0.001	0.00020	0.0050	SGC, 2014 detected N_2O in a cold start cycle, measurement on Euro VI CNG vehicle with TWC. Weighted value of cold and warm cycle.
LNG	$PM_{2.5}$	0.0004	0.00020	0.00080	HBEFA 4.1, Euro VI tractor truck. 100% percent SD assumed, since no data on uncertainty.
LNG	BC	0.00006	0.000030	0.00012	HBEFA 4.1, Euro VI tractor truck. 100% percent SD assumed, since only HBEFA data is used and no info on measurement values.

*Upper and lower limit for an uncertainty range estimated from measurements in previous reports, or estimated as described in column "Motivation".

Table 9: Engine emission factors for heavy duty CNG vehicles 2019. The uncertainty indicates the range in measured values. For full time series, see appended Excel file "Weighted emission factors for methane fueled road vehicles".

Vehicle category	Pollutant	EF 2019 (g/MJ)	Estimated lower limit*	Estimated upper limit*	Motivation
HGV	CH_4	0.018	0.011	0.031	HBEFA 4.1
Bus	CH_4	0.016	0.011	0.024	HBEFA 4.1 and literature
HGV	CO	0.055	0.028	0.11	HBEFA 4.1 and literature, excluding outlier in Willner (2013)
Bus	CO	0.050	0.025	0.10	HBEFA 4.1 and literature
HGV	NO_X	0.065	0.043	0.10	HBEFA 4.1 and literature
Bus	NO_X	0.252	0.17	0.38	HBEFA 4.1 and literature
HGV and Bus	SO_2	0.00056	0.00040	0.00078	S-content of 10 mg/Nm^3, could be as low as 6 mg/Nm^3.
HGV	N_2O	0.005	0.0010	0.025	SGC 2014. Note high uncertainty, could be closer to 0.001 and similar to LNG SI trucks for modern vehicles.
Bus	N_2O	0.001	0.00050	0.0020	N2O from Speirs et al. (2019) and fuel consumption from HBEFA. Consistent with Hedegaard Gravesen, 2015.
HGV	$PM_{2.5}$	0.00046	-	-	HBEFA 4.1
Bus	$PM_{2.5}$	0.0038	-	-	HBEFA 4.1
HGV	BC	0.00007	-	-	HBEFA 4.1
Bus	BC	0.00057	-	-	HBEFA 4.1

*Upper and lower limit for an uncertainty range estimated from measurements in previous reports, or estimated as described in column "Motivation".

For CO, CH_4 and NO_X measured with portable emission measurement system (PEMS), there is a variation in test results between vehicle types as well as individual tests. According to Vermeulen et al. (2017), the reproducibility for an on-road test is about 5%. In addition, there is an added uncertainty to what extent LNG vehicles operation will differ from the reference test route used in the in-service conformity test (which affects mainly NO_X) and the share of CH_4 of measured total hydrocarbons.

For SO_2, the uncertainty is related to S-content of fuel. The range of S-content varies between less than 1 ppm to 5 ppm in literature and data from LNG suppliers. Sulfur content in CNG also varies between data from fuel suppliers, but an average of 10 mg/Nm^3 has been chosen as a recommendation. The addition of sulfur from odorization equals 6 mg/Nm^3 (Energigas Sverige, 2014), which indicates a lower limit for odorized gas.

No studies on gas driven heavy duty vehicles that address emissions of other compounds have been found. Emission factors from the EMEP/EEA air emission inventory guidebook are therefore recommended to use for pollutants other than the ones listed in Table 8 and Table 9. The Table 3-20 in the guidebook includes Tier 2 emission factors for source category 1.A.1.a, reciprocating engines using natural gas (EMEP/EEA, 2019). The engines for which the emission factors are presented are gas fired stationary reciprocating engines but can be used as an approximation. NH_3, PCB and HCB are not estimated. The recommended emission factors are listed in Table 10.

Table 10. Recommended emission factors for natural gas-engines 2019, from EMEP/EEA guidebook 2019.

Pollutant	EF (g/MJ)	Estimated lower limit*	Estimated upper limit*	Motivation
Pb	0.00000004	6.7E-09	2.4E-07	95% confidence interval according to EMEP/EEA (2019) reaches between a lower limit at 1/5 of value and an upper limit 5 times higher than estimated emission factor. We extend the uncertainty range for the metal emissions to account for potential removal prior to liquefaction. The uncertainties in emission factors for PAHs and dioxins are more difficult to estimate but are considered high enough to be relevant also for the marine LNG engines.
Cd	0.000000003	5.0E-10	1.8E-08	
Hg	0.0000001	1.7E-08	6.0E-07	
As	0.00000005	8.3E-09	3.0E-07	
Cr	0.00000005	8.3E-09	3.0E-07	
Cu	0.00000001	1.7E-09	6.0E-08	
Ni	0.00000005	8.3E-09	3.0E-07	
Se	0.0000002	3.3E-08	1.2E-06	
Zn	0.00000291	4.9E-07	1.7E-05	
PCDD/F	0.00000000000057	1.9E-13	1.7E-12	
Benzo-a-pyrene	0.00000000120	2.0E-10	7.2E-09	
Benzo-b-fluoranthene	0.000000009	1.5E-09	5.4E-08	
Benzo-k-fluoranthene	0.00000000170	2.8E-10	1.0E-08	

There are no available measurements on $PM_{2.5}$ and BC from HPDI and SI engines respectively. There could be differences between technologies, but this is not established. NH_3 were not measures in any of the studies.

Table 11 shows possible emission factors, for non-engine emissions, as g/MJ fuel used in the vehicle. Non-engine emissions are however not automatically proportional to the fuel consumption but will vary heavily depending on operations.

