Design solutions to minimize Boil-off

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Executive Summary

The LNG Blue Corridor project is focused on demonstrating the use of LNG as truck fuel and to define a road map for future large scale development of the market.

Compared to conventional fuels, natural gas rates lower CO\textsubscript{2} and NOx emission values. This makes from LNG the best alternative to diesel on HD engines.

Methane, as the main component of LNG, is a greenhouse gas to be considered with particular attention. Being 84 times more potent than CO\textsubscript{2}, uncontrolled methane slip could be disastrous in a pump-to-wheel balance.

This document describes the different sources from where this methane could attempt to escape to the atmosphere. Several literature have been consulted, giving an overview of this methane slip scope in some common use cases.

In this report, from the different combustion technologies available to how the operations and logistics could be managed, several solutions have been considered. Engineering advances and a better knowledge of how boil-off affects the composition of LNG, is leading to a progressive decrease of methane emissions.

To minimize them further must be a main target, if LNG is called to substitute Diesel and compete with other incoming technologies.
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1 Introduction

1.1 Aim of this deliverable

The benefits of LNG trucks in terms of greenhouse gas reduction (due to lower tailpipe emissions) could potentially be neutralized if the technology on stations and trucks is not managing boil-off gases properly.

Boil-off gas is generated when heat from the environment is transferred to the LNG, causing the product to evaporate. This heat in-leak and consequent evaporation of the methane is a permanent process, which is not problematic as long as the pressure increase generated in the fuel tanks (vehicle or station) stays below the MAWP (Maximum Allowable Working Pressure). Should the pressure in the tanks raise to this MAWP, for safety reasons, the safety valves will allow the gas to escape to the atmosphere.

This emission of methane gases is affecting the good environmental balance of LNG, being methane a greenhouse gas which is much stronger than e.g. CO₂. Thus, proper management of this boil-off gas is a must for all the agents along the LNG chain, and the emission of methane must be limited to a strict minimum, or completely eliminated. The manual venting of gas in order to manage tank pressure is not acceptable.

Fortunately, there are various possibilities to come to effective BOG (Boil-Off Gas) management, by use of technology, or just by taking care of good practices and day to day follow-up of the stations and the trucks.
2 Design Solutions on the vehicles

When considering greenhouse gas and more specifically methane emissions (including boil off, venting or methane slips) on LNG vehicles, the following two types of emissions should be distinguished:

- On-engine emissions, including exhaust emissions (tailpipe) and engine venting (also called crankcase emissions or blow-by gases);
- Off-engine emissions, i.e. venting due to LNG boil-off in the tank, eventually manual venting and leaks.

This section provides an analysis of carbon dioxide (CO2) and methane (CH4) emissions from LNG trucks, with a specific focus on methane. The current technologies implemented in Euro VI (and Euro V) LNG trucks are explained. The available data from literature, OEMs and the LNG Blue Corridors project are analyzed in the attempt to understand the reasons for the main differences and the real performance of Euro VI LNG vehicles with regards to CO2 and CH4 emissions. Then some solutions to further reduce methane emissions are proposed.

2.1 Current solutions and performance

2.1.1 On-engine emissions

2.1.1.1 Engine technology comparison

The amount and the reasons for engine methane emissions vary a lot with the gas engine design and combustion system. Different engine and vehicle technologies produce different methane emissions and therefore use different mitigation solutions. Please refer to LNG BC report D2.1 “Euro V final technical solutions” for additional technology description.

2.1.1.1.1 Spark ignited (SI) technology

Spark ignited (SI) engines are characterized by a pre-mix of fuel and air on the compression stroke and ignition from a spark plug. Due to their combustion system, such engines with pre-mixed combustion generally show rates of unburned or partially burned air/fuel mixtures. The combustion of the air/fuel mixture is not always complete in all areas of the combustion chamber; therefore some methane remains unburned. Methane emissions in the atmosphere can be avoided by optimization of the combustion (combustion chamber and overall engine design, combustion strategy, etc.) as well as by the use of after-treatment systems.

SI engines are Otto cycle engines operating either with stoichiometric combustion or lean-burn combustion. Even though both combustion technologies were used by OEMs up to Euro V, all Euro VI SI engine models available in the market are now operating with stoichiometric combustion (e.g. models from Iveco, Volvo, Scania\textsuperscript{2}, Mercedes\textsuperscript{3}). Near-stoichiometric systems are easy to ignite and to burn out and usually, their exhaust gas temperatures are very high which is very beneficial to exhaust gas after treatment systems.

