
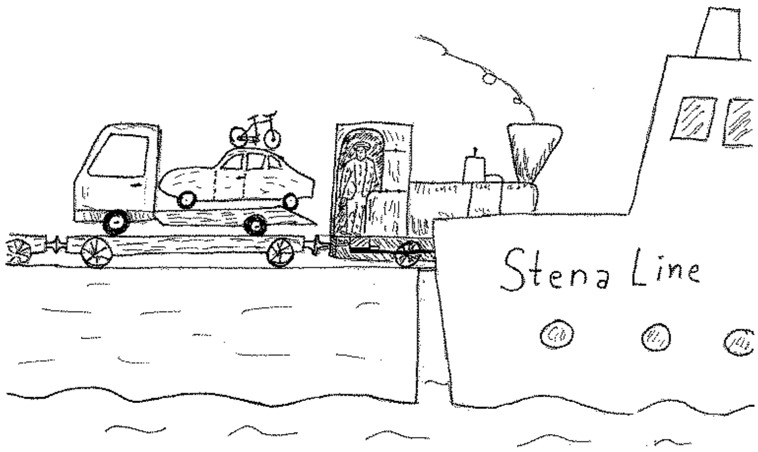



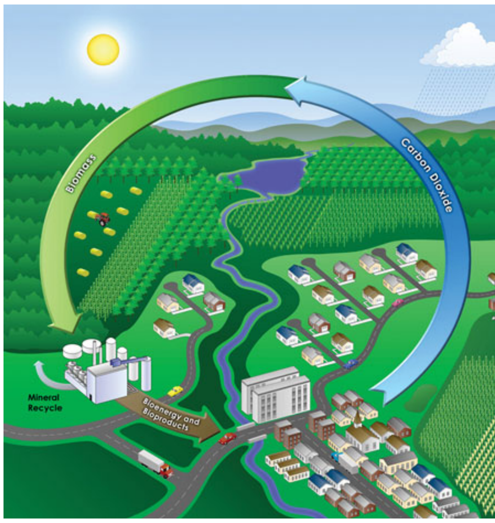

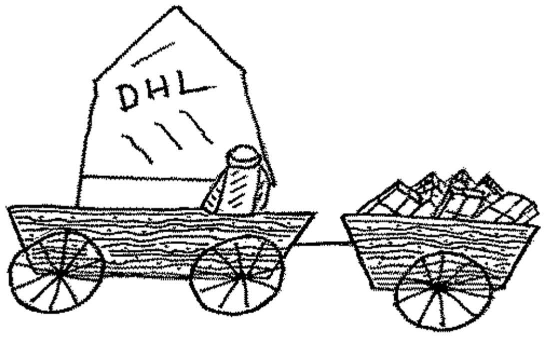

GreCOR

WP7 — Pilot projects

Evaluation of the environmental impact from using liquefied natural gas or biogas to fuel trucks for heavy duty transport

European Union The European Regional Development Fund

Illustrations: Claes Pihl

Title Evaluation of the environmental impact from using liquefied natural gas or biogas to fuel trucks for high capacity transport

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Executive summary

Highlights

This pilot indicates that for heavy-duty road transport, the greenhouse gas emissions can be reduced by using available dual-fuel technology as follows:

- for liquefied biogas (LBG) blended with diesel – more than 30% reduction,
- for liquefied natural gas (LNG) blended with diesel – no reduction.

If only the CO_2 emissions were counted, then dual-fuel with LNG would mean a small improvement compared to pure diesel combustion. However, when including the "methane slip" in the analysis, then we get a different picture with dual-fuel with LNG being at best break even with conventional diesel combustion. Methane slip refers to a small fraction of the liquefied gas going through the engine uncombusted and thus entering the atmosphere. The problem with methane slip is that methane is a much more powerful greenhouse gas than CO_2, so even a small methane slip will outweigh the benefits of the CO_2 reductions.

The more than 30% reduction of greenhouse gas emissions when replacing the LNG by the renewable alternative LBG is significant. The main reason for the reductions not being even higher is that the engine is not running on pure liquefied gas but a blend with diesel. The substitution rate depends greatly on usage, but the experience form this pilot is that it is difficult to get a higher substitution rate than 60% with the technology in use today.

As technology is being further developed, future dual-fuel systems should be able to work at much higher substitution rate and with methane slip eliminated. If expectations are fulfilled, the reduction of greenhouse gas emissions will be around 80% compared to diesel propulsion. The remaining 20% come mostly from the process of producing the biogas from waste material.

Background

Natural gas is often proposed as a future more environmentally friendly fuel alternative to diesel, considered to cause less CO_2 emissions than other fossil fuels. If it is converted into liquid form, it is called LNG for liquefied natural gas, and it becomes easier to store and transport, without the need for a local gas net of pipelines.

If the source of gas is biogas instead of natural gas, you get LBG for liquefied biogas. Since LBG is not a fossil fuel, the net emissions of CO_2 are reduced substantially – in simplified theory down to zero.

Purpose

The purpose with this pilot was to investigate the environmental impact from using LNG and LBG as a complementary fuel together with diesel in trucks that are used for heavy duty transport.

Methodology

Two Volvo MethaneDiesel trucks owned by PostNord Logistics were used for the investigation. Volvo installed a logging system, and the two trucks could be observed while in normal service. Also a literature study was made and the knowledge gained in this pilot comes both from test results and from other published reports.

Impact Evaluation

Global Warming

Figure 1 is a comparison of how different fuels lead to different emissions of greenhouse gases. The emission levels are presented on a scale as CO_2 equivalents. If only CO_2 emissions were counted, then

LNG would appear to be less harmful than diesel, but when the methane (CH_4) slip is included in the calculations, then the greenhouse gas emissions get slightly higher for LNG than for diesel.

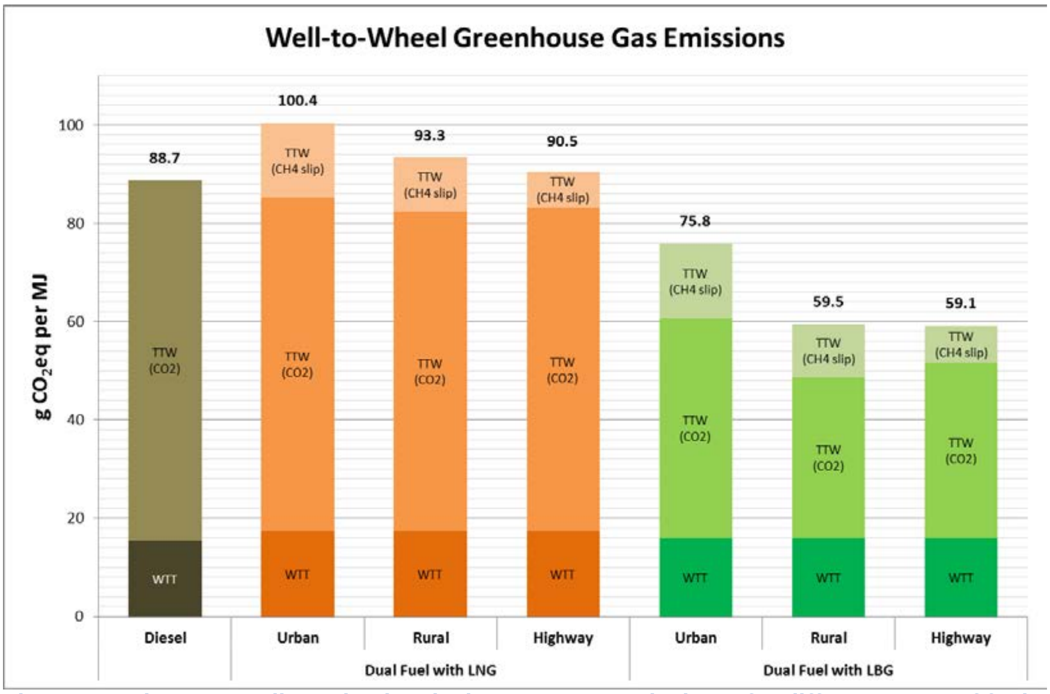

Figure 1 Figure 1. Well-to-wheel emissions as CO_2 equivalents for different types of fuels and usage.

The bottom darker parts of the bars in Figure 1 represent the well-to-tank emissions, or emissions associated with producing and transporting the fuel. For this part there are no dramatic differences between the three fuel types. The small differences between diesel, LNG and LBG relates to the energy needed for the fuel production, with LNG production being slightly more energy consuming than diesel production and LBG production somewhere in between. The technology within the truck will have no impact on this well-to-tank part, so even with an “ideal” methane engine that causes no methane slip and runs without having to blend in any diesel, the greenhouse gas reduction would be rather 80% than 100%.

The mid tank-to-wheel sections of the bars in Figure 1 (or top section for diesel) represent the CO_2 emissions form the actual combustion in the truck engine. The LNG combustion is actually slightly better than the diesel combustion in this aspect. Also the numbers get better when the truck is used for typical regional transport on highway. For LBG, these numbers are zero for the actual methane combustion, but since the substitution rate is lower than 100%, the result for dual-fuel becomes as shown in Figure 1

The top contributions are the methane slip. This depends very much on usage, and the best numbers (the lowest) are for highway driving. Methane slip with LBG is assumed to be the same as for LNG.

Local Environment and Health

The dual-fuel technology used in Volvo FM MethaneDiesel results in lower and lower NO_x emissions. For CO emissions and particular matter, it is not a clear picture. Different published research show significant reductions as well as significant increase.

Economy

With the price level of today in Sweden for LNG and LBG, the investment in a dual-fuel truck instead of a conventional diesel truck will not give a return on investment. So the motive for investing in a methane-diesel truck must be something else – presumably an environmental ambition.

Analysis

The knowledge gained in this pilot study can be summarized as follows.

- As for fighting the global warming problem
  - LBG is much better than diesel,
  - LNG ≈ diesel. (They are both fossil.)
- As for influence on local environment, NO_x emissions are reduced compared to pure diesel drive.

For CO emissions and particles, the effects of dual-fuel drive are more uncertain. If however the methane-diesel trucks are used mainly for regional transport and not for local transport in the city, then these emissions will not be the main issue.

Finally it must be noted that dual-fuel technology is still developing. Major improvements in substitution rate and decrease or elimination of methane slip are expected in the near future. Figure 2 gives a sneak peek of what might be expected from the future as technology is further developed.

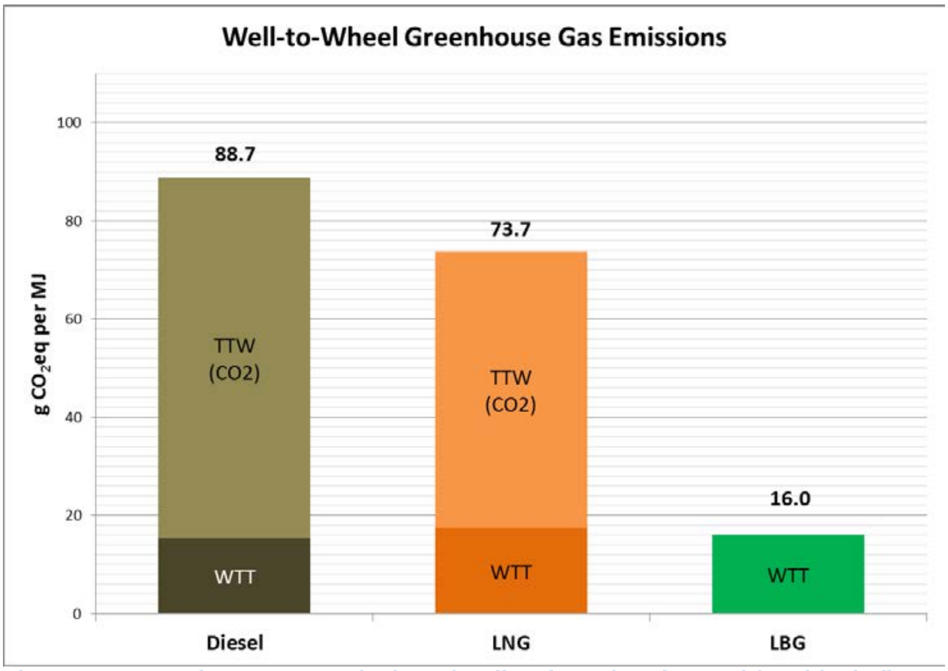

Figure 2 Greenhouse gas emissions for diesel combustion and for "ideal" (hypothetical) combustion of LNG or LBG without methane slip and disregarding the need for blending in diesel in dual-fuel technology, i.e. 100% substitution rate.

Recommendations

It is recommended that PostNord use their methane-diesel trucks for longer regional transports when possible. The environmental gains will then be greater compared to for local distribution. It is also vital that as much LBG as possible is used in favor of LNG. Today when filling liquefied gas at the FordonsGas station located at Stigs Center in Gothenburg, their "BiGreen" fuel contains 50% LBG, and therefore the greenhouse gas emissions are decreased by approximately 20%.

Also for environmental reasons it is recommended that other transport companies follow the example of PostNord and make use of dual-fuel technology together with biofuel. In long term, if the technology is being further developed and the LBG supply is increased, this will enable substantial decrease of greenhouse gas emissions.

For the methane-diesel truck to be a "green vehicle", it needs to be fuelled with LBG. LNG may be an "alternative" fuel in some sense, but it is still a fossil fuel. A recommendation to politicians is to use their available control mechanisms to favor biofuels. For LBG to make a breakthrough on a larger scale, it needs to be an attractive alternative also economically, not only for environmental reputation.

Biogas needs to become cheaper than fossil gas. In Sweden today, it is actually the opposite[1] due to higher production cost for biogas compared to natural gas. A taxation policy that favors LBG over LNG is needed.

[1] FordonsGas charges more for their product ”Grön100”, which is 100% renewable, than they charge for their standard methane gas, which is a bit over 50% renewable.