Table 11. Non-engine methane emission factors, and estimated uncertainties, for heavy duty vehicles 2019. Boil-off and blow-off applies to LNG vehicles only.

Emission type	EF	unit	Estimated lower limit*	Estimated upper limit*	Motivation
Boil-off	0.01	g/MJ	0.0033	0.030	Literature estimate 0.006-0.028 by Vermeulen et al., 2017, at boil-off rate of 0.4-1.8% per day and 1-5 days per year.
Blow-off	0.02	g/MJ	0.0067	0.060	Average of Nylund & Wenstedt, 2019 and Vermeulen et al. 2017. Large uncertainties in how frequent blow-off occurs.
Tank system and pipe leakage	0.2	ng/MJ	0.067	0.60	AVL measurement of 0.75 micrograms of leakage per day, annual mileage of 50 000 km and energy usage of 12 MJ/km.

*Upper and lower limit for an uncertainty range estimated from measurements in previous reports, or estimated as described in column “Motivation”.

There are large uncertainties to non-engine emissions. Leakage from tank system and pipes can be considered negligible. Possible BOG emissions will likely increase with an older fleet in need of repair and more vehicles at stand-still. This effect has not been possible to quantify.

Light duty road vehicles

Besides trucks and buses, methane is also used as a fuel in passenger cars and light duty trucks. There are also a small number of light duty vehicles (about 250 vehicles) in Sweden which are fueled by LPG (Liquefied petroleum gas). Emissions from LPG vehicles are not covered by this report.

Methane fuel for light duty road vehicles

Only CNG (not LNG) is used as a fuel in light duty transport. There are both passenger cars and light duty trucks fueled by CNG. Sales of new vehicles is moderate; approximately 1% of vehicles sold are CNG-fuelled. In total, there were 41,600 passenger cars and 8,700 light duty trucks fueled by CNG in 2019 (Trafikanalys, 2020). Sales are expected to remain low or possibly decrease slightly, as leading passenger car original equipment manufacturers have announced that they will stop develop new CNG models (Waldholz, 2020; Söderholm, 2017). CNG fuel for light duty vehicles is the same fuel used by CNG trucks. Fuel properties can be found in Table 2.

Methane engines in light duty road vehicles

Light duty vehicles on the market are either bi-fuel vehicles with two fuel tanks: a petrol tank and a gas tank that can both be used for driving, or mono-fuel vehicles with a main gas tank and a small petrol tank that is used during engine start. Typical mono-fuel vehicles are VW Caddy and Opel Zafira, and typical bi-fuel vehicles are Volvo V70 and VW Passat (Kågeson & Jonsson, 2012).

There are no HPDI or dual fuel engines in passenger cars. Stoichiometric combustion with a 3-way catalyst is the dominating technology for light duty vehicles (Saanum et al., 2007), as opposed to heavy duty vehicles where lean burn combustion is used for vehicles that fulfill Euro V or earlier standards.

Emissions from methane driven light duty vehicles

Emission standards for light duty vehicles are set in g/km for regulated pollutants. Emission standards are the same for all passenger cars but are divided into three classes for light duty trucks differed by reference weight, see Table 12, Table 13, and Table 14 for an overview of the values in the applicable emission standards. HBEFA emission factors are calculated by weighting, according to the Swedish fleet composition in each reference weight class, together to class specific emission factors.

HBEFA emission factors for all pollutants except SO_2 are recommended in this report. SO_2 emission factors for methane vehicles are currently missing in HBEFA. SO_2 emission factors are instead calculated by fuel methane content.

Table 12: Emissions standards passenger cars, positive ignition, and Light Commercial Vehicles (LCV) class N-1I (g/km). Council Regulation (EU) 715/2007.

Stage	CO	HC	NMHC	NOx	Particle number (PN) (#/km)
Euro 4	1.0	0.1		0.08	
Euro 5	1.0	0.1	0.068	0.06	
Euro 6	1.0	0.1	0.068	0.06	6.0×10^{11}

Table 13: Emissions standards Light Commercial Vehicles (LCV) class N1-II, positive ignition (g/km). Council Regulation (EU) 715/2007.

Stage	CO	HC	NMHC	NOx	Particle number (PN) (#/km)
Euro 4	1.81	0.13		0.10	
Euro 5	1.81	0.13	0.090	0.075	
Euro 6	1.81	0.13	0.090	0.075	6.0×10^{11}

Table 14: Emissions standards Light Commercial Vehicles (LCV) class N1-III, positive ignition (g/km). Council Regulation (EU) 715/2007.

Stage	CO	HC	NMHC	NOx	Particle number (PN) (#/km)
Euro 4	2.27	0.16		0.11	
Euro 5	2.27	0.16	0.108	0.082	
Euro 6	2.27	0.16	0.108	0.082	6.0×10^{11}

Emission factor overview and recommendations – light duty road vehicles

Methane emissions for light duty vehicles range around 0.004-0.005 g/MJ according to HBEFA. This includes emissions from engine (methane) slip. No boil-off or blow-off is expected since all vehicles are CNG and not LNG vehicles.

Emission factors for CO for Light Commercial Vehicles (LCV) are expected to increase by 2030, most likely due to the overserved increase in CO emissions from ageing vehicles (Sjödin et al., 2018) and an expected increase in age for LCVs.

All recommendations in this section are based on HBEFA data or EMEP/EEA data.

Methane

Table 15 shows HBEFA emission factors for methane emissions recalculated to g/MJ and the Swedish fleet in 2019.

Table 15: HBEFA emission factors for 2019 recalculated to g/MJ.