There are simple, proven and reliable exhaust gas after-treatment systems for stoichiometric SI engines: mostly 3-way catalyst and EGR (Exhaust Gas Recirculation) system. For near stoichiometric conditions of the combustion mixture, the 3-way catalyst is a very reliable and efficient technical solution. It is a very efficient system to convert HC, NOx and CO into CO\textsubscript{2} and H\textsubscript{2}O in stoichiometric SI engines. Indeed, 3-way catalysts are effective when the engine is operated within a narrow band of air-fuel ratios near the stoichiometric point, such that the exhaust gas composition oscillates between rich (excess fuel) and lean (excess oxygen). Such after-treatment systems are sufficient to reach Euro VI emission requirements.

More details about methane emissions in SI engines can be found in the CIMAC position paper “Methane and Formaldehyde Emissions of Gas Engines”\textsuperscript{4}.

As for engine venting, some OEMs (e.g. Cummins ISL G engine) have implemented closed crankcase ventilation (CCV) for their Euro VI natural gas engines; it is a new remote mounted system to re-cycle blow-by gases now counted in the engine emissions.

### 2.1.1.1.2 Dual fuel technology (indirect injection)

In this report the term “dual fuel” refers to dual fuel indirect ignition, which is also called fumigation. In this technology, natural gas and air are pre-mixed at low pressure on the compression stroke. Compression ignition is provided with high pressure diesel ignition. Like spark ignited engines, dual fuel engines operate with pre-mixed combustion and therefore generally also show high rates of unburned or partially burned air/fuel mixtures, for the same reasons as SI engines.

Unlike Euro VI SI engines, a dual fuel engine operates with lean burn combustion. Lean burn systems require advanced ignition technologies and - in contrast to rich burn systems - their exhaust gas temperature is significantly lower. For this reason, 3-way catalysts do not perform well for lean gas mixtures. Under lean conditions different exhaust gas after-treatment technologies must be foreseen to reach Euro VI emission requirements. One option is to use a methane oxidation catalyst in addition to a 3-way catalyst.

\textsuperscript{2} https://www.scania.com/group/en/a-passion-for-gas/


Unburned methane emissions in the exhaust gas can be further reduced by after treatment systems like catalytic oxidation. However current methane oxidation catalyst technology does not yet fulfill Euro VI emission requirements. The main issues are the following:

- Reliable catalytic methane oxidation requires exhaust gas temperatures above 500 to 600°C. In this temperature range conversion rates of 90% and more can be realized. Below 400 to 500°C the conversion rate decreases rapidly.
- Besides the significant temperature depended conversion rate, oxidation catalysts get poisoned very fast even by small amounts of sulfur (H2S) or similar components. The application of catalytic methane oxidation for gases with sulfur content like biomethane is problematic.

The main target for methane oxidation catalyst in dual fuel engines is therefore to raise the conversion rate even at low exhaust gas temperatures and to make the oxidation catalyst resistant against poisoning. Development of suitable after-treatment solutions enabling such dual fuel engines to meet Euro VI emission requirements is currently ongoing (e.g. in the EU funded Horizon 2020 HDGAS project\(^5\)).

2.1.1.3 High pressure direct injection (HPDI) technology\(^6\)

High pressure direct injection (HPDI) engines are compression ignition engines characterized by a diesel-like combustion process in which there is air only in the compression stroke and high pressure natural gas is injected directly into the combustion chamber. Ignition is provided by a diesel pilot. Note that this technology is sometimes called “dual fuel” even though it is very different from the dual fuel (indirect injection) technology described in the previous section.

The HPDI technology retains the operating principles of the base diesel engine—direct injection near top-dead-center, auto-ignition, diffusion combustion, and the thermodynamic Diesel cycle—and so retains its operating characteristics. The use of diesel-style diffusion combustion means that HPDI engines require no intake air throttle for air-fuel-ratio control, allowing HPDI engines to operate at lean air-fuel ratios.

Such gas engines with direct injection and a diesel-like diffusion based combustion show a very different emission behavior than gas engines with a pre-mixed combustion system (i.e. SI and dual fuel engines). They are not limited by knocking at high loads and their HC emissions are low. HPDI’s late-cycle injection and non-premixed combustion gives it an inherent advantage in terms of unburned methane emissions, with very little methane in the crevices and near-wall regions. This limits unburned emissions both from the tailpipe as well as ensuring that the crankcase blowby gases are free of methane.