Acronyms

AVL – Anstalt für Verbrennungskraftmaschinen List
AR4 – Fourth Assessment Report (from IPCC)
AR5 – Fifth Assessment Report (from IPCC)
CAN – controller area network, a vehicle bus standard for data communication
CAP – Clean Air power
CDE – carbon dioxide equivalents
COP – Conference of Parties (of UNFCCC)
CO_2eq –carbon dioxide equivalents
DEP – diesel exhaust particles
DME – dimethyl ether
DPM – diesel particulate matter
Defra – Department for Environment Food & Rural Affairs (UK)
ECU – engine control unit
EMS – European Modular System
ETC – European Transient Cycle
GHG – greenhouse gas
GPRS – General Packet Radio Service
GREET – the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (US)
GTP – global temperature potential
GWP – global warming potential
HCT – high capacity transport (utilizing longer and heavier vehicles)
HCTC – high capacity transport corridor (mentioned in GreCOR application)
HPDI – high-pressure direct injection
HVO – hydrated vegetable oils
ILCD – life cycle impact assessment
IPCC – Intergovernmental Panel on Climate Change
IR – infrared
ITS – Intelligent Transport System
JEC – a research collaboration between JRC, EUCAR and Concawe
JRC – Joint Research Centre (EC)
LBG – liquefied biogas
LCA – life cycle assessment
LHV – lower heating value
LNG – liquefied natural gas
MTC – Motortestcenter (part of AVL)
PAH – polycyclic aromatic hydrocarbons
PEMS – portable emissions measurement system
PM – particulate matter
RED – Renewable Energy Directive (EU)
ROI – return on investment
SGS – Svenskt Gastekniskt Center
TTW – tank-to-wheel
TNO – Toegepast Natuurwetenschappelijk Onderzok (Applied Scientific Research) (Netherlands)
UNFCC – the United Nations Framework Convention on Climate Change
VAT – value added tax
VCA – Vehicle Certification Agency (UK)
WHVC – World Harmonized Vehicle Cycle
WTT – well-to-tank
WTW – well-to-wheel

Explanations

AVL – an Austrian automotive research institute

AVL MTC Powertrain Engineering Scandinavia – Scandinavian subdivision of AVL

BiGreen – a liquefied gas fuel mix provided by FordonsGas, consisting of 50% LNG and 50% LBG

carbon dioxide equivalents – (for a gas) the amount of CO_2 that would have the same GWP

Clean Air Power – a company specializing on dual-fuel technology

dual-fuel mode – when the vehicle is running on a mixture of diesel and liquefied gas (LNG or LBG), as opposed to when it is running on pure diesel

dual-fuel technology – technology for running a diesel engine on a mixture of diesel and liquefied gas (LNG or LBG

E.ON – a Swedish energy company that offers gas and biogas but not yet liquefied gas.

ETC test cycle – a test cycle for emission certification of heavy-duty diesel engines in Europe

FIGE – a former German institute

FIGE Cycle – a transient vehicle testing cycle, today replaced by the ETC test cycle

FordonsGas – a Swedish company with methane gas filling stations, either compressed or liquefied, either natural gas or biogas or a combination

GPRS – a standard for sending messages via 2G or 3G cellular communication

Grön100 – a compressed gas fuel provided by FordonsGas, consisting of 100% CBG

MethaneDiesel – a label used by Volvo on their trucks that are adapted to be (partly) driven on LNG or LBG

portable emissions measurement system – a lightweight 'laboratory' used to test or assess emissions from e.g. trucks for the purpose of compliance

methane-diesel truck – in general terms, a truck with dual-fuel technology as e.g. Volvo FM MethaneDiesel

PostNord – a provider of communication and logistics to, from and within the Nordic countries, a result of a fusion between the national postal services of Sweden and Denmark

replacement rate – substitution rate

substitution rate – how much of the diesel that is substituted for methane gas in the combustion

TNO – a Dutch organization for independent research

Westport – a company working with combustion technology such as dual-fuel technology

Links

AVL – www.avl.com
Carrera – www.carrera-toys.com
Clean Air Power – www.cleanairpower.com
Concawe – www.concawe.eu
Defra – www.gov.uk/government/organisations/department-for-environment-food-rural-affairs
EMS – www.modularsystem.eu
E.ON – www.eon.se
FordonsGas – www.fordonsgas.se
GreCOR – www.grecor.eu
GREET – https://greet.es.anl.gov/
Interreg IVB North Sea Region – www.northsearegion.eu
IPCC – www.ipcc.ch
JEC – http://iet.jrc.ec.europa.eu/about-jec
JRC – https://ec.europa.eu/jrc
TNO – www.tno.nl
VCA - www.vca.gov.uk
Westport – www.westport.com
World Harmonized Vehicle Cycle (WHVC) – www.diesel.com/standards/cycles/whvc.php

Content

GreCOR – Green Corridor in the North Sea Region

GreCOR – Green Corridor in the North Sea Region – is an Interreg IVB North Sea Region project that started 1 January 2012 and will end in June 2015. GreCOR promotes the development of a co-modal transport corridor in the North Sea Region. Important in this collaborative approach, is the that the focus is not only on the corridor itself, but also on secondary networks and the hubs, and the regional hinterland around the Green transport corridor between Oslo and the Randstad area (Amsterdam, Rotterdam, The Hague and Utrecht).

GreCOR has 13 partners and a total budget of 3.7 M€. The overall aim is to improve knowledge about the logistic needs and conditions and develop a strategy for the further promotion of environmentally friendly transports in the corridor. GreCOR focuses simultaneously on infrastructure and logistics for "greening" of transport and to make the region more competitive. The activities in GreCOR and the strategy will be a contribution to the EU objectives for transport as expressed in the White paper from 2011 "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system"

The work in GreCOR was performed in seven work packages. More information at: www.grecor.eu

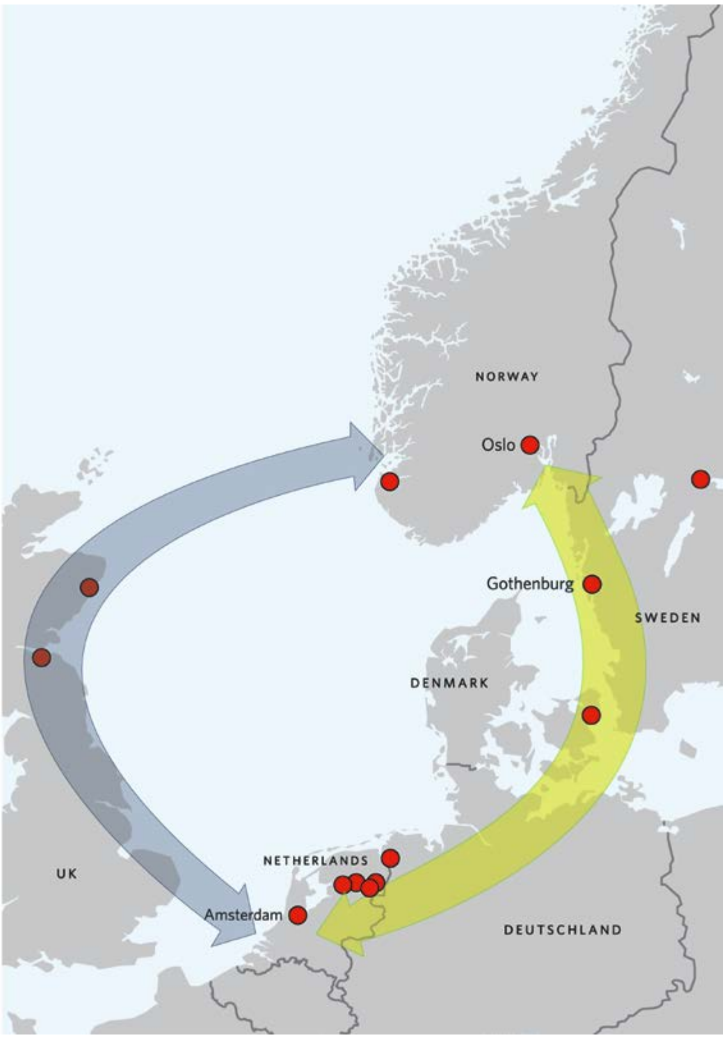

Figure 2. Map of the Corridor including locations of all project partners.

Introduction to Liquefied Gas Pilot

Natural gas is an often proposed alternative to oil based fuels for use in combustion engines. It is considered the least environmentally harmful fossil fuel, since it has the lowest levels of CO_2 emissions per unit energy. Natural gas may be converted into liquid form for ease of transport and storage. It is then called LNG for liquefied natural gas. The main component of natural gas is methane.

Biogas is another alternative fuel, which is also a gas mixture of mostly methane. It is produced from regionally available raw materials such as recycled waste. If biogas is used as a fuel, then the CO_2 emissions from the combustion are part of a natural circulation and the net carbon footprint may be reduced to close to zero – not counting the CO_2 emissions from producing the biogas. Liquefied biogas is referred to as LBG.

Volvo has in its product range a truck model that can be fuelled with LNG or LBG. It is named Volvo FM MethaneDiesel and it is driven on a mixture of diesel and gas. The dual-fuel technology in these trucks is supplied by a company called Clean Air Power. In this study two such vehicles owned by PostNord Logistics are used for evaluating the environmental impact from using natural gas as a fuel for heavy duty transport.

Background

The topic for work package 7, activity 5, is to test, verify and evaluate high capacity transport concepts that will make long distance road transport more sustainable. One of the concepts is the use of methane-diesel driven trucks.

The term HCTC for High Capacity Transport Corridor is mentioned in the project application, and it is here used in a very wide sense that includes not only longer and heavier vehicles (EMS) but also intelligent transportation systems (ITS) and the use of alternative fuels. (The term HCT for High Capacity Transport normally refers strictly to the introduction of longer and heavier vehicles and will not be used in this report.)

Purpose & Aim

The purpose of the study was to answer to the following two questions:

1. What is the environmental and economic impact of using methane-diesel vehicles compared to conventional diesel propulsion?
2. What is the recommendation to PostNord for how to get the most value out from their methane-diesel trucks?

Theory

Natural Gas and Biogas as Vehicle Fuel

Natural gas is often proposed as a future more environmentally friendly fuel alternative to diesel. It consists primarily of methane and it is considered to cause less CO_2 emissions than other fossil fuels. Before being used as a fuel, it is either compressed to CNG (compressed natural gas) or cooled down to liquid form, LNG (liquefied natural gas). There are a number of technologies for running vehicles on CNG or LNG or in different combinations with gasoline/petrol or ethanol, but in general CNG is only used together with otto technology, i.e. an engine normally running on gasoline/petrol, typically a (bi-fuel) automobile or a city bus or a truck used for shorter missions, whereas LNG is a viable alternative for use in a more efficient diesel engine, though not in pure form, as will be explained below.

Another advantage with LNG compared to CNG, is that it obviously takes less space for the same amount of energy. Otherwise it would not be an alternative for long-haul transport. The fact that LNG doesn't take up much space makes it ideal for distributing to far away filling stations without too much infrastructure (i.e. without pipelines).

One concern with LNG is that it needs to be used while it is still cold. It works best for trucks that are continuously used and refilled with LNG on a daily basis. This ensures that not too much of the LNG has gone over to gas form. If it takes longer between refills, then the process for filling LNG gets more complicated and takes more time (see Appendix B), because then gas has to be taken out from the truck tank at the same time as being filled with liquid.

An alternative to natural gas is biogas, which also consists primarily of methane. Biogas is produced by the breakdown of organic matter in the absence of oxygen, from regionally available raw materials such as recycled waste. If biogas is used as a fuel, then the CO_2 emissions from the combustion are part of a natural circulation and the net carbon CO_2 emissions from that part are therefore zero. The production of the biogas will cause some CO_2 emissions that cannot be neglected, but in total the carbon footprint will be much lower compared to fossil natural gas.

The biogas is either compressed to CBG (compressed biogas) or cooled down to LBG (liquefied biogas). It can then be used in exactly the same way as CNG and LNG. One way of making use of biogas is that LNG can be blended in with LBG. As an example the Swedish gas supplier FordonsGas has a product named BiGreen, which consists of 50% LNG and 50% LBG.

Methane-Diesel Propulsion

Diesel engines work on the principle of compression ignition. Air is first drawn into a cylinder where it is highly compressed – far more so than in a petrol/gasoline engine. It is this high 'compression ratio' that makes a diesel engine more efficient than its counterpart. Diesel fuel is injected into the cylinder at high pressure, near the point of maximum compression. The combination of diesel fuel, and heated compressed air within the cylinder, results in ignition. The fuel and air combination burns rapidly, increasing pressure and temperature, driving the piston back down the cylinder with great force. This sudden release of energy generates the power of the engine.

As mentioned above today's technology for using LNG in a diesel engine means running the engine on a mixture of diesel and LNG, thus it is named *dual-fuel* technology, and you are driving either in dual-fuel mode or in pure diesel mode. With CAP dual-fuel technology there is no change to the basic architecture of the diesel engine – or to the principle of diesel combustion. The engine itself is virtually unaltered, except for the addition of a gas injection system and an externally-fitted ECU. The dual-fuel in-cylinder temperatures and pressures remain within the limits of pure diesel operation, so the converted engine operates within the normal range of the original engine. In a dual-fuel engine, however, the diesel fuel injector works like a liquid spark plug. Highly pressurized, it ignites a mixture of compressed gas and air in the cylinder. Tests have shown that the addition of dual-fuel components do not affect the base engine's robustness or durability. Tests performed in a single cylinder test engine at Volvo [1] indicate a factor 0.98 lower efficiency compared to conventional diesel combustion.