Vehicle category	Technology	Pollutant	EF (g/MJ)	Comment
Passenger car	bi-fuel CNG/petrol	CH_4	0.004575	Uncertainty unknown
LCV	bi-fuel CNG/petrol	CH_4	0.005062	Uncertainty unknown

For full time series, see appended Excelfile “Weighted emission factors for methane fuelled road vehicles”.

Other pollutants

Table 16 shows HBEFA emission factors valid for 2019, for pollutants BC, CO, N_2O, NH_3, NMVHC, NO_X and $PM_{2.5}$. SO_2 emission factors are calculated based on sulfur fuel content.

No studies on gas driven heavy duty vehicles that address emissions of other compounds have been found. Emission factors from the EMEP/EEA air emission inventory guidebook are therefore recommended to use for pollutants other than the ones listed in Table 15 and Table 16. The Table 3-20 in the guidebook includes Tier 2 emission factors for source category 1.A.1.a, reciprocating engines using natural gas (EMEP/EEA, 2019). The engines for which the emission factors are presented are gas fired stationary reciprocating engines but can be used as an approximation. NH_3, PCB and HCB are not estimated. The recommended emission factors are the same as for heavy duty trucks and are listed in Table 10.

Table 16: HBEFA emission factors for 2019 recalculated to g/MJ

Vehicle category	Technology	Pollutant	EF (g/MJ)	Un-certainty: Lower and upper limits	Comment
Passenger car	bi-fuel CNG/petrol	BC (exhaust)	4.92E-05		Uncertainty unknown
Passenger car	bi-fuel CNG/petrol	CO	0.240555		Uncertainty unknown
Passenger car	bi-fuel CNG/petrol	N_2O	0.000157		Uncertainty unknown
Passenger car	bi-fuel CNG/petrol	NH_3	0.010992		Uncertainty unknown
Passenger car	bi-fuel CNG/petrol	NMVHC	0.004129		Uncertainty unknown
Passenger car	bi-fuel CNG/petrol	NO_X	0.038531		Uncertainty unknown
Passenger car	bi-fuel CNG/petrol	$PM_{2.5}$	0.000328		Uncertainty unknown
Passenger car	bi-fuel CNG/petrol	SO_2	0.00056	0.00028 - 0.0011	Uncertainty based on range of S-content from 6-23 ppm from fuel suppliers, with a most likely value of 10 ppm
LCV	bi-fuel CNG/petrol	BC (exhaust)	0.000272		Uncertainty unknown
LCV	bi-fuel CNG/petrol	CO	0.689843		Uncertainty unknown
LCV	bi-fuel CNG/petrol	N_2O	0.000125		Uncertainty unknown
LCV	bi-fuel CNG/petrol	NH_3	0.009235		Uncertainty unknown
LCV	bi-fuel CNG/petrol	NMVHC	0.005529		Uncertainty unknown
LCV	bi-fuel CNG/petrol	NO_X	0.015288		Uncertainty unknown
LCV	bi-fuel CNG/petrol	$PM_{2.5}$	0.001811		Uncertainty unknown
LCV	bi-fuel CNG/petrol	SO_2	0.00056	0.00028 - 0.0011	Uncertainty based on range of S-content from 6-23 ppm from fuel suppliers, with a most likely value of 10 ppm

*Upper and lower limit for an uncertainty range estimated from measurements in previous reports, or estimated as described in column “Motivation”.

Ships

Methane fuel for ships

The use of LNG as a marine fuel has increased significantly the last two decades. In 2010, 1.4% of the delivered ships were built for LNG-propulsion. This share increased to 5.7% in 2017 and further to 13.5% by 2018 (Le Fevre, 2018). Historically, LNG is used by LNG tankers, for which cargo boil-off have been a fuel for several decades. Regionally stricter rules for ships' emissions of sulfur and nitrogen oxides, and a relatively low price for LNG compared to marine gasoil (MGO) has increased the number of ship types that use LNG as fuel. CNG is not used as a marine fuel.

Many of the marine LNG engines that are delivered today have problems with unburned methane passing through the engine and being emitted with the exhaust gases. The methane-slip has been estimated at around 2.3-4.1% for the engines that are in operation today (Stenersen and Thonstad, 2017). The slip is big enough to cause LNG to be comparable to, or worse than, MGO for greenhouse gas emissions, measured as CO2-equivalents (Thomson et al., 2015; Winnes et al., 2020; Pavlenko et al., 2020). From a 100-year perspective, the difference between the two alternatives is small (Winnes et al., 2020) but it becomes more significant in a short-time perspective. Some studies still indicate that GHG emissions from LNG can be less than from fuel oil (Baresic et al., 2018; Bengtsson et al. 2012; Schuller et al., 2019; Thomson et al., 2015; Yaramenka et al., 2019).

The climate impact could also be reduced by replacing LNG with a non-fossil liquefied biogas (LBG). However, the availability of LBG is uncertain and there is a growing demand for LBG from other sectors. LBG has so far been used in marine engines for demonstration purpose only.

From an air quality perspective, the LNG fuel has many advantages compared to the traditional marine fuels. The emissions of sulphur dioxide (SO_2) are low due to low or non-existing sulphur content of the gas. The low sulphur content also contributes to low particle levels, and the absence of fuel aromatics is also keeping the particle formation low. Further, the most widely used marine LNG engines have significantly less emissions of nitrogen oxides (NO_X) than the traditional marine diesel engines. The natural gas produces approximately 25% less emissions of carbon dioxide (CO_2) per energy unit than fossil oil; it has a higher energy content per carbon content than e.g. marine gasoil.