\(^5\) [http://www.hdgas.eu/project/scope/](http://www.hdgas.eu/project/scope/)

HPDI engines use same after-treatment systems as diesel engines. For Euro VI trucks, these can include e.g. a diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalytic reduction (SCR) system (including a urea doser and ammonia slip catalyst). Even so, achieving the Euro VI limit of 0.5 g/kWh target is challenging, especially as engine aftertreatment systems do not provide significant methane oxidation at diesel-like temperatures and oxygen fractions.

The key factors enabling low methane emissions are relatively high combustion temperatures over most of the cycle, which help to oxidize the methane in-cylinder, and tight control over the injection event. This ensures that the right amount of fuel is injected at the right time, to minimize over-mixing of early injected fuel and to avoid rich pockets in late-injected fuel. This allows an HPDI engine to avoid excessive methane spikes over a transient cycle. The composite methane emissions, including both cold- and hot-start cycles, remain below the legislated Euro VI limits.

### 2.1.1.2 Euro VI requirements

Exhaust emissions of engines for Euro VI vehicles are regulated by the UNECE Regulation No. 49\(^7\), Rev.6 of this regulation does cover emissions of natural gas engines. Euro VI limits for heavy-duty vehicles were introduced in Regulation 595/2009, and were amended by Regulations 582/2011 and 133/2014.

The Euro VI regulation does include hydrocarbon (HC) emission limits – either on total hydrocarbons (THC), or on both non-methane hydrocarbons (NMHC) and methane (CH4), depending on the type of engine, as shown in the table below. Note that the limit values for HPDI engines are the same as for PI engines.

<table>
<thead>
<tr>
<th>Emission Limits</th>
<th>CO (mg/kWh)</th>
<th>THC (mg/kWh)</th>
<th>NMHC (mg/kWh)</th>
<th>CH4 (mg/kWh)</th>
<th>NOx (mg/kWh)</th>
<th>NH3 (ppm)</th>
<th>PM mass (mg/kWh)</th>
<th>PM number (10^11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHSC (CI)</td>
<td>1,500</td>
<td>130</td>
<td></td>
<td>400</td>
<td>10</td>
<td>10</td>
<td>8.0 x 10^11</td>
<td></td>
</tr>
<tr>
<td>WHTC (CI)</td>
<td>4,000</td>
<td>160</td>
<td>500</td>
<td>460</td>
<td>10</td>
<td>10</td>
<td>6.0 x 10^11</td>
<td></td>
</tr>
<tr>
<td>WHTC (CI)</td>
<td>4,000</td>
<td>160</td>
<td>500</td>
<td>460</td>
<td>10</td>
<td>10</td>
<td>6.0 x 10^11</td>
<td></td>
</tr>
</tbody>
</table>

*Table 1 provides the emissions limits that apply to this Regulation.*

Figure 2-1 Euro VI Emission Limits (R49 regulation)

These Euro VI limits include eventual methane emissions (venting) from the engine. In the case of a closed crankcase, manufacturers shall ensure that the engine’s ventilation system does not permit the methane emissions.
emission of any crankcase gases into the atmosphere. If the crankcase is of an open type, the emissions shall be measured and added to the tailpipe emissions.\(^8\)

In addition to these stationary and transient tests (resp. WHSC and WHTC) on test bench, Euro VI regulation also introduced In-Service Conformity Testing of Real-World Emissions with in-use testing requirements that involve field measurements using PEMS (Portable Emissions Measurement Systems). The testing is conducted over a mix of urban (0-50 km/h), rural (50-75 km/h) and motorway (> 75 km/h) conditions, with exact percentages of these conditions depending on vehicle category. First in-use test should be conducted at the time of type approval testing.\(^9\)

This testing requirement and other additional measures, such as the shift to world harmonized test cycles for stationary and transient testing, and the inclusion of cold-start testing, have greatly improved the certification test and its ability to guarantee real-world achievement of the Euro VI emission limits.\(^10\)

For Euro VI vehicles, the risk of discrepancies between homologation values and real driving emission data is therefore greatly reduced.

### 2.1.1.3 Literature analysis

The main recent public documents and studies available containing information on GHG and more specifically methane emissions from LNG trucks are analyzed in this section. They are listed here:

- The European “Greenhouse Gas Intensity of Natural Gas” report published in May 2017 prepared by Think step on behalf of NGVA Europe\(^11\)
- The French “Projet Equilibre” preliminary results published in April 2017\(^12\)
- The West Virginia University (USA) study “Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector” (published in December 2016 by Environmental Science & Technology)\(^13\)
- The UK Department for Transport (DfT) “Low Carbon Truck and Refuelling Infrastructure Demonstration Trial Evaluation” (reports published in July 2015, December 2016 and January 2017)\(^14\)