Greenhouse Gas Emissions

Greenhouse gases (GHG) are gases that absorb and emit thermal radiation, also called heat radiation, i.e. electromagnetic radiation within the infrared (IR) range. They contribute to global warming by absorbing heat radiation from the Earth that would otherwise have been emitted into space, and some of that is then radiated back to Earth's surface, see

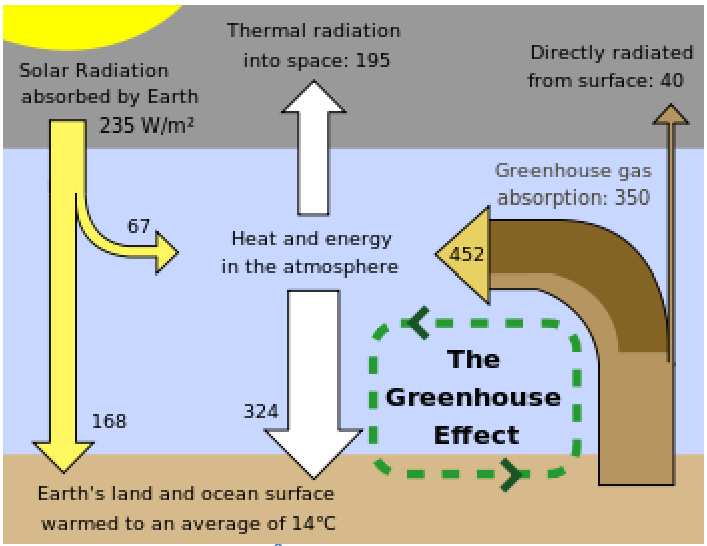

Figure 3 Heat energy flows [W/m^2] between space, atmosphere and Earth's surface. (Picture stolen from Wikipedia)

Without the greenhouse gases the average surface temperature on Earth would have been 33˚C lower, so they are necessary for life on Earth as it is today, but with too high concentrations of greenhouse gases the Earth will get warmer than today and there will be environmental consequences such as rise in sea levels. Burning of fossil fuels comes with emission of carbon dioxide and other greenhouse gases. This and also clearing of native forests have led to a 40% increase of carbon dioxide in the atmosphere today compared to when the industrial revolution started about 250 years ago.

Politics

Today there is a political movement to fight the global warming problem. The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty first signed in Rio de Janeiro in 1992. Its objective is to stabilize greenhouse gas concentrations at a level that will avoid harmful human impact on the Earth's climate. UNFCC today has 196 parties, who have met annually since 1995 in Conference of the Parties (COP). In 2010 an agreement was made that global warming should be limited to 2.0˚C above the pre-industrial level. Suggestions have been made to lower this limit to 1.5˚C at the 2015 COP.

The Intergovernmental Panel on Climate Change (IPCC) is a scientific association within the UN that produces reports to the UNFCCC. IPCC does not carry out research on its own but does assessment on published literature from thousands of scientists and other experts. The latest assessment was the Fifth Assessment Report (AR5) was completed in 2014.

Global-Warming Potential

The global-warming potential (GWP) is a relative measure of how much heat is trapped in the atmosphere due to a certain greenhouse gas. Carbon dioxide is chosen as the reference, so for carbon dioxide GWP is set to 1. For other gases the GWP is defined as the ratio of how much heat is trapped by a certain gas in relation to how much would be trapped by an equal mass of carbon dioxide. Since the rate of chemical breakdown is very different for different substances, this ratio is different depending on the time horizon. For instance methane has an atmospheric lifetime of only 12 years (i.e. half-life of $12 \ln(2) \approx 8$ years), and the global-warming potential (under certain assumptions) is 84 over a 20 year period and 28 for 100 years.

In this pilot values for a 100-year period are used, as this is commonly used in LCA studies and recommended in the ILCD handbook [2]. In Table 1 below global warming potentials over 100 years are given for three exhaust gases that need to be considered when dealing with methane-diesel trucks.

Table 1 Global warming potential for exhaust gases.

Exhaust gas	GWP (100 years)
carbon dioxide, CO_2	1
methane, CH_4	28
nitrous oxide, N_2O	265

The values in Table 1 are taken from AR5 [3].

Methane Slip

Methane slip corresponds to an incomplete combustion of methane in the cylinders of the engine, releasing methane on the exhaust side. Recently it has come to knowledge that the methane slip is more significant than was earlier believed. Since methane has a much higher global warming potential, see Table 1, it only takes a small amount of methane slipping through the combustion to outweigh rather big CO_2 reductions.

Pollutant Emissions

Exhaust from diesel combustion contains a number of substances that have environmental effects such as acidification and health consequences such as asthma or lung cancer. Motor vehicle emissions are a major contribution to the smog problem in some larger cities. A few of the more important diesel exhaust gases are listed in Table 2 below.

Table 2 A range of diesel combustion emissions, regulated emissions in bold.

Emissions		Examples of environmental or health proplems
Mono-nitrogen oxides	**NO_x**	acidification, eutrophication, toxic if inhaled
Carbon monoxide	**CO**	toxic, inhibits oxygen feed
Hydrocarbons	**HC**	toxic if inhaled or ingested
Nitrous oxide	N_2O	vitamin B12 deficiency
Aldehydes	R-CHO	toxic, contribute to smog
Ammonia	NH_3	eutrphication, toxic to aquatic animals
Polycyclic hydrocarbons	PAH	carcinogenic, mutagenic, teratogenic (for some PAHs)

Particulate Matter (PM)

Airborne particular matter is known to cause health problems such as asthma and lung cancer. Diesel particulate matter (DPM) consists of soot (or soot nanoparticles) and aerosols. Soot is impure carbon particles resulting from incomplete combustion of hydrocarbons, e.g. diesel. The term aerosol includes both fine solid particles and liquid droplets. See a comparison of a number of particular matters in Figure 4 below.

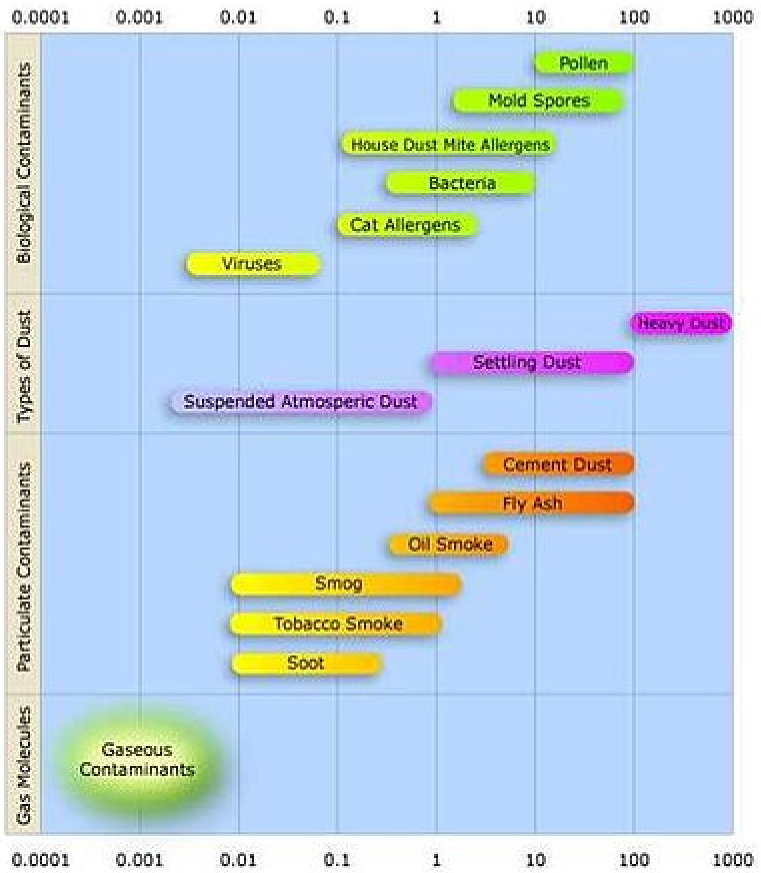

Figure 4 Examples of particular matter and size distribution in micrometers. (Picture stolen from Wikipedia)

Globally particular matter caused by human activities are minor (10%) compared to natural particular matter, but since the higher concentrations tend to be in congested area, they still cause a significant amount of health problems. Diesel particular matter is linked to heart and vascular problems.

Climate Effects

Particular matter also has an effect on the Earth's climate by changing the amount of incoming solar radiation. Aerosols seem to have a cooling effect on the atmosphere, but the uncertainties in these predictions are very large at the moment. Figure 5 illustrates the effect in relation to other factors that have an effect on Earth's climate.

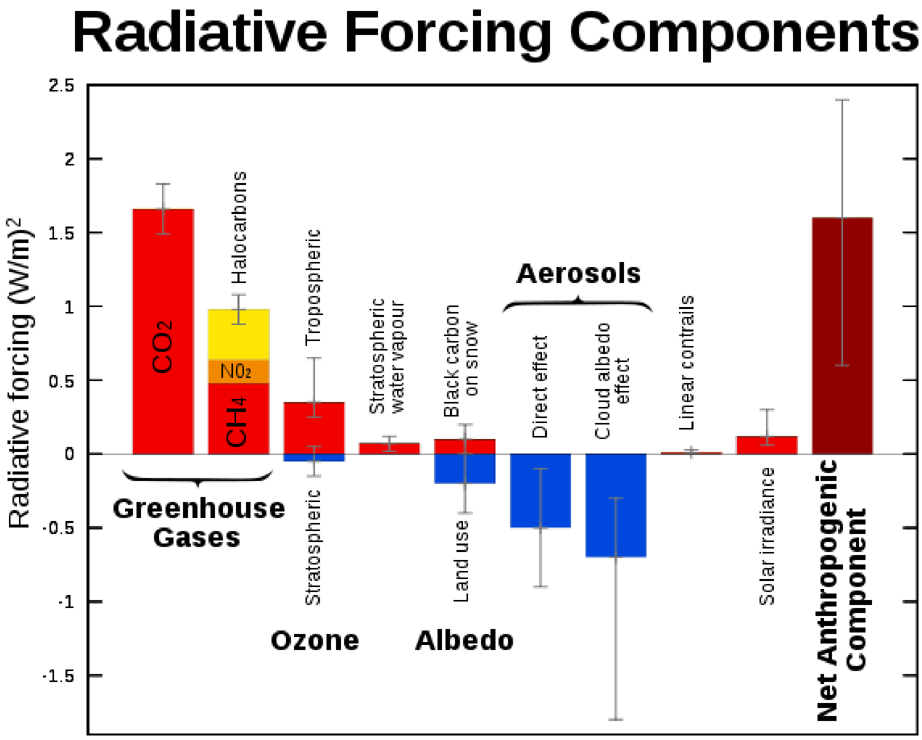

Figure 5 Radiative forcing components as estimated by the IPCC in 2005. (Picture stolen from Wikipedia)

By radiative forcing is meant the difference between the solar irradiation absorbed by the Earth and the energy radiated back to space is called the radiative forcing or climate forcing. The total solar radiation received on a given surface is called solar irradiation or insolation (not the same as insulation). It may be expressed as a power [W/m2] or integrated during a given time period and then expressed as an energy [MJ/m2], e.g. "daily radiation" if recorded during a day.

Life-Cycle Assessment (LCA)

Life-cycle assessment is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e. from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling).

Well-to-wheel (WTW) is the specific life-cycle assessment used for transport fuels and vehicles. The analysis is often broken down into the stages entitled well-to-tank (WTT) and tank-to-wheel (TTW). The first stage, which incorporates the feedstock or fuel production and processing and fuel delivery or energy transmission, and is called the "upstream" stage, while the stage that deals with vehicle operation itself is sometimes called the "downstream" stage. The whole chain then is called well-to-wheel (WTW).

Properties of Fuels

Fuel conversions in this report will be based on heat of combustion (ΔH_c°), which is the energy released as heat when a compound undergoes complete combustion with oxygen.

It may be expressed for instance per mass of fuel, and it may be called heating value, energy value or caloric value. The heat of combustion for fuels is expressed as either of higher heating value (HHV) or lower heating value (LHV). These concepts are related, and the difference between them will not be explained here, but in this the report the LHV values will be used for comparing energy content between fuels. This is the measure used by JRC [4], see Table 3 further down.

The energy contents of natural gas and biogas may vary a little depending on the origin of the gas, and depending on source of information, we get slightly different numbers. Below both calculations based on JRC data and data from FordonsGas are presented for comparison. The analysis in this report will then be based on the FordonsGas data.

Energy Content according to JRC

From JRC [4] and by assuming LNG to have the same lower heating value and CO_2 emissions as CNG has, we get fuel properties according to Table 3 below.

Table 3 Density, energy content and tank-to-wheel CO_2 emissions per unit of fuel.

Fuel	Density	LHV	CO_2 emissions	
	kg/dm^3	MJ/kg	kg per kg fuel	g per MJ fuel
LNG	(0.41 to 0.50)	45.1	2.54	56.3
Diesel	0.832	43.1	3.16	73.3

(Density for LNG varies depending on temperature and will not be needed for the analysis in this report.)

Using the data of Table 3, it can be concluded that 1 kg LNG gives the same energy as 1.05 kg diesel, which is identical to 1.26 l diesel, and we get the following conversion factors:

- 1 kg LNG ↔ 1.26 l diesel
- 1 l diesel ↔ 0.79 kg LNG

Energy Content according to FordonsGas

From FordonsGas (see Appendix A), we have energy contents according to Table 4 below.

Table 4 Energy content for LNG, LBG and diesel fuels.

Fuel	Energy content
LNG	13.7 kWh/kg
LBG	13.5 kWh/kg
Diesel	9.8 kWh/l

The data in Table 4 gives conversion factors as follows:

- 1 kg LNG ↔ 1.40 l diesel
- 1 kg LBG ↔ 1.38 l diesel
- 1 l diesel ↔ 0.72 kg LNG ↔ 0.73 kg LBG

When calculating the carbon footprint for driving on FordonsGas' BiGreen fuel, the paid for content of 50/50 LNG/LBG will be assumed, but when comparing fuel consumption and economy to diesel, the actual content of 100% LBG in BiGreen will be assumed.