There are no regulations on hydrocarbon emissions from combustion in marine engines in international shipping, and the existing methane engines are not combined with any catalytic aftertreatment in the exhaust gas.

Methane engines in ships

The LNG engines in ships are either spark ignition engines or compression ignition engines:

- The spark ignited engines are more common on small vessels than on large ships and are of a lean burn type, referred to as lean burn spark ignition (LBSI) engines. The power of these engines is often in the range 0.5-8 MW (RollsRoyce/Kongsberg, Wärtsilä). The slip of methane is high although lower than from low pressure dual fuel engines. These engines are in the following referred to as LBSI engines, for lean burn spark ignition engines. These engines comply with the strictest marine emission limits for NO_x (IMO Tier III).

- The low-pressure dual fuel (LPDF) engines operate on a combination of the Otto cycle and Diesel cycle principle. These engines are the most common type, both from a global perspective and in a Swedish context. They can either be of a 4-stroke type or a 2-stroke type, of which the 4-stroke type is more used. The engines are an attractive choice since the LNG infrastructure for the marine market is still not fully developed and the dual fuel engines allow these ships to run on either a marine fuel oil or LNG. These engines are in the following referred to as LPDF engines, for low pressure dual fuel engines, and specified by 2-stroke or 4-stroke where relevant.

  In the LPDF engines, a mixture of air and gas is introduced to the combustion chamber. A small amount of gasoil or other liquid fuel is used as ignition fuel, functioning like a liquid spark plug, in each combustion cycle, and the air and gas mixture is then combusted. The share of energy from the ignition oil is approximately 1-5 %.

  The methane emissions are expected to be lower from the 2-stroke LPDF engines than from 4-stroke engines. This is mainly due to the placement of cylinder intake of combustion air and gas (Nylund et al., 2016). Published emission measurement studies on the 2-stroke engines are scarce and available data on the methane slip is from an engine manufacturer's test bed emission measurements.

  The low-pressure LNG engines comply with the strictest marine emission limits for NO_x (IMO Tier III).

- There are also high-pressure dual fuel engines (HPDF). These engines operate on the diesel cycle and the fuel is ignited directly upon injection in the combustion chamber. The share of energy from the ignition oil is approximately 1-5 %. All marine engines of the high-pressure type operate on the 2-stroke cycle. The methane slip from these engines is low, since no gas is present in the cylinder during the compression stroke and all gas is combusted directly upon injection. On the other hand, NO_x emissions are comparable to those from operations on MGO, and aftertreatment of NO_x would be necessary to comply with the strictest NO_x emission limits.

LNG steam turbines and gas turbines exist on a few large LNG fuelled gas carriers. These engines are old and phased out. They are not relevant for a Swedish context and are not further treated in this report.

The share of different engine types in the LNG driven international fleet are presented in Figure 1 and the share of engine types when excluding the LNG carriers are presented as Figure 2. In both cases approximately 75% of the engine power, which can be assumed to be proportional to the fuel consumed, are installed in 4-stroke engines. A differentiation of power installed in the 4-stroke engines between LBSI and LPDF shows that the power installed in LBSI is approximately 1 % of the total (IHS, 2020).

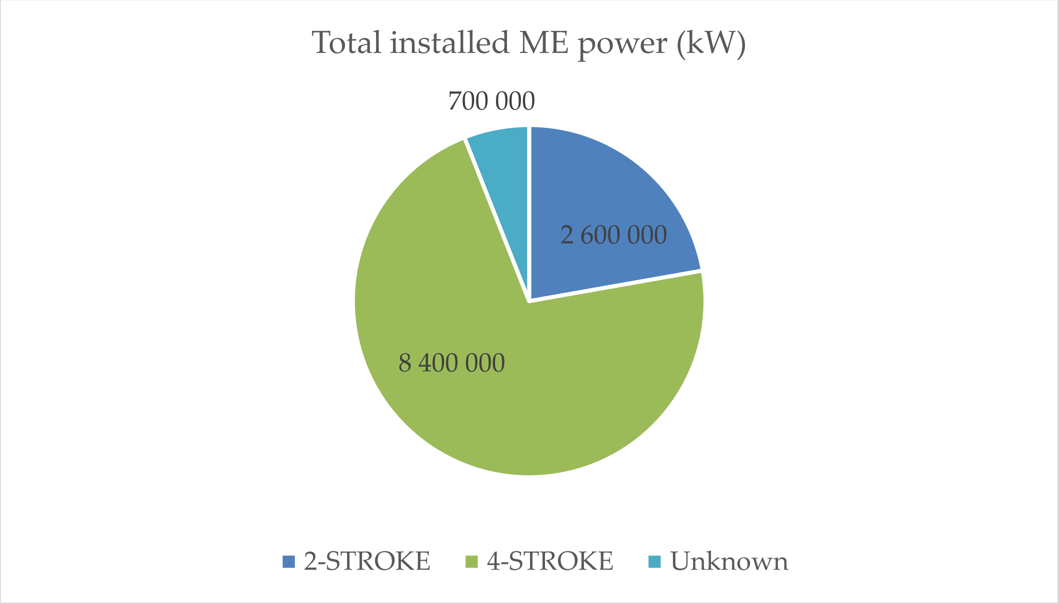

Figure 1. Total installed main engine (ME) power in LNG driven ships worldwide (IHS, 2020).