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\(^8\) R49 regulation (E/ECE/324/Rev.1/Add.48/Rev.6), section 5.2.3. [https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2013/R049r6e.pdf](https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2013/R049r6e.pdf)


\(^11\) Accessible from [http://ngvemissionsstudy.eu/](http://ngvemissionsstudy.eu/)


\(^13\) Accessible from [http://pubs.acs.org/doi/full/10.1021/acs.est.5b06059](http://pubs.acs.org/doi/full/10.1021/acs.est.5b06059)

- The Transport & Environment (T&E) study “The role of natural gas and biomethane in the transport sector” (published in 2016), conducted by Ricardo\textsuperscript{15}
- The TNO reports “Truck of the Future – CO2 reduction year 2016” (published in 2016)\textsuperscript{16} and “The Netherlands in-service emissions testing programme for Heavy-Duty 2011-2013” (published 2014)\textsuperscript{17}
- The JEC – Well to Wheel analysis in version 4a (published in 2013)\textsuperscript{19}

Note that the Exergia “Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas” (published in 2015) is not listed here as it is focused on well-to-tank (WWT) emissions and does not cover the emissions from vehicles.

2.1.1.3.1 European “Greenhouse Gas Intensity of Natural Gas” report (2017)

This new study, prepared by Thinkstep on behalf of NGVA Europe, has characterized tank-to-wheel greenhouse gas emissions of Euro VI natural gas heavy duty vehicles (HDVs) using spark ignited (SI) and HPDI engines. Primary data was collected from vehicle manufacturers (OEMs) for vehicles in long haul use. The basis of the assessment was a 40 t tractor-trailer combination in long haul use with 75% payload.

The data provided by HDV manufacturers contain the relative CO2 emission advantage and/or the relative fuel consumption performance of the Natural Gas HDV technologies mentioned in long haul use compared with a baseline diesel HDV.\textsuperscript{20}

\textsuperscript{15} Accessible from https://www.transportenvironment.org/sites/te/files/publications/2016_02_TE_Natural_Gas_Biomethane_Study_FINAL.pdf

\textsuperscript{16} Accessible from http://www.rwslleomgingen.nl/onderwerpen/mobilitiet/publicaties/brandstofbesparing/

\textsuperscript{17} Accessible from https://www.tno.nl/media/3443/hdv_in_service_testing_tno_2014_r10641.pdf

\textsuperscript{18} Accessible from http://www.theicct.org/sites/default/files/publications/ICCT_NG-HDV-emissions-assessmnt_20150730.pdf


\textsuperscript{20} Section 6.2.3, pages 75-76 of the report
As per Annex F of the report, data used for the Tank-to-Wheel assessment of HDVs are results from simulations and calculations based on engine dynamometer tests as well as on real-life measurements of the vehicle performance. Data sets were provided by five OEMs. Average CO2 reduction of natural gas vs. diesel Euro VI HDVs in long haul use are respectively 12.0% for HDV with SI engine and 20.4% for HDV with HPDI engine (as reflected in the above table).

2.1.1.3.2 French “Projet Equilibre” preliminary results (2017)

As part of the Equilibre Project, a comparative analysis of CO2 emissions for several available models of Euro VI 44T natural gas and diesel trucks is being performed. The mid-term report published in April 2017 covers the first six months of tests for six trucks (three natural gas and three diesel trucks). Each vehicle is instrumented to retrieve CO2 emissions from the engine. Methane emissions are not covered in this report.

The preliminary data analysis on given road types shows that average CO2 emissions of the natural gas trucks are on average 2% lower than those of diesel trucks on motorways and 11% lower on roads crossing small towns.

A more detailed, more exhaustive analysis of all road types, based on fifteen vehicles tested under actual operating conditions over a period of one year, will be presented at a later stage of the project. The current preliminary data should therefore not be considered sufficient to draw conclusions about vehicles’ emissions.

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21 Annex F, Table F-2, page 169
2.1.1.3.3 West Virginia University study “Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector” (2016)

This study was published online late December 2016 by the journal Environmental Science & Technology and the results greatly expand on the very limited data on methane emissions from natural gas vehicles.

This study is focused on the US market and GHG emissions of engines compliant with US EPA 2010 emission standards. It is considering two engine technologies: SI stoichiometric and HPDI. Given the US market focus, this study’s results are only partially applicable to the European market, where the emissions regulations differ. Indeed, for a given technology the engine design and calibration is optimized in a different way depending on the emission limits for which it is developed, which can lead to significant differences in terms of tailpipe emissions.