Energy Content according to CAP

The logging system from Clean Air Power (CAP) measures the consumed fuel of both diesel and liquefied gas. The system also takes care of recalculating the measurements into liters of diesel equivalents. Their calculations are based on the assumption that 0.72 kg LNG has the same caloric value as 1 liter of diesel, and no compensation is made for if the LNG is replaced by LBG, thus

- 1 l diesel $\leftrightarrow$ 0.72 kg LNG $\leftrightarrow$ 0.72 kg LBG

Assessments of Investments

Suppose a certain investment I is meant to generate yearly earnings or savings x during a period of n years after the investment is made. Then for a certain cost of capital, or imputed rate of interest, denoted i, the present value PV of these earnings or savings then is

$$PV = x\left(\frac{1}{(1+i)} + \frac{1}{(1+i)^2} + \ldots + \frac{1}{(1+i)^n}\right).$$

If $PV \geq I$, then the investment can be considered as profitable. This is one way of deciding whether an investment seems to be sound or not, and it is this method that will be used in this report when judging under which circumstances the investment in a methane-diesel truck will pay off.

Methodology

Both data collection and a literature study were carried out. Impact on greenhouse gas emissions was studied mostly by analyzing measurements, whereas the learnings about other emissions and particulate matter came from studying published material.

Data Collection

Two Volvo MethaneDiesel trucks owned by PostNord Logistics were used for the investigation (see Appendix B). Volvo installed a logging system from Clean Air Power (CAP) (see Appendix C) and the two trucks were observed while in normal service.

Experimental Design

No actual experiments were designed; the test objects were studied while in normal service. However, in order to get reference data, a portion of the measurements were collected while the truck was forced to drive in pure diesel mode. Normally this was done by letting one truck drive on dual-fuel and the other one on pure diesel and switching turns every week.

Literature Study

A literature study was carried out with the aim of finding information of tailpipe emissions, other than carbon dioxide. A number of other emissions are present in the exhaust, which can be measured using e.g. portable emissions measurement systems (PEMS). Other studies [5] [6] [7] [8] [9] have been made aiming at measuring and analysing dual-fuel exhausts. These studies have been reviewed and data from the most interesting studies [5] [8], in terms of similarities with this pilot, are presented in the Result chapter of this report.

In this chapter data found in literature on TTW emissions, other than carbon dioxide and methane, are presented. The data is from tests described in two reports: TNO 2013 R11367 [5] and AVL MTC REPORT OMT 1032 [8]. These tests were selected based on similarities with the PostNord Logistics truck tests; they are on-road tests (in contrast to e.g. engine dynamometer tests) and the truck uses the CAP dual-fuel system.

In Table 5 the relevant tests made in these two studies are summarised:

Table 5 Overview of TNO report [5] and AVL MTC report [9].

Report	TNO 2013 R11367	AVL MTC REPORT OMT 1032
Title	On-road emission measurements with PEMS on a Euro V heavy-duty truck with an OEM dual-fuel	Enhanced Emission Performance and Fuel Efficiency for HD Methane Fuelled Engines
Truck model	Volvo FM460	Volvo
Type/configuration	Tractor (4x2) + semi-trailer	Tractor + semi-trailer
Emission standard	Euro V	Euro V
DF system supplier	Clean Air Power (CAP)	Clean Air Power (CAP)
Type of tests	On-road emission tests with PEMS	On-road emission tests with PEMS
Fuel used	EN590 diesel + LNG	MK 1 diesel + LBG

In the TNO study [5], two different trips were driven: the TNO reference trip for heavy-duty vehicles and the Euro VI N3 trip as required according to EU legislative specifications for testing in-service conformity. The TNO reference trip was driven with different test weights. In the AVL MTC study [8], two test trips were driven: one in the

Gothenburg area and one in the Stockholm area. A summary of the tests is given in Table 6.

Table 6 Overview from tests in TNO report [5] and AVL MTC report [8].

Test ID	Weight tonne	Urban %	Rural %	Highway %	Trip dist. km	Average subst. rate %
TNO, HD ref. trip	19,8	*	*	*	-	43
TNO, HD ref. trip	29,9	*	*	*	-	56
TNO, HD ref. trip	39,9	*	*	*	-	57
TNO, Euro VI N3	29,9	20**	25**	55**	-	51
AVL MTC,	40	38	22	40	220	61
AVL MTC, Stockholm	20	43	17	40	77	***

*) Data is not given in report, but the trip is aimed to "represent typical Dutch urban, rural and motorway conditions".

**) According to Euro VI N3 trip specifications.

***) Data is not given in report.

All the tests were driven both with the engine in diesel mode, using only diesel, and in dual-fuel mode. The average substitution rates calculated for the tests, when driving in dual-fuel mode, are similar to the substitution rates in the PostNord truck tests, ranging from around 40% to around 60%, as can be seen in Table 6 above.

Economical Investigation

When judging the economy for investing in a methane-diesel truck, the following assumptions will be used as a starting point:

- Investment cost: 400,000 SEK
  (the additional cost for having a truck adapted to methane-diesel propulsion)
- Time of ownership by PostNord: 10 years
- Total distance run during ownership: 1,200,000 km
- Price diesel: 13.27 SEK/l (gross)
- Price LNG: 17.90 SEK/kg (gross)

Fuel gross prices are according to FordonsGas, www.fordonsgas.se, to date December 1st of 2014. Swedish value added tax (VAT) is 25% of net value. The net prices then become

- Price diesel: 10.62 SEK/l
- Price LNG: 14.32 SEK/kg

Using the energy content information from Table 3, the LNG price can be expressed as:

- Price LNG: 10.40 SEK per l diesel eq.

Thus, with the prices of today, LNG (or LBG) is actually only insignificantly cheaper than diesel, and calculation of return on investment will not be meaningful.

Field studies

In order to see how the methane-diesel trucks functioned in real operation, we went along as passengers on a couple of transport missions. To these occasions we also brought a questionnaire that was used as a basis for interviewing the drivers, see Appendix D.

Results

Substitution Rate

Test results have a strong connection to usage of the trucks. Substitution rates are typically higher for long drives at higher speed with warmer engine and higher power output. The opposite, with lower substitution rates, goes for shorter drives at lower speed, typically in the city. We therefore did a classification of measurements from transport missions according to average vehicle speed. Also, to avoid side effects from when the LNG tank is running low and the truck may be in pure diesel mode, only measurements from when the LNG tank was at least 20% full were kept. The resulting average substitution rate is presented in Table 7.

Table 7 Substitution rate depending on usage.

Average vehicle speed	Category	No. of trips	Total distance		Substitution rate
km/h			km	%	%
below 40	"Urban"	141	1118	12%	40
40 to 70	"Rural"	112	4399	46%	56
above 70	"Highway"	64	3972	42%	52
Overall:		317	9489	100%	53

The three different vehicle speed ranges will be categorized “urban”, “rural” and “highway” as in Table 7 throughout the rest of this report, regardless of the actual route. This is a simplification. Hopefully it will not distort any results in a way that makes the analysis more uncertain.

When calculating the overall substitution rate, the total liquefied gas consumption for all trips was compared to the total fuel consumption for all trips.

Carbon Footprint

Well-to-Tank

The well-to-tank studies include all known greenhouse gas emissions for extracting and getting the fuel ready at the filling station. A comparison between diesel, LNG and LBG is illustrated in Figure 6 below.

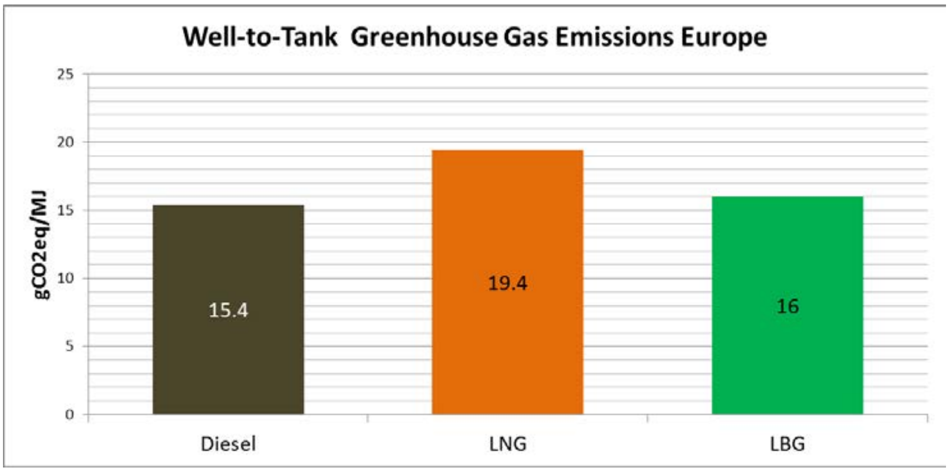

Figure 6 WTT greenhouse gas emissions according to JRC study [10] for Europe.

From JRC [11] we have the level for the diesel fuel and LNG. Well-to-tank emissions for LBG can be very different depending on raw material and pathway used. Here we will use the value 16 g CO_2eq per MJ, which is according to RED methodology for CBG mentioned in JEC [10]. Figure 6 shows that WTT emissions are comparable for all three of diesel, LNG and LBG with LNG slightly higher than the other two.

Methane Slip

Based on a TNO report [5], the levels of methane slip were estimated according to Table 1 below.

Table 8 Methane slip according to usage of truck.

Use case	Methane Slip	
	mg CH_4 per g CO_2	g CH_4 per MJ LNG
Urban	8	0.45
Rural	6	0.34
Highway	4	0.23

Nitrous Oxide

For completeness, also the third major greenhouse gas, N_2O, should be mentioned. The SGC literature study [7] indicates N_2O emissions according to below.

Table 9 Methane slip according to usage of truck. The numbers are average values from three tests, see Figure 3 on Page 26 in the SGS report [7].

Fuel mode	N_2O emissions		
	mg/kWh	mg/MJ	g CO_2eq per MJ
Dual-fuel	26	7.3	1.9
Diesel	23	6.4	1.7

These numbers correspond to a couple of percent of the total greenhouse gas emissions measured as CO_2 equivalents, and the difference between diesel drive and dual-fuel drive is only 0.2 g CO2eq per MJ. That will not be significant when everything is added up, and therefor this contribution to total greenhouse gas emissions is left out in the well-to-wheel sum-up in Figure 4 further down.

Tank-to-Wheel

Tank-to-wheel greenhouse gas emissions are strongly connected to substitution rates, see Table 7. Given these, the TTW GHG emissions are calculated and presented in Table 10 below.

Table 10 Tank-to-wheel emissions for Europe

		Diesel	Dual-Fuel					
			Urban		Rural		Highway	
Relative efficiency		1	0.98		0.98		0.98	
Diesel usage		1	0.60		0.44		0.48	
Gas usage (substitution rate)		0	0.40		0.56		0.52	
Gas type		-	*LNG*	*LBG*	*LNG*	*LBG*	*LNG*	*LBG*
CO_2 emissions	[g/MJ]	73.3	67.8	44.7	65.0	32.6	65.8	35.7
CH_4 emissions (methane slip)	[g/MJ]	0	0.54	0.54	0.39	0.39	0.26	0.26
	[g CO_2eq/MJ]	0	15.2	15.2	10.9	10.9	7.4	7.4
N_2O emissions (laughing gas)	[mg/MJ]	6.4	7.3	7.3	7.3	7.3	7.3	7.3
	[g CO_2eq/MJ]	1.7	1.9	1.9	1.9	1.9	1.9	1.9
TTW GHG emissions	**[g CO2eq/MJ]**	**75.0**	**85.0**	**61.8**	**77.9**	**45.4**	**75.1**	**45.0**

The relative efficiency factor 0.98 for dual-fuel drive is from rig testing with a single cylinder engine at Volvo [1], as mentioned in the Theory section.

Well-to-Wheel

Summing up the two previous sections, Figure 7 is obtained.

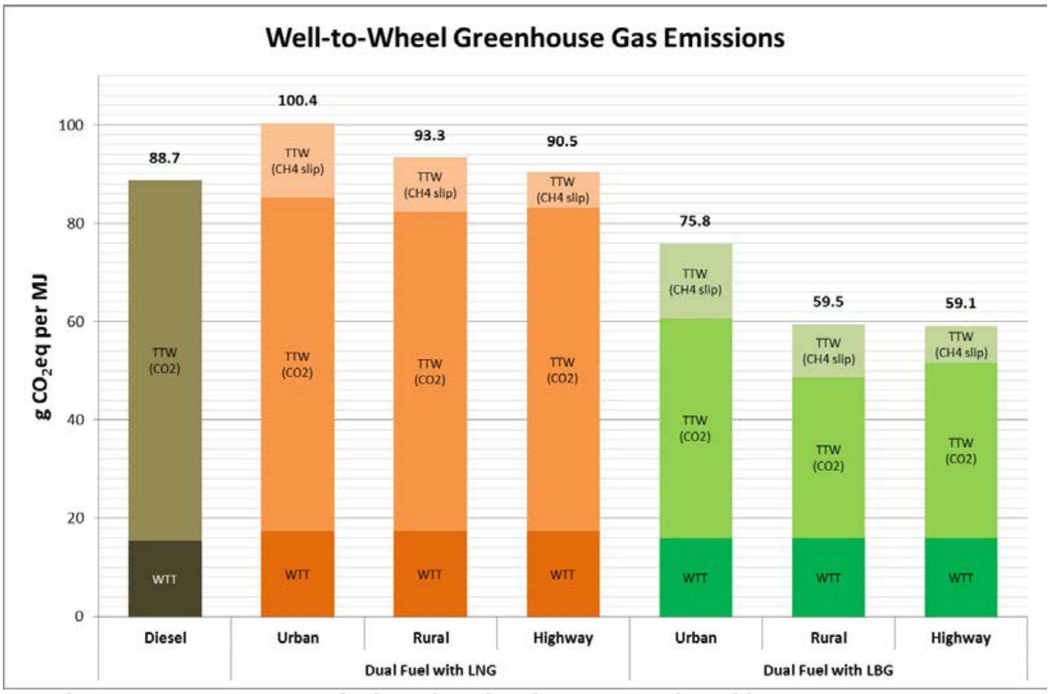

Figure 7 WTW GHG emissions for Diesel versus Dual-Fuel in Europe.