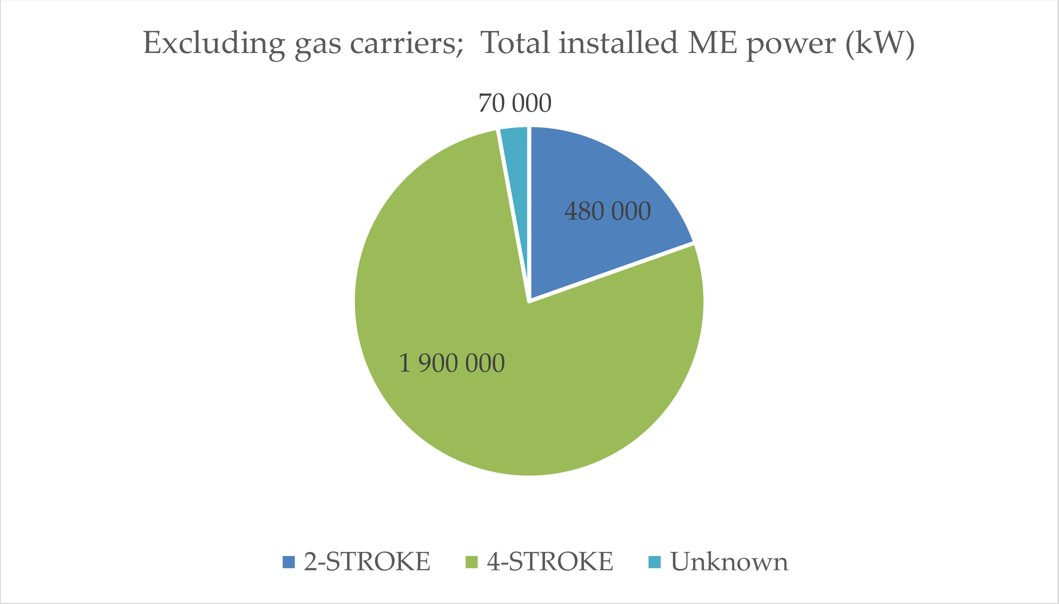

Figure 2. Total installed main engine (ME) power in LNG driven ships worldwide excluding the liquefied gas carriers (IHS, 2020).

4-stroke engines dominate also the LNG driven fleet known to traffic Swedish water, Figure 3. The Swedish traffic presented in Figure 3 is based on an inventory made by Yaramenka et al., 2019, for the Swedish Gas Association (Yaramenka 2018; Yaramenka et al., 2019). The included ships were delivered between 2013 and 2019, and also two older ships that have been retrofitted with dual fuel LNG-engines. It is expected that these values are representative for Sweden 2019. It is further expected that the shares of different engine types, Figure 3, are good approximations of the marine LNG consumption in different engine types, for LNG sold in Sweden to ships.

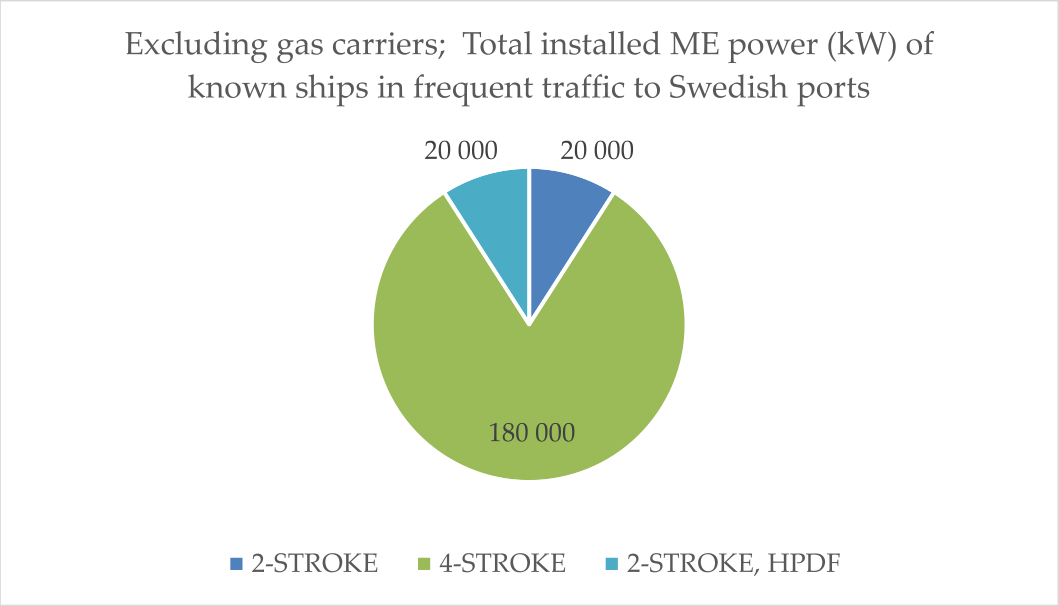

Figure 3. Total installed main engine (ME) power in LNG driven ships in traffic to and from Swedish ports (Yaramenka et al. 2019, IHS, 2020)

Emissions from methane driven ships

Methane emissions

Tank and supply system

Specific measurements on methane leakage from the crank case on ships are missing and an estimate of 1 g/kWh is, given by Pavlenko et al. (2020), is the only available approximation. This is based on previous measurements of the flow to the crank case from the cylinder, the so-called blow by and the known relative content of methane in this blow by gas. The blow-by occurs for all engines of 4-stroke type. Some marine engine designs include a closed crank case system but is not common practice.

No measurements of unintentional leakages from the fuel supply system are available. The emissions from leakages are not possible to quantify but are most likely negligible in the context of other emission sources. They are not further considered in the preparation of emission factors in this report. Occasionally, there are ventilations of the systems at preparations for repair and maintenance work. No quantifications are found specifically for ships and the extent to which ventilations are needed is not known. For LNG driven trucks, intentional ventilations are estimated to 0.02 g/MJ, see Table 11, which could possibly be used as an estimate also for ships. It seems plausible that they should not differ significantly.