Thus, the global warming impact is similar or slightly stronger for LNG compared to diesel, as it is with the methane slip associated with the first generation dual-fuel technology of today. LBG on the other hand significantly reduces the carbon footprint and more so in use cases where the substitution rate gets higher. In other than urban (low speed) use cases, dual-fuel with LBG means a 33% reduction of the carbon footprint compared to diesel drive. Well-to-tank greenhouse gas emissions are minor compared to tank-to-wheel for diesel and for LNG, but as the tank-to-wheel figures get better for LBG the well-to-tank figures become relatively more important.

Well-to-Wheel for PostNord

To calculate the greenhouse gas emissions for the PostNord vehicles, we need to consider how they are put to use. Assuming the distribution of trip categories and substitution rates of Table 7 and the use of “BiGreen” fuel with 50/50 distribution of LNG/LBG, we get a picture as in Figure 8 below.

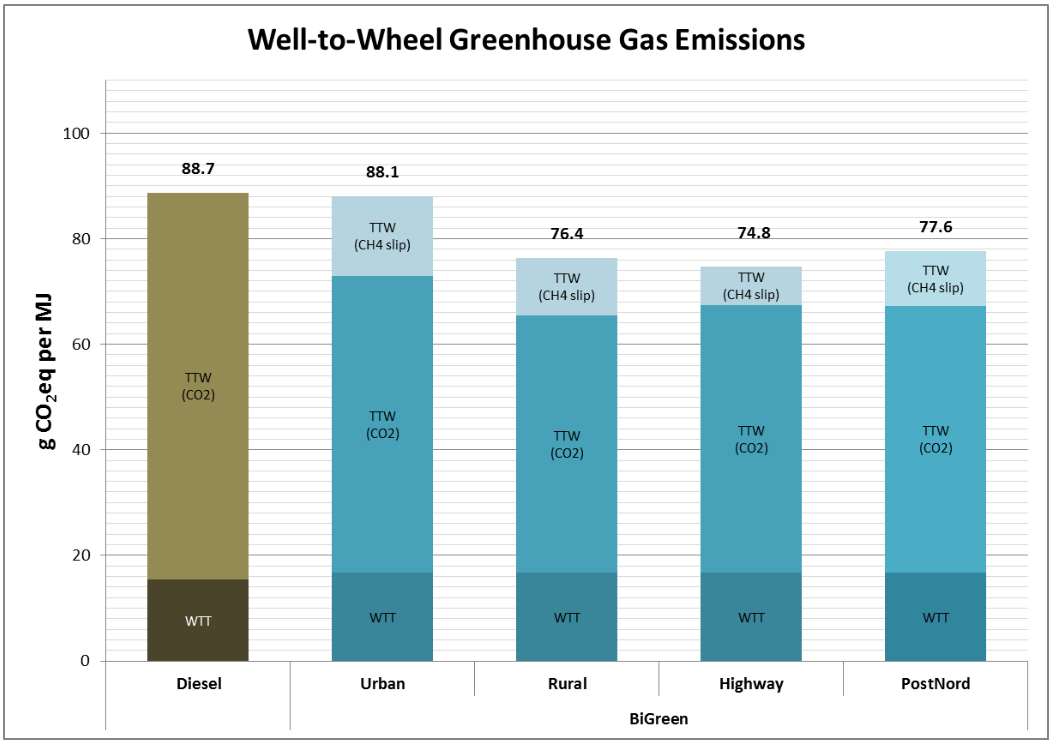

Figure 8 WTW GHG emissions for BiGreen fuel and for PostNord today.

Local Environmental Influence – Emissions and Particles

Mono-nitrogen oxides – NO_X

The resulting tank-to-wheel NO_x emissions are presented in Figure 9. For all six tests NO_x emissions are lower when driving in dual-fuel mode.

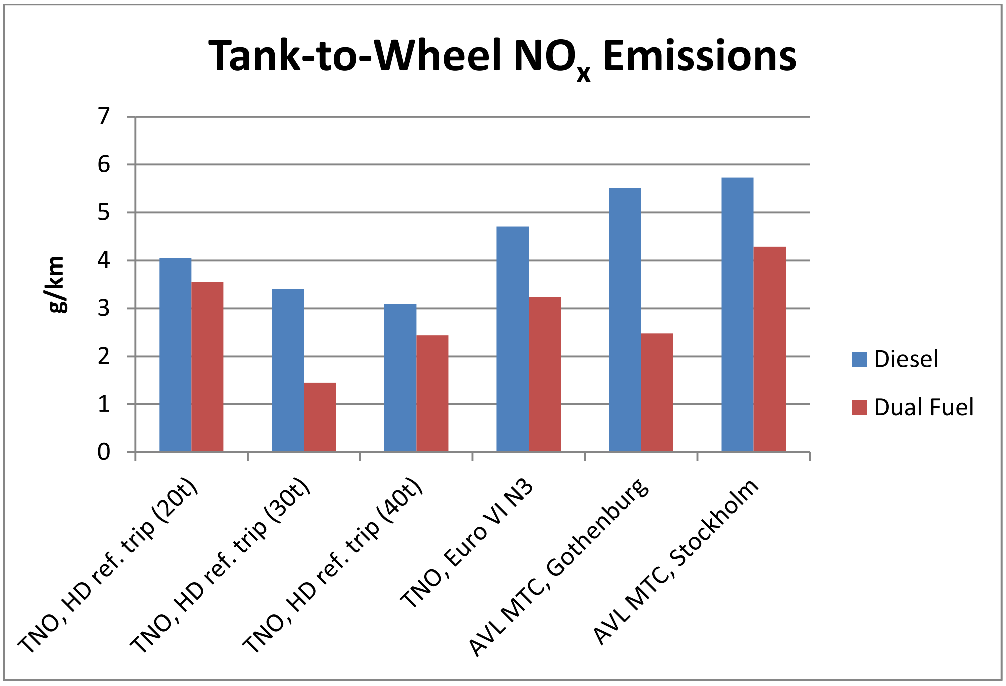

Figure 9 **Tank-to-wheel NO_x emissions.**

Carbon monoxide – CO

The CO emissions are presented in Figure 10 below.

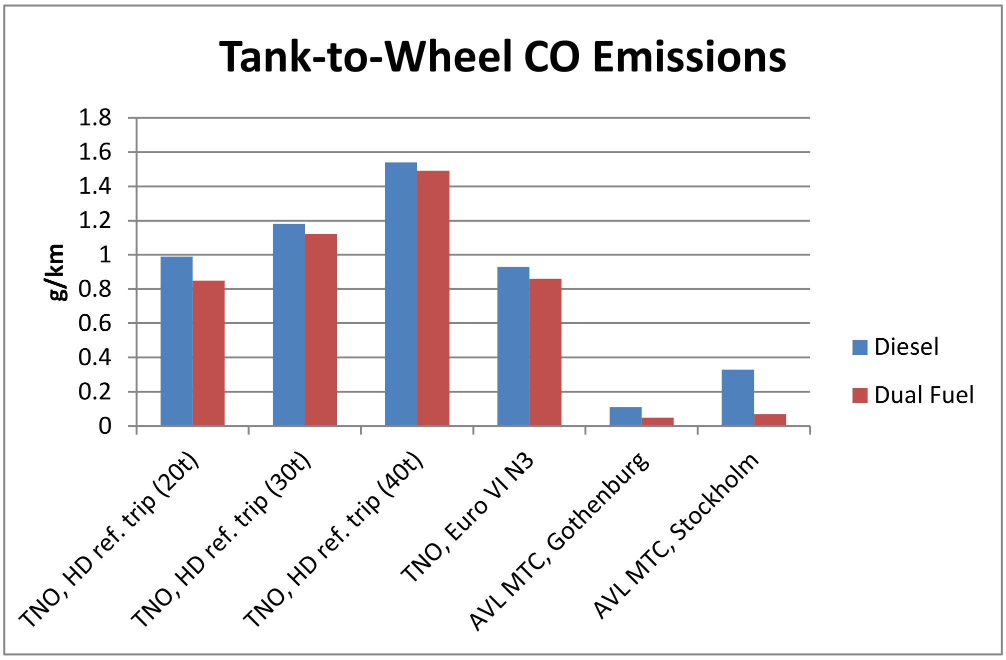

Figure 10 **Tank-to-wheel carbon monoxide emissions according to six different investigations.**

The AVL MTC tests [8] results in significantly lower CO emissions than the TNO tests [5] do, and this is independent on fuel mode. In the TNO tests the emissions are slightly lower for dual-fuel mode than for pure diesel mode. In the AVL MTC tests the emissions are significantly lower for dual-fuel. It should also here be mentioned that in one of the AVL MTC chassis dynamometer tests (FIGE test cycle) the CO emissions for dual-fuel mode was significantly higher than the CO emissions for diesel mode.

Hydrocarbons – HC

Both the TNO [5] tests and the AVL tests [8] indicate that the hydrocarbon emissions are practically zero from diesel combustion but significant for dual-fuel, see Figure 11.

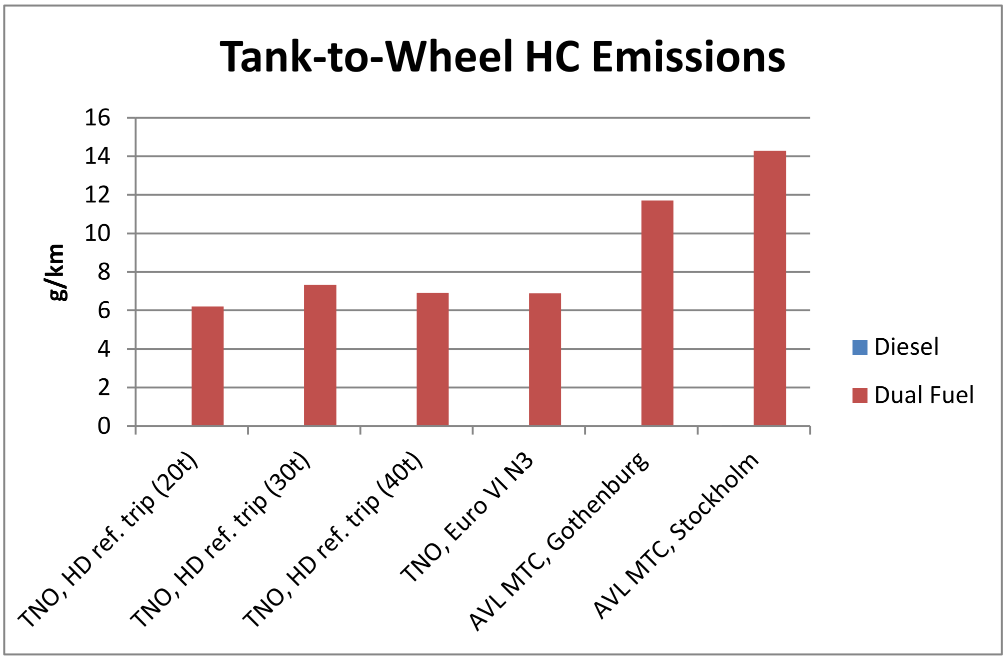

Figure 11 Tank-to-wheel carbon monoxide emissions according to six different investigations.

It is assumed that these hydrocarbons emitted from dual-fuel combustion are essentially the methane slip, which is not toxic locally, and presumably there are no significant levels of other hydrocarbons.

Particulate matter – PM

Emissions of particulate matter (PM) were only measured in the AVL MTC tests (see Figure 11).

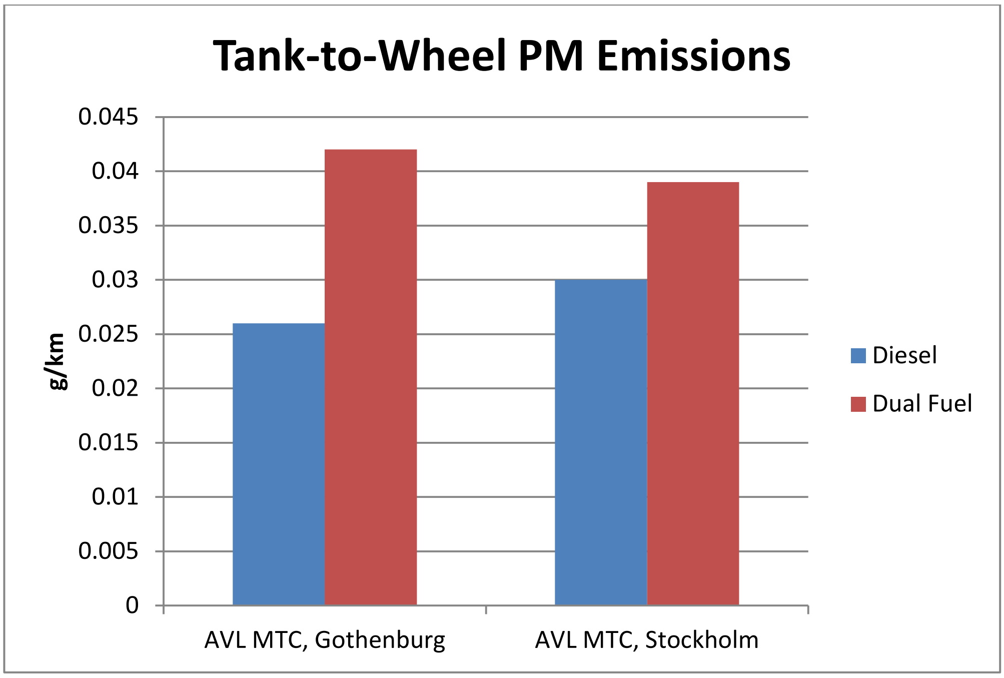

Figure 12 Emissions of particles according to two AVL tests.