There are however no suggestions in literature that the boil-off from the tanks are as high as from trucks. The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), provides an international standard for ships using low-flashpoint fuel. The Code explicitly states that venting of fuel vapour for control of the tank pressure is not acceptable except in emergency situations. Technical solutions to deal with fuel that evaporate during storing in tanks include reliquefaction of vapours, thermal oxidation of vapours, pressure accumulation, and liquefied gas fuel cooling (IMO, 2019) No estimate on emissions from boil-off is therefore included in the recommendation on methane boil-off for ships.

Engine emissions

Methane emissions from marine engines have been measured in a few studies. The results from these measurements are presented in Table 17.

Mainly measurements on 4-stroke engines have been published (Ushakov et al., 2019, Lehtoranta et al., 2019, Anderson et al., 2015). One study including total hydrocarbon measurements on a low pressure 2-stroke engine have been published by the engine manufacturer (Nylund et al., 2016). We assume that the hydrocarbons are only methane and weigh emissions according to test cycle E2/E3 (see Table 18).

Table 17. Emission measurement studies on marine LNG engines.

Study engine	Engine type	Engine load (%)	CH_4 (g/kWh)	Study
Average 7 engines	LPDF 4-stroke	Weighted	6.9	Ushakov et al., 2019,
Average 9 engines	LBSI	Weighted	4.05	Ushakov et al., 2019,
Test bed engine	LPDF 4-stroke (CNG)	0.4	13.8	Lehtoranta et al., 2019
		0.85	5.6	Lehtoranta et al., 2019
Cruise/Ferry	LPDF 4-stroke	0.4	3.4	Anderson et al 2015
		0.9	2.975	Anderson et al 2015
		0.32	4.25	Anderson et al 2015
		0.72	0.935	Anderson et al 2015
		0.29	5.695	Anderson et al 2015
Test bed engine	LPDF 2-stroke	Weighted	3.2	Nylund et al., 2016

Weighting of emissions at different engine loads shall be made according to the E2/E3 cycles in the NO_X technical code, see Table 18. The published measurement have been weighed considering the test cycles although, as seen in Table 17, the measurements by

Lehtoranta et al. (2019) and Anderson et al. (2015), were not conducted at these exact engine loads.

Table 18. Test cycles E2 and E3, IMO NO_X technical code

Power	100%	75%	50%	25%
Weighting factor	0.2	0.5	0.15	0.15

Pavlenko et al. (2020), do not present any original measurement studies but compile knowledge on primarily methane emissions from LNG-driven ships. Conclusions by Pavlenko et al. (2020) are drawn after reviewing the measurement studies referred to in Table 17 together with data from engine manufacturers and desktop studies on methane emission factors. Their conclusions are here presented in Table 19. The presented emission factors are approximated in order to be representative for specific engine emissions according to E2 and E3 test cycles.

Table 19. Emission factors suggested by Pavlenko et al 2020 for methane from marine LNG engines

	EF (g/kWh)	Thermal efficiency
Lean burn spark ignition engine	4.1	48%
Low pressure dual fuel, 4 stroke engines	5.5	48%
Low pressure dual fuel, 2 stroke engines	2.5	50%
High pressure dual fuel, 2 stroke engines	0.2	53%
Steam turbine	0.04	28%
Gas turbine	0.06	37%

Older engines

Engine manufacturers have put effort in technology development that address and reduce the methane emissions the last decade. Marintek conducted a survey of methane slip from the few LNG engines on ships in Norway in 2010 (Marintek, 2010). These measurement data, see Table 20, represent early methane engine technology. These engines were mainly installed on smaller ships like coastal ferries and offshore supply ships. The methane slip reported is significantly higher than on more modern ships and is due to design efforts by engine manufacturers to reduce the methane slip.

Table 20. Methane emissions from early installations of marine methane engines (Marintek, 2010)

Engine type	CH_4 emission factor (weighted according to ISO cycle)	
	kg CH_4/ton LNG	g CH_4/kWh
Lean burn spark ignition	44	8.5
Low pressure dual fuel	80	15.6

Engine load

Emissions from different engine loads are customary to give weight according to those described in test cycles E2 and E3 in the NO_X technical code. Discussions with a Swedish ship owner company with several LNG-driven ships in its fleet reveals that the operation of ships is automatically switched to “gasoil mode” at engine loads below approximately 25%. This means no LNG is used at the low engine loads, which would be beneficial for lowering emissions since they increase significantly at engine loads below 25% (Ushakov et al., 2019).

Other pollutants

A selection of emissions of other combustion gases are available in some of the measurement studies presented above (see Emissions from methane driven ships/Methane emissions). The emission factors concluded from these studies are presented in Table 21 (g/kWh) and Table 22 (g/MJ).

NO_X emissions are low for all low-pressure engines compared to similar engines operated on marine fuel oil. Estimates by engine manufacturer MAN are that NO_X emissions from an LNG engine is approximately 13-24% lower per kWh that those from its fuel oil driven counterpart but can be expected to be equally high as for MGO combustion for HPDF engines (MAN Diesel & Turbo, 2015, and MAN Diesel & Turbo 2015a).

Particle emissions are only available from one source (Anderson et al., 2015). Stenersen and Thonstad (2017) estimate emissions of particles to be reduced by >99%, 95-98%, 95-98%, and 30-40% for LBSI engines, LPDF 4-stroke engines, LPDF 2-stroke engines and HPDF 4-stroke engines, respectively. MAN estimate PM reduction of approximately 40% in a HPDF 2-stroke engine (MAN Diesel &Turbo, 2015). No emission measurement studies covering BC from marine LNG engines are found. Lehtoranta et al. (2019a) states that measurements of elemental carbon from LNG combustion show low emissions but the study does not provide any data.

A list of pollutants not covered by any emission measurement study on marine engines and emission factors that are recommended to use are those for reciprocating natural gas engines in the EMEP/EEA guidebook for air emissions inventories (EMEP/EEA, 2019).

Table 21. Emission factors as g/kWh from marine LNG engines.

Study engine	Engine type	Engine load (%)	NO_x (g/kWh)	CO_2 (g/kWh)	PM_{tot} (g/kWh)	NMVOC (g/kWh)	CO (g/kWh)	Study
Average 7 engines	LPDF 4-stroke	Weighted	1.9	444.2		0.38	1.86	Ushakov et al., 2019,
Average 9 engines	LBSI	Weighted	1.3	472.4		0.38	1.74	Ushakov et al., 2019,
Test bed engine (CNG)	LPDF 4-stroke	0.4	3.6	490			3.7	Lehtoranta et al., 2019 and 2019a
		0.85	2.7	410			1.6	Lehtoranta et al., 2019 and 2019a
Cruise/Ferry	LPDF 4-stroke	0.4	0.7	451			3.8	Anderson et al 2015
		0.9	0.95	398	0.002		2.7	Anderson et al 2015
		0.32	0.7	454			4.3	Anderson et al 2015
		0.72	0.5	414			1.4	Anderson et al 2015
		0.29	0.9	485			4.8	Anderson et al 2015

Table 22. Emission factors as g/MJ from marine LNG engines.

Study engine	Engine type	Engine load (%)	NO_x (g/MJ)	CO_2 (g/MJ)	PM_{tot} (g/MJ)	NMVOC (g/MJ)	CO (g/MJ)	Study
Average 7 engines	LPDF 4-stroke	Weighted	1.9	444.2		0.38	1.86	Ushakov et al., 2019,
Average 9 engines	LBSI	Weighted	1.3	472.4		0.38	1.74	Ushakov et al., 2019,
Test bed engine (CNG)	LPDF 4-stroke	0.4	3.6	490			3.7	Lehtoranta et al., 2019 and 2019a
		0.85	2.7	410			1.6	Lehtoranta et al., 2019 and 2019a
Cruise/Ferry	LPDF 4-stroke	0.4	0.7	451			3.8	Anderson et al 2015
		0.9	0.95	398	0.002		2.7	Anderson et al 2015
		0.32	0.7	454			4.3	Anderson et al 2015
		0.72	0.5	414			1.4	Anderson et al 2015
		0.29	0.9	485			4.8	Anderson et al 2015

Emission factor overview - ships

The emission factor of methane is very much dependent on the type of engine used. A weighting procedure should consider the amount of LNG that is used in the different engine types. All engines except HPDF have relatively low NO_X emissions that can be assumed to fulfil MARPOL Tier III levels.

Emission factor recommendation - ships

Results from measurement studies are given weights approximating the weights in test cycle E2/E3 in order to have one emission factor per studied engine.

An average emission factor is calculated for all the different substances for each engine type. If only one estimate or measurement result is available, this value is used. The uncertainties are very high.

The power installed in different engine types on the ships in frequent traffic to and from Swedish ports is used to weigh the emission factors together to a single emission factors by substance. The emission factors can be used for emissions from LNG sold as marine fuel in Sweden.

Often, emissions from measurement studies on ships are presented in the unit g/kWh (engine out). In order to present emissions as g/MJ fuel used in the engine, the efficiency of each engine type needs to be estimated. This is done by considering information from the engine manufacturers. The CO_2 emissions can also be used to estimate how much CH_4 that is combusted, subtracting methane slip and thereafter assuming complete combustion. These calculations indicated a slight overestimate of thermal efficiency by engine manufacturers and these values were adjusted for better agreement with measurement data.

Most marine engines are dual fuel engines. With a few exceptions, we consider all engine out emissions from these engines as the combined result of combustion of marine gasoil and natural gas. It is not possible to separate between the two when measuring emissions, and the reporting can accordingly not split them. Different engines are reported to need different shares of energy from the pilot fuel: LPDF 4-stroke 2%, LPDF 2-stroke 1%, and HPDF 2-stroke 5%.

A sulphur content of 3 mg/kg in natural gas is assumed.

The recommended emission factor for methane for 2019 is presented in Table 23.

Methane from fuel and supply systems on board the ship is estimated to 0.1 g/MJ, dominated by emission to atmosphere via the crank case. The uncertainties are very high.

Table 23. Recommended methane emission factor for marine LNG-engines 2019.

Engine type	EF CH_4 g/MJ	Estimated lower limit*	Estimated upper limit*	Relative weight**	Motivation
LBSI 4-stroke	0.50	0.33	0.75	0.3%	From measurements presented by Ushakov et al. (2019) is confirmed by Pavlenko et al. (2020).
LPDF 4-stroke	0.79	0.53	1.2	80%	Average of specific emissions from Ushakov et al. (2019) is 6.9 g/kWh. Pavlenko et al. (2020) concludes on 5.5 g/kWh. The lowest measured emission (2.3 g/kWh) is significantly lower than any other. Engine manufacturers state that they will reach 2% slip. This will equal 3 g/kWh. Hence the high uncertainty
LPDF 2-stroke	0.41	0.21	0.82	10%	Only one measurement published by an engine manufacturer. The lower methane slip from LPDF 2-stroke engines compared with the LPDF 4-stroke engines is theoretically correct. Uncertainty is high, since no independent measurement studies are published.
HPDF 2-stroke	0.045	0.023	0.090	10%	Pavlenko et al. (2020) states 0.2 g/kWh, and discussion with engine manufacturer gives a most probable value of 0.39 g/kWh. Emission measurements are scarce but point to the value of HC emissions stated by engine manufacturers, also published in their brochures. This can be expected to be methane to a majority. The uncertainty range is high due to lack of measurement data.
Weighted emission factor – all engines	**0.68**	0.43	1.1	**-**	**-**

*Upper and lower limit for an uncertainty range estimated from measurements in previous reports, or estimated as described in column "Motivation".