For both tests PM emissions were higher when driving in dual-fuel mode. The result is not as clear as the NO_x result though. In addition to the on-road tests AVL MTC also conducted chassis dynamometer tests (using WHVC and FIGE test cycles). These tests showed a different result. PM emissions in dual-fuel mode were here lower or equal to PM emissions in diesel mode.

Relation to regulations

AVL MTC also made an attempt to relate the test results to Euro V emission limit values.

The CO emissions are well below the limit values, the difference between diesel and dual fuel in this case (Figure 10) could therefore be considered of less importance.

NO_x and PM emissions, on the other hand, are closer to the limit values.

As for hydrocarbons, there is a limit value set to 1.1 g/kWh (approx. 0.31 g/MJ) on a certain ETC [12] test cycle, but it doesn't apply to diesel nor methane-diesel vehicles, only gas vehicles. Even though the data illustrated in Table 10 comes from road tests that cannot be compared straight off with a certification cycle, it is an indication that the methane emissions could be an issue. Anyway, the general picture here is that the methane slip is not a major problem for local environment, only for global warming, which is already considered.

Unregulated emissions

In addition to the regulated emissions (CO, HC, NO_x and PM) and CO_2, a number of other TTW emissions are released. In the SGC investigation by Willner [7] several chassis dynamometer tests have been made to analyse such emissions, for a Volvo truck operated both in diesel mode and dual-fuel mode. No detailed results will be presented in this report, but some conclusions from the study could be worth mentioning:

- When the truck was operated in dual-fuel mode, the levels of formaldehyde were considerable higher compared to for diesel mode. Formaldehyde and acetaldehyde were the dominated pollutants of the aldehydes measured.

- When the engine was operating in dual-fuel mode, slightly higher levels of nitrous oxide (N_2O) compared to diesel mode could be observed, as described in Table 9.
- No emissions of ammonia (NH_3) were detected in any test.
- Emissions of polycyclic aromatic hydrocarbons (PAH) were significantly lower in dual-fuel mode. A probable explanation is higher content of PAH in diesel fuel compared to LBG.

Fuel Consumption

Fuel consumption was measured and for each trip the fuel consumption in liters of diesel equivalents is known. One problem however when comparing consumption for dual-fuel drive to consumption for pure diesel drive is that every trip is unique with different average vehicle speed, different gross weight and a different pattern of accelerations and decelerations. To really eliminate influence from such variations, we would need two trucks with exactly the same cargo going exactly the same route together. For obvious reasons this is not the case. The only possibility was to observe and measure during normal duty. Table 11 gives an overview of under what circumstances measurements have been collected.

Table 11 An overview over how a number of measures distributed on the three speed categories and also three weight categories. "Light" is for gross weight under 16.7 tonne and "heavy" means above 25.7 tonne.

		Trip distribution %			Total distance %			Total fuel consumption %			Average torque demand %			Substitution rate %		
		Light	Middle	Heavy	Light	Middle	Heavy	Light	Middle	Heavy	Light	Middle	Heavy	Light	Middle	Heavy
DF	Urban	6	22	16	1	4	6	1	4	9	23	25	38	10	39	40
DF	Rural	6	9	20	4	8	35	3	6	40	31	28	39	41	52	59
DF	Highway	1	17	2	2	33	8	1	26	8	29	30	39	54	56	38
Diesel	Urban	26	12	7	3	3	3	3	3	4	21	27	36	-	-	-
Diesel	Rural	18	7	8	11	7	14	9	6	15	26	30	36	-	-	-
Diesel	Highway	6	3	12	9	6	43	6	5	47	27	29	39	-	-	-

The thresholds for the weight categories were chosen so that one third of the data set fits in each category. As you can see, there are some noticeable differences between the data sets for dual-fuel drive and pure diesel drive. For instance 43% of the covered distance on pure diesel is with heavy load and highway speed, but only 8% for dual-fuel. Also notice the significantly higher average torque demand for dual-fuel compared to diesel for the combination light weight and rural speed. Another difference is that it seems that the trips on diesel have been both more often with light load and more often with heavy load, whereas the dual-fuel trips have been more often with middle weight load. Yet another difference that was seen was that there was more data from diesel trips compared to dual-fuel trips, 19000 km compared to 9000 km. Data collection was going on for a period before introducing the routine for driving on pure diesel every other week, so it would have been more according to expectations if it was more data for dual-fuel.

All in all the differences between the two data sets dual-fuel and diesel are too many, for just comparing the aggregated fuel consumptions straight off. Figure 12 shows a graph, where fuel consumption versus vehicle weight is plotted for each of the nine category combinations for both dual-fuel and pure diesel. The dots are connected with piecewise linear interpolation and extrapolation for higher weights. Also the aggregated categories are plotted against the average gross weight (weighted against distance) with one marker for dual-fuel and one for diesel.

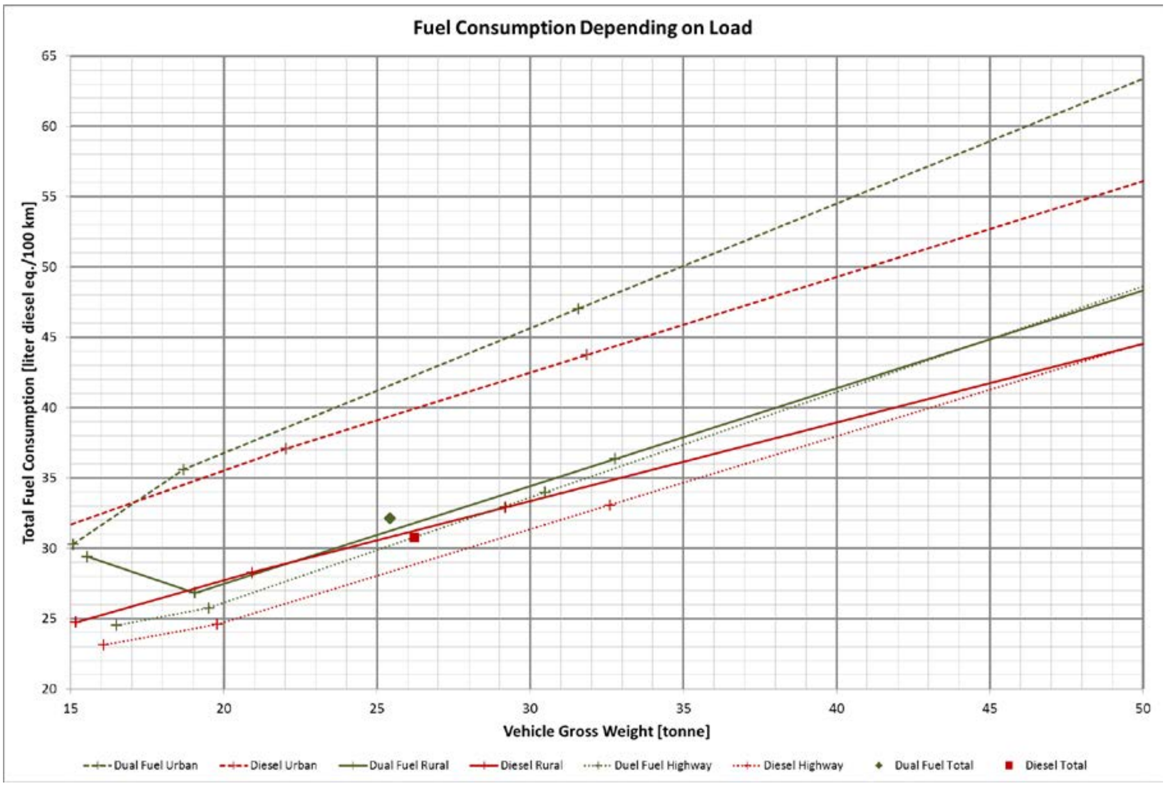

Figure 13 Fuel Consumption in relation to vehicle weight and broken down into nine categories, weight categories connected with piecewise linear interpolation (and extrapolation above heavy weight). Also data points for the aggregated fuel consumptions for dual-fuel and diesel without any categorization.

Even after breaking down the data into categories like this, it is not a very clear picture. For low vehicle weights it looks especially uncertain.

If all weights below 20 tonne are disregarded due to uncertainty and all weights above 35 tonne are disregarded in order not to rely too much on extrapolation, it can be read from the graph (with some simple calculations) that the fuel-consumption for dual-fuel is within 0% to 9% above that for pure diesel.

To come further, we estimate the fuel consumption within each category, using the mean gross weight within each weight category, see Table 13. 15.6, 20.0 and 32.0 are the average gross weights within category and the estimated fuel consumptions are for these weights. Before calculating the weighted average values, we need to decide on the weights, and for this we choose the mean values of the total fuel consumption from Table 11, shown together with the mean values in Table 12. The fuel consumptions and their weighted average values are then calculated and shown in Table 13 below. The numbers in Table 13 indicate that the fuel consumption for dual-fuel drive is 5.6% higher than for driving on diesel.

Table 12 Distribution of total consumed fuel for dual-fuel and diesel and also the mean values, which will be used when weighting together the total fuel consumption in Table 13 below.

		Total fuel consumption %		
		Light	Middle	Heavy
DF	Urban	1	4	9
	Rural	3	6	40
	Highway	1	26	8
Diesel	Urban	3	3	4
	Rural	9	6	16
	Highway	7	5	47
Mean	Urban	2	4	7
	Rural	6	6	28
	Highway	4	16	27

Table 13 Fuel consumption for each of nine categories and weighted ...

		Fuel consumption				
		l diesel eq. per 100 km				% of diesel
		tonne			weighted average	
		15.6	20.0	32.0		
DF	Urban	31.1	36.8	46.6	33.0	105.6%
	Rural	29.3	27.5	35.1		
	Highway	24.1	26.1	34.4		
Diesel	Urban	32.2	35.6	43.2	31.3	100.0%
	Rural	25.0	27.7	33.9		
	Highway	23.0	24.8	32.0		

For comparison, also let's see what the two aggregated data points of Figure 12 would tell us. By using help lines with similar slope as the other lines, it can roughly be estimated that against the 25 tonne gridline that dual-fuel consumption is roughly 31.7/29.9 - 1 ≈ 6.0% higher than that for diesel. (So maybe the above exercise with the categories wasn't absolutely necessary.)

Methane Slip

The methane slip shown in Table 10 corresponds to added fuel consumption for dual-fuel mode according to Table 14. The lower heating value of 45.1 MJ/kg from Table 3 was used to convert from slip per MJ to slip per kg.

Table 14 Methane slip in relation to total fuel consumption

		Urban	Rural	Highway
CH_4 emissions (methane slip)	[g/MJ]	0.54	0.39	0.26
	[g slip/kg fuel]	24.49	10.92	7.36
	%	2.4%	1.1%	0.7%

Economy

Assuming a 5.6% increase of fuel consumption for dual-fuel drive compared to pure diesel drive, we get fuel cost per distance according to Table 15 below.

Table 15 Fuel cost per kilometer for dual-fuel versus diesel.

Fuel mode		Dual-Fuel	Pure diesel
Fuel consumption	$l_{diesel\ eq.}$/100 km	33.0	31.3
Substitution rate		53%	0%
Fuel price	SEK/$l_{diesel\ eq.}$	10.50	10.62
Cost over distance	SEK/km	3.47	3.32

(Fuel consumption in Table 15 is based on the mean use case distribution in Table 12, whereas the substitution rate is based on the dual-fuel use case distribution in Table 12. This will have minimal impact on the economic evaluation below.)

Table 15 shows that with fuel prices of today dual-fuel drive is actually more expensive per kilometer than driving on pure diesel. So the investment in a methane-diesel truck will never give return on investment. Instead we calculated at what maximum LNG price, the investment in a methane-diesel truck hypothetically would be a profitable investment. The numbers from this calculation are shown in Table 16 below.

Table 16 Price cuts needed on LNG for a dual-fuel truck to be as good an investment as a conventional truck. Mixed usage with a substitution rate of 46% was assumed.

Imputed rate of interest		0%	5%	10%
Needed yearly saving	SEK	40 000	51 802	65 098
Needed saving over distance	SEK/100 km	33.33	43.17	54.25
Needed price cut on fuel	SEK/$l_{diesel\ eq.}$	1.01	1.31	1.64
Needed price cut on LNG or LBG	SEK/$l_{diesel\ eq.}$	1.92	2.49	3.13
	SEK/kg	2.67	3.46	4.35
	%	-19%	-24%	-30%
Needed max price on LNG or LBG	SEK/kg	11.65	10.86	9.97

Since to the author of this document, it is not obvious how to assign cost of capital, three different examples are given in Table 16. The figures indicate that the price in BiGreen need to come down with twenty to thirty percent for the methane-diesel truck to become an economical investment.

The needed yearly saving is based on an investment cost of 400 000 SEK and time of ownership of 10 years (from the Methodology section) and the present value formula (from the Theory section). Needed saving over distance is based on a yearly distance of 120000 km. the price per liter diesel equivalents is converted into price per kg BiGreen by assuming 1 kg BiGreen $\leftrightarrow$ 1.39 l diesel.

For the economic calculation above to hold, there must be enough filling stations so the liquefied gas tank never goes empty.

Results from Field Trips

Power and Drivability

It seems to be a general opinion that the methane-diesel trucks are weaker while driving on dual-fuel compared to pure diesel. Two out of three drivers witnessed on this and one out of three didn't know. The weakness was noticed when driving with heavy load and trailer.

When the truck switches between pure diesel mode and dual-fuel mode, there is a power dip for about three seconds. This happens around 20 to 30 seconds after start and also when it is running low on liquefied gas or if the truck chooses pure diesel mode for some other reason. Some regard this as something you get used to, whereas someone mentioned it as a traffic danger.

Filling Procedure for Liquefied Gas

None of the drivers had any suspicions about gas leaking out, not when fueling and not on any other occasion either.

Normally, if gas is filled up every day, the filling procedure is free of hassles.

If it is longer between fillings, it gets a bit more complicated and time consuming. If the truck has been standing still over the weekend, the "double hose fueling" (see Appendix B) is needed, which takes a little longer. If it has been standing for longer, then it takes even longer, like an hour. It is a little easier if someone from the FordonsGas crew is there to help. One reason for the truck not being fueled with gas often enough may be that some of the drivers are not educated in the filling procedure.

Normally, when everything goes according to schedule, the trucks are fueled every weekday, and the longest time the stay parked are from Friday 9 p.m. until Monday 5 a.m.

It has happened that the filling procedure has malfunctioned for no obvious reason, or at least it has seemed to malfunction when more than ten minutes of filling has not been indicated by a higher gas level. One explanation might be that there is uncertainty about the indicated gas level, see next section.

Indication of Liquefied Gas Level

Uncertainty for gas level indication has been noticed among drivers. "Strange that it wanders. Sometimes it goes from 2 to 3 diodes" was one comment. The indicator for gas level in Volvo FM MethaneDiesel is shown in Figure 13.

Figure 14 Indicator for liquefied gas level in Volvo FM MethaneDiesel.

Usage

The two investigated trucks have much been used for long-haul transport from Gothenburg to Strömstad or Oslo. These longer trips were often with full cargo and a trailer hooked on to the truck. In addition to these transports the two trucks were also used for regional transport to locations typically within 100 kilometers, and also they were used for local distribution a little bit.

Analysis

The most important conclusions from this study are the following:

- LBG has a radically lower carbon footprint than that of diesel.
- LNG is comparable to diesel. They are both fossil.
- NO_x emissions are reduced with dual-fuel technology.
- Dual-fuel is still under development, so its full potential is yet to see.
- Methane gas propulsion cannot be motivated for pure economic reasons today, not with the fuel prices in Sweden at the moment.

Carbon footprint

The use of LBG as a fuel for long-haul can dramatically lower the carbon footprint, whereas LNG is more on level with diesel or even slightly worse, when it comes to greenhouse gas emissions.

Also the carbon footprint is decreased if the dual-fuel vehicles are primarily used for higher vehicle speeds, not for urban distribution. It seems that the important is to avoid the really low vehicle speeds (below 40 km/h) but above that it seems not important if the really high speeds (above 70 km/h) are used. A little reservation is in place here, since the use case combination heavy load and high speed was not one for which a lot of data was collected (see Table 11). The general opinion amongst engineers in this field seems to be that the higher speed, heavier load and higher power output, the better a dual-fuel system is utilized, and considering available data and uncertainties this cannot be argued against.

Local Environment

NO_x emissions are significantly reduced with dual-fuel drive. This NO_x reduction is obtained regardless of whether the truck is fuelled with LBG or LNG. NO_x contributes to the smog problem in larger cities, so the reduction of NO_x is obviously advantageous to the city environment and health.

Fuel Consumption

Measurements indicate that fuel consumption in liter of diesel equivalents over distance is increased by five to six percent for dual-fuel propulsion compared to running on conventional diesel. A two percent increase can be expected from the 0.98 relative efficiency indicated in one cylinder testing at Volvo [1] with dual-fuel technology. Then approximately one to two percent is explained by methane slip, see Table 14. This leaves us with one to three percent increased fuel consumption still unexplained, see Table 17.

Table 17 Increase of fuel consumption for dual-fuel versus diesel. A simplification is that the total is assumed to be the same for all three use cases. Then an estimation of the "unexplained" is calculated.

Extra consumption for DF compared to diesel	Urban	Rural	Highway
0.98 efficiency as measured in one-cylinder-testing	2.0%	2.0%	2.0%
Methane slip	2.4%	1.1%	0.7%
Unexplained	1.1%	2.4%	2.8%
Total (disregarding use case)	**5.6%**	**5.6%**	**5.6%**

So, measurements indicate an increase of fuel consumption of a few percent for a methane-diesel truck compared to a conventional, and only part of this increase is explained at the moment. We can only speculate, but a not too wild guess would be that the efficiency factor of 0.98 for dual-fuel technology does not reflect the whole truth when put in real use. Dual-fuel is still an emerging technology.

In this project we chose conventional diesel propulsion as a reference. It seemed like the most relevant when judging a long-haul or regional transport application. Traditionally however, a gas engine has often been an otto engine, and compared to that an engine based on diesel technology is much more efficient and saves fuel, typically 25% [13].

Economy

With fuel prices of today, there is no economic motive for investing in a truck with dual-fuel technology. Diesel is not expensive enough compared to liquefied gas. Also for a large fleet owner, the price for diesel may be a question of bargaining, whereas the price for liquefied gas is more given. So the motive today for investing in a methane-diesel vehicle has to be other than economic.

Today and the future

Potentially LBG could lower the carbon footprint for long-haul dramatically. There are some areas of improvement to work with before the full potential can be utilized.

- **Fuel blend.** In some regions LNG is available but not LBG. In Sweden the situation is better, with FordonsGas offering “BiGreen” with a 50/50 blend of LNG/LBG. So future carbon print reductions depend on how biofuel supply will develop.
- **Substitution rate.** In this pilot we have seen substitution rate ranging from 40 to 60 percent depending on truck usage. With new dual-fuel technology under development, such as HPDI from Westport, substitution rates up to 95% are expected.
- **Methane slip.** Today the methane slip means a significant limit to the environmental gain with liquefied gas as a fuel. The expectations from future dual-fuel technology is that the methane slip will be reduced or eliminated.

If all three of these issues are improved according to expectations, an 80% reduction of greenhouse gas emissions should be within reach in the future. Figure 14 shows a comparison between diesel combustion and LNG or LBG combustion in a “dream engine” that combusts the liquefied gas according in a diesel process but without any methane slip and without having to blend in diesel.

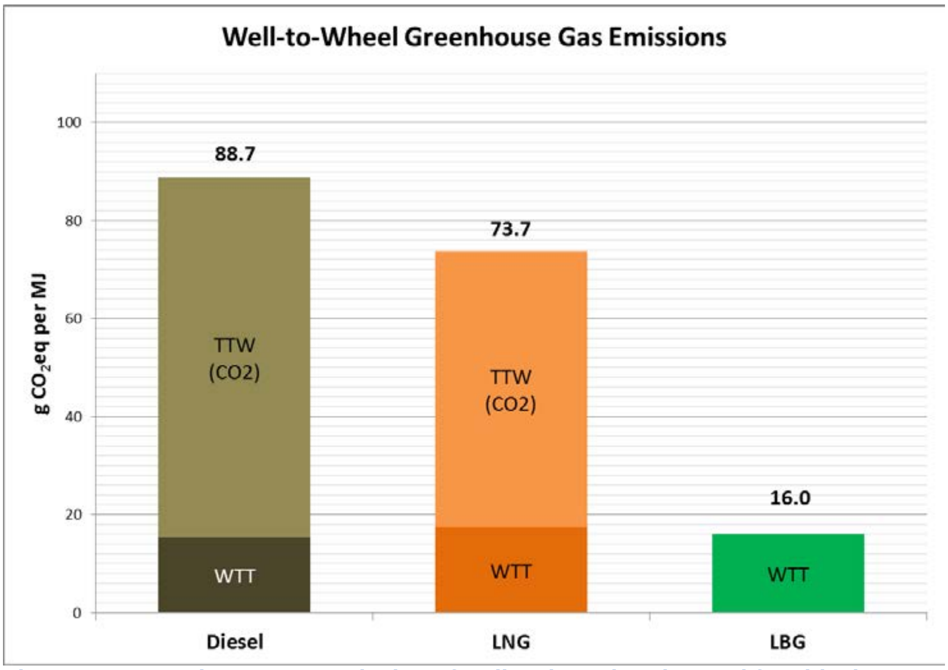

Figure 15 Greenhouse gas emissions for diesel combustion and for "ideal" (hypothetical) combustion of LNG or LBG without methane slip and disregarding the need for blending in diesel in dual-fuel technology, i.e. 100% substitution rate.

The emission levels shown in Figure 15 are for a hypothetic engine, but they give an idea of what to aim at for future use of liquefied gas. These "ideal" figures indicate an 82% reduced carbon footprint for LBG compared to diesel and a 17% reduction for LNG. It is only a thought experiment, but it gives an idea of the theoretic limits of dual-fuel technology.

A 17% reduction of greenhouse gases may seem like a worthwhile improvement compared to the diesel usage of today. Another way to look at it however would be that LNG would prolong the fossil era here on Earth with a hundred years or so. The 82% reduction of greenhouse gases for LBG on the other hand would be something really worth striving for.

Recommendations

Recommendations to the World

The recommendation to society and politicians is to use available stimuli to favor the use of liquefied biogas (LBG). Using LBG as a fuel for long-haul in the methane-diesel trucks available today will decrease greenhouse gas emissions by 40%. A future decrease of up to 80% may be accomplished with the help of further developments of the dual-fuel technology.

This study focused on LNG and LBG, but there are other alternative fuels to consider too. For long-haul transportations, the greenhouse gas emissions should be the focus, but other biofuels, such as biodiesel, DME, HVO etc., may also reduce greenhouse gas emissions (similar to LBG) and be good for environment. This report has no conclusions about these other biofuel, but also it says nothing against these alternatives.

The trucks studied in this pilot get their liquefied gas fuel at the FordonsGas station located at Stigs Center in Gothenburg. Their liquefied gas product “BiGreen” is composed by 50% LBG and 50% LNG. The obvious recommendation to FordonsGas is to continue their work to get a higher percentage of LBG in their BiGreen blend

The recommendation to politicians is to provide the conditions that will make LBG an economic alternative as well as an environmental. If the goal is to reduce the carbon footprint from heavy duty truck transport, then the LBG need to become less expensive than both LNG and diesel. In Sweden today it is actually the opposite[2]. Due to higher production cost, biogas is priced higher than fossil gas.

Recommendations to PostNord

PostNord is recommended to continue their operation of dual-fuel trucks. At the moment, with current price on methane gas versus diesel, there is no economic motive for continuing with these methane-diesel vehicles, but if they are fuelled with BiGreen from FordonsGas they do leave a significantly smaller carbon footprint compared to driving on pure diesel.

For minimizing the carbon footprint as much as possible, these trucks should be used primarily for longer and heavier transport, not for urban low-speed distribution, see Figure 8. If they are used for urban distribution, then at least the NO_x emissions are reduced with dual-fuel drive, so the contribution to the smog problem is reduced compared to conventional diesel drive.

From what can be seen from data and form information on schedules, the judgment is that these trucks are already being used in a way that utilizes them in a good way. If we are to come with any recommendation, it would be to whenever possible exchange urban distribution missions for regional transport missions.

A final comment to PostNord would be that it is important to keep many enough drivers educated on the filling process for liquefied gas.

Recommendation to Gas Distributers

As an alternative to their standard methane gas (not liquefied), FordonsGas also offers the possibility to sign up for 100% renewable gas, “Grön100”, at some extra cost. Why not have the same offer for those customers who are willing to pay a little extra to get a 100% renewable alternative to the liquefied gas BiGreen?

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[2] FordonsGas charges more for their product ”Grön100”, which is 100% renewable, than they charge for their standard methane gas, which is a bit over 50% renewable.

One hurdle when implementing the use of liquefied gas in a transport operation is the filling process, which requires education of the drivers. If it would be possible to develop a future simpler filling process, it would certainly smooth the way for use of liquefied gas.

Recommendation to Volvo

The recommendation to Volvo is to continue with their venture within methane-diesel vehicles, but in order to make an environmental contribution, the emphasis in the marketing should be more in connection to renewable LBG and less in connection to LNG.

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Team Members at Volvo

Table 1 Engineering team

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… and many more.

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Appendix A – Energy Content of Fuels from FordonsGas

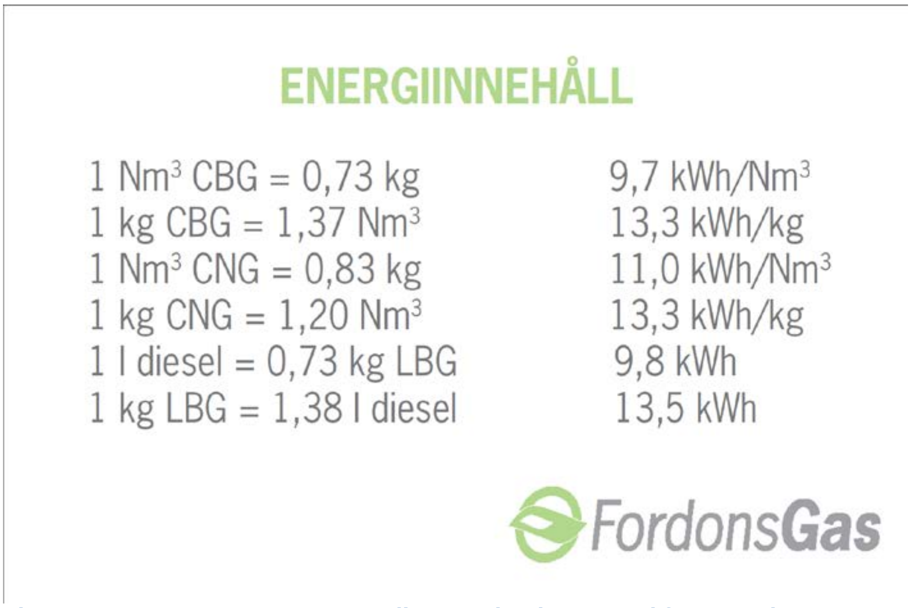

Figure 16 Energy contents according to a business card from FordonsGas.