**from installed LNG engine power on ships in Swedish waters

Other emissions from the consulted measurement studies are weighed to a joint emission factor using the same relative weights for the different engine types, as the methane emissions. The recommended emission factors for NO_X, CO, NMVOC, SO_2, and PM are presented in Table 24.

Table 24. Recommended emission factors for CO_2, NO_X, CO, NMVOC, SO_2 and particulate matter for marine LNG-engines 2019.

Technology	Pollutant	EF 2019 (g/MJ)	Estimated lower limit*	Estimated upper limit*	Motivation
Weighted emission factor – all engines	CO_2	54.7	50	60	The methane slip for each engine type is subtracted from the emission factor for natural gas combustion in national reporting (56.54 g/MJ) before calculating weighted emissions. Uncertainty of the methane slip gives a total uncertainty estimate of 10%.
Weighted emission factor – all engines	NO_X	0.30	0.23	0.39	Emission factors within the different categories varies with a standard deviation around the average of approximately 30%
Weighted emission factor – all engines	CO	0.23	0.18	0.30	Emission factors within the different categories varies with a standard deviation around the average of approximately 30%
Weighted emission factor – all engines	NMVOC	0.043	0.029	0.065	Emission factors within the different categories varies with a standard deviation around the average of approximately 50%
Weighted emission factor – all engines	SO_2	0.00013	0.000043	0.00039	The uncertainty is related to S-content of fuel. The range of S-content varies between less than 1 ppm to 5 ppm in literature and data from LNG suppliers.
Weighted emission factor – all engines	TSP/ PM_{10}	0.0026	0.00065	0.010	Very difficult to estimate and lack of measurements cause a high uncertainty of the emission factor.

*Upper and lower limit for an uncertainty range estimated from measurements in previous reports, or estimated as described in column "Motivation".

No measurements of N_2O emissions for marine LNG-engines have been found. The IPCC guidelines for greenhouse gas inventories do not contain any values on N_2O from stationary reciprocating engines (IPCC, 2006). We can therefore not recommend any emission factor to use for marine LNG engines.

All PM is expected to be in the $PM_{2.5}$ category. The same emission factor can thus be used for TSP, PM_{10} and $PM_{2.5}$. BC emissions varies between engines and for the same engine in different operational modes. The share of BC of total PM2.5 are also dependent on sulphur content of fuel, since a high sulphur content can make sulphate particles dominate particle mass. Measurement studies from marine engines constitutes seem to converge around an average share of BC that is 30% of $PM_{2.5}$ (e.g. ICCT, 2016, and Winnes et al., 2020). The emission factor for BC is then 0.00078 g/MJ. The uncertainty is high and estimated to 200%.

For other emissions we recommend that the EMEP/EEA guidebook from 2019 is used. The Table 3-20 in the guidebook includes Tier 2 emission factors for source category 1.A.1.a, reciprocating engines using natural gas (EMEP/EEA, 2019). The engines for which the emission factors are presented are gas fired stationary reciprocating engines but can be used as an approximation. NH_3, PCB and HCB are not estimated. The recommended emission factors are the same as for heavy duty trucks and are listed in Table 10.

Details on the weighting procedure is given in the appended Excelfile “Weighted methane emissions from LNG fueled ships”.

There is on-going development at engine manufacturers to reduce the slip and the work has been successful resulting in significant reductions of slip since the problem was observed. There seems however to be a limit for slip reduction by design measures (Pavlenko et al, 2020). Future emissions can be expected to be reduced, but it is not likely that this will influence the emission factors from the fleet in the years 2020, 2025, and 2030, included in this inventory. We further do not recommend to use other emission factors for methane for the ships to and from Swedish ports for the years 2015, 2016, 2017, and 2018, since old ships (pre 2010) for which other emission factors have been established have not been in service around the Swedish coast. Before 2015, LNG driven vessels might have visited Swedish ports in separate occasions but it is not believed that any marine LNG were sold prior to 2015.

We also cannot motivate any changes in the composition of engine types used on the ships in Swedish traffic between the years included in this study. Thus, the same weighting is applied for all years.

Emissions that can be expected to decrease in the future are NO_X emissions following the introduction of a Nitrogen Emission Control Area (NECA) in the North Sea and the Baltic Sea in 2021. This requires emissions to be reduced significantly from all ships built on, or after 2021, that operate in the area. This would affect the emission factors of NO_X from high pressure dual fuel engines corresponding to 10% of the total installed power. In a study by IVL for Transport an Environment, the NO_X emissions from shipping in general at the introduction of a NECA in these areas were estimated to be reduced by 19% between 2020 and 2025, and by 34% between 2020 and 2030. The calculations considered expected turnaround time, the composition of the fleet in the area, increased transport demand, and efficiency improvement for different ship types (Winnes et al., 2016). These factors (19% and 34%, respectively) are applied to the emission factor used for HPDF engines to estimate future emissions for 2025 and 2030. Values for 2019 and 2020 are assumed to be the same.

For full time series, see appended Excelfile “Weighted emission factors for methane fuelled ships”.

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