Figure 15 shows the information on energy content that FordonsGas has printed on the backside their business cards. In addition to this, FordonsGas has given us the information that

$$1 \text{ kg LNG} \leftrightarrow 13.7 \text{ kWh}.$$

Another piece of information from FordonsGas is that even though their product BiGreen is sold as a 50/50 mixture between LNG and LBG, it actually physically consists of 100% LBG. However, only 50% renewable fuel can be accounted for when calculating the carbon footprint. This is due to the fact that the LBG content not “paid for” is compensated by less biogas being blended into the other fuel products from FordonsGas. The biogas content in all fuel combined (BiGreen and “fordonsgas”) supplied by FordonsGas is 50%. (FordonsGas also provides a product called “Grön100,” which consists of 100% CBG.)

Appendix B – The Test Objects

The two test objects were Volvo rigid trucks model FM MethaneDiesel (http://www.volvotrucks.com/trucks/global/en-gb/trucks/new-trucks/Pages/volvo-fm-methanediesel.aspx) with 460 hp and 6x2 axle configuration. Their identities are according to Table 18 below.

Table 3 Test vehicles.

Registration plate	PostNord ID	Project ID
JRM 876	99.302	5001
NZX 889	99.303	5002

Filling Procedure

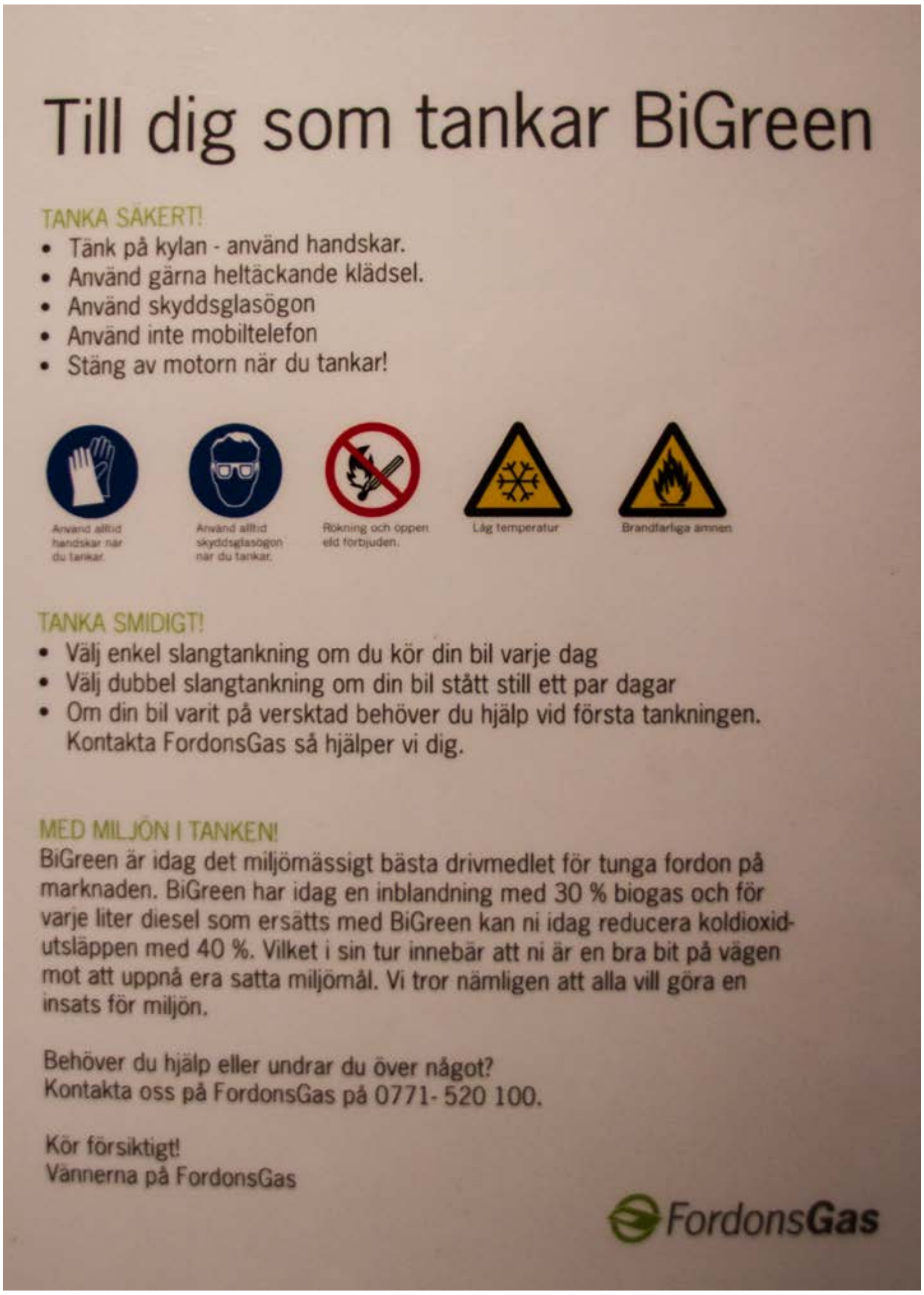

Figure 17 Procedure for filling BiGreen. Page 1.

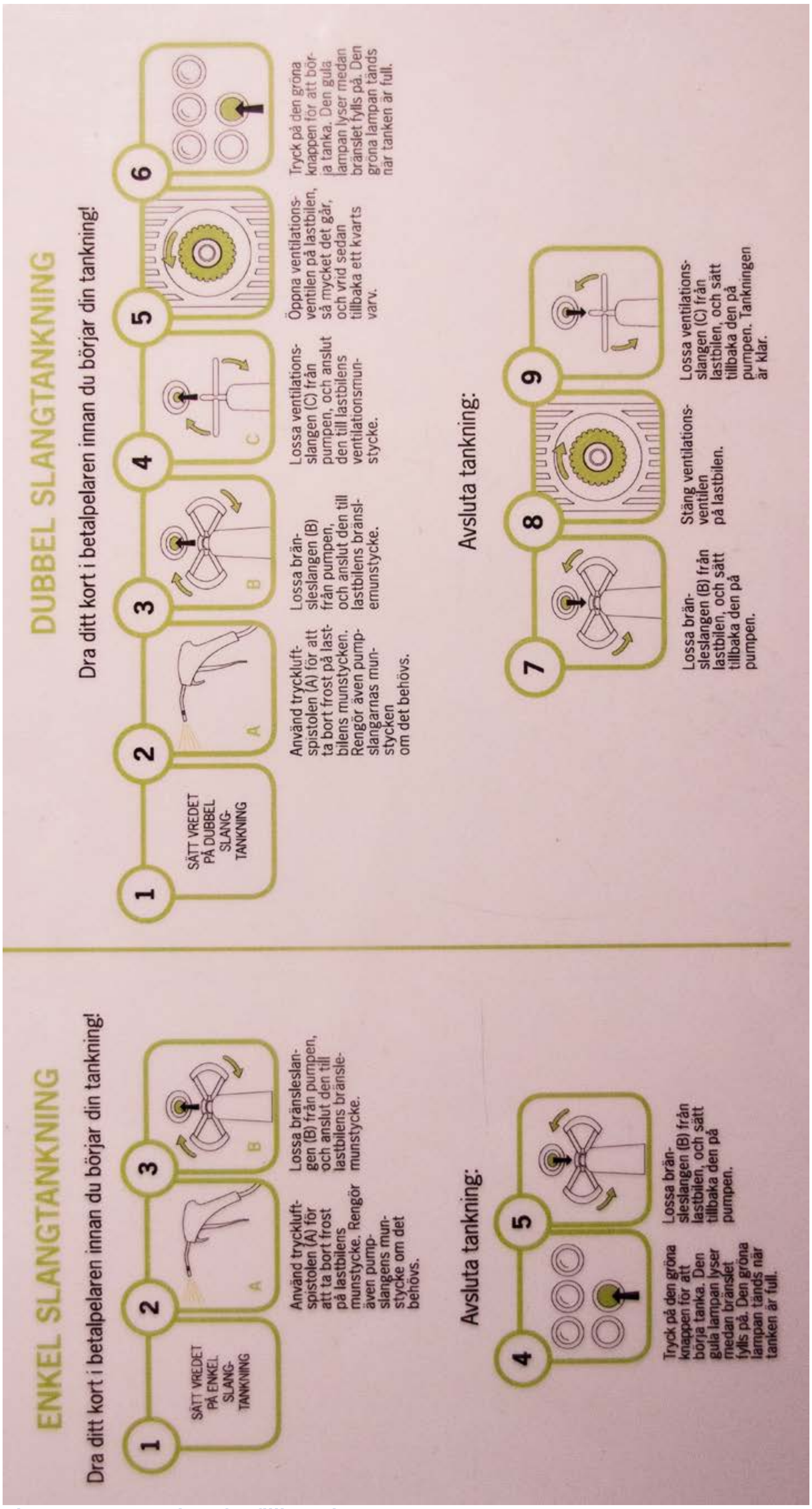

Figure 18 Procedure for filling BiGreen. Page 2.

Filling Procedure Explained in English

Basically there are two procedures for filling BiGreen at FordonsGas filling station:

- One-hose filling,
- Double-hose filling.

One-hose filling means plain and simple filling from station to truck through one hose. It works well if the liquefied gas fuel in the truck is still cold and not much of it has gone over to gas form. This is the normal case if the truck is used continuously and fueled every day.

If it has been a longer time since the last filling then some of the liquefied gas fuel has evaporated into gas state, and the pressure from that gas needs to be released in order to give room for the new liquefied fuel, hence two hoses, one for filling liquefied gas from the filling station to the truck and one hose for letting gas out from the tank in the truck and back to the filling station.

If the truck is left standing too long, then eventually too much of the liquefied fuel will evaporate and the gas pressure will get too high for the tank. A safety valve will then let the surplus gas out. This is obviously a case of waste.

Appendix C – Clean Air Power Chart Recorder

The Chart Recorder is a useful tool for recording engine signals, both the signals from the dual-fuel system and also e set of CAN signals available in the vehicle.

The full list of signals logged by the CAP Chart Recorder:

- Coolant Temperature: Displays the Engine Coolant Temperature Engine Coolant Temperature is recorded from the J1939-7 Data link. The temperature must be above a threshold to run in Dual-fuel mode (MethaneDiesel 65°C, Genesis Edge 72°C)
- CNGT (deg C): Displays the temperature of the vaporized gas as it enters the Gas injector manifold assembly. It should read close to ambient temperature when the engine is cold.
- QGas(mg/inj): Shows the quantity of gas being injected into a single cylinder per firing (expressed in milligrams of diesel per injection)
- QNet (mg/inj): Shows the total quantity of gas plus diesel being injected into a single cylinder per firing (expressed in milligrams of diesel per injection)
- QCom (mg/inj): Shows the commanded amount of gas plus diesel per firing for a single cylinder (expressed in milligrams of diesel per injection)
- Knock Counter: Records the highest knock counter value for all six individual cylinders. (If knock counter reaches 10,000 then a Knock fault is set)
- Engine Speed: Displays the Engine RPM's. Engine Speed is read from the J1939-7 Data link.
- Lambda CNG: Measures lambda (air-fuel ratio / stoichiometric air-fuel ratio) when gas is being used
- MAP Error (KPa): Measures the difference between the actual Manifold pressure and the required Manifold pressure to obtain correct air-fuel ratio for gas combustion
- Actual Tab Position (% Open): Shows the actual open position in % of the TAB valve paddle
- Gas Pressure: Displays the pressure of the vaporized gas as it enters the Gas injector manifold assembly.
- Commanded Tab Position (% Open): Shows the demanded open position in % of the TAB valve paddle which is determined by the Hawk ECU
- Vehicle Speed (KPH): Displays the road speed of the vehicle. Vehicle Speed is recorded from the J1939-7 Data link.
- CNGP2 (KPa): Measures the gas pressure at the Regulator (MethaneDiesel only)
- Boost Pressure: Records the Boost pressure. Boost pressure is taken from the J1939-7 Data link (MethaneDiesel) or from the CAP TMAP Sensor (Genesis Edge)
- % Torque: Measures the torque delivered by the engine
- Substitution (%): Shows the amount of Gas (expressed as equivalent litres of diesel) that is being burnt that instead of Diesel in % form
- Solenoid Voltage: Displays the voltage being supplied to the Gas Injectors, Shut Off Valve and Lock Off Valve
- SCR Temperature: Measures the Exhaust gas temperature as it enters the SCR. SCR temperature is taken from the J1939-7 Data link.

These signals will be enough for providing information on torque, power and fuel consumption and indirectly CO_2 emissions, but there are no measure points in the exhaust, so it cannot be used for measuring emissions such as NO_x, carbon monoxide or particulate matter.

Appendix D – Questions to Drivers (in Swedish)

Om man jämför med ren dieseldrift i denna eller en motsvarande dieselbil, hur upplevs det att köra denna bil med gasdrift (blandning gas/diesel) inkopplad?

Känns den annorlunda på något sätt?

Behöver man köra annorlunda?

Känns den starkare, svagare eller samma?

Är det i vissa situationer den känns annorlunda eller starkare eller svagare?

Tankning

Hur ofta tankar du?

Hur lätt är det att se hur mycket man har kvar i gastanken?

Hur tycker du tankningen fungerar?

Misstänker du något läckage vid tankning?

Misstänker du läckage vid annat tillfälle?

Vid service?

Efter kortare stillestånd?

Efter längre stillestånd?

Vid start?

Vid avstängning?

Annat tillfälle?

Kan du beskriva en typisk körning?

Hur mycket last?

När avlastning/pålastning?

Typ av väg?

Övrigt?

Hur länge står bilen mellan körningar?

Medel?

Max?

Något annat att påpeka? Något ytterligare vi borde ha frågat?

www.grecor.eu

European Union The European Regional Development Fund