In this study, methane emissions from HD natural gas fueled vehicles were characterized. A novel measurement system was developed to quantify methane leaks and losses. Engine related emissions were characterized from twenty-two natural gas fueled transit buses, refuse trucks, and over-the-road (OTR) tractors. During this study, the market was dominated by Cummins-Westport 9 L ISL G stoichiometric natural gas engines and Westport Innovations 15 L HPDI engines. Cummins-Westport 12 L ISX G stoichiometric natural gas engines were deployed during the study.
According to the study, vehicle tailpipe and crankcase emissions were the highest sources of methane.\textsuperscript{22}

![Diagram showing methane emissions sources](http://pubs.acs.org/action/showImage?doi=10.1021%2Facs.est.5b06059&iName=master.img-000.jpg&type=master)

Figure 2-4 Pump-to-wheels (PTW) methane emissions from the heavy-duty (HD) transportation sector in g/kg fuel used and percentage of total PTW methane emissions (Environment & Science Technology article)

Engine methane emissions (including tailpipe, crankcase vent and HPDI fueling system vent methane emissions) from the different engines and applications are shown in Figure 4\textsuperscript{23} of the article, also found below.

\textsuperscript{22} [http://pubs.acs.org/action/showImage?doi=10.1021%2Facs.est.5b06059&iName=master.img-000.jpg&type=master](http://pubs.acs.org/action/showImage?doi=10.1021%2Facs.est.5b06059&iName=master.img-000.jpg&type=master)

\textsuperscript{23} [http://pubs.acs.org/action/showImage?doi=10.1021%2Facs.est.5b06059&iName=master.img-005.jpg&type=master](http://pubs.acs.org/action/showImage?doi=10.1021%2Facs.est.5b06059&iName=master.img-005.jpg&type=master)
As per the article, “these emissions values are high in comparison to current and projected future SI and HPDI engines, and the authors do not believe that trucks of this type will be prevalent in future populations”.

Westport Fuel Systems commented in a news release that “the natural gas vehicle industry has already implemented technology solutions to dramatically minimize, or in some cases, eliminate the largest sources of methane emissions from vehicle tailpipe, crankcase ventilation, and dynamic venting that were identified in the study. Westport™ HPDI 2.0 features further improvements to maximize the GHG benefits of natural gas, such as the capture of dynamic venting. For the North American market, the newly launched ISL G Near Zero 8.9L and ISB6.7 G engines from Cummins Westport Inc. feature closed crankcase ventilation that significantly reduces engine-related methane emissions.”

The emission figures from this study can therefore not directly be extrapolated to Euro VI products.


This evaluation is focused on HGV emissions testing commissioned by the UK Department for Transport (DfT) as a follow-up of the Low Carbon Truck Trial (LCTT) covered in the following section. Its

24 Westport Fuel Systems news release January 11, 2017
objective was to carry out vehicle testing across a representative range of gas-fuelled HGVs to quantify
the scale of the methane slip issue. As mentioned in the report, “it is important to emphasize that the
testing was commissioned to measure tailpipe emissions of greenhouse gases and air quality
pollutants only. Such measurements do not take into account any bio-content of the fuel.” The test
programme used the track-based test procedures with emissions measurement via Portable Emissions
Monitoring System (PEMS).

“The tests covered the following natural gas vehicles/technologies:

- Four dedicated OEM Euro VI natural gas vehicles, including two 40t artics (340hp and 320hp), one
  18t rigid and one 7t van
- One LCTT dual fuel (DF) diesel/natural gas retrofit conversion to a Euro V 44t artic vehicle
- One DF (diesel/natural gas) retrofit conversion to a Euro VI 44t artic vehicle”

Note that the retrofit conversion vehicles did not go through homologation process after conversion.
These are dual-fuel retrofit technologies applied to what were originally conventional Euro V or Euro VI
diesel vehicles. There is therefore no guarantee that they comply with the Euro V or Euro VI
regulations.

This evaluation is particularly relevant for the present analysis as it is to date one of the rare
independent testing of tailpipe GHG emissions of Euro VI NG HDVs that includes methane slips. As it is
also very comprehensive, some paragraphs of the report are included in this section.

Methane Slip – Extract from the LowCVP report (Executive Summary):

“Measurement of methane emissions was outside the scope of the LCTT and, more generally, there is
currently a lack of real-world data on both methane slip and air quality pollutant emissions from
dedicated gas and dual-fuel commercial vehicles.

In the first phase of research into this methane slip issue, a DfT research project in 2014/15 designed
and trialled an HGV emissions testing protocol and made recommendations for further tests. That
research, by Ricardo-AEA, also explored the causes of methane slip and summarized previous research
into the phenomenon. It showed how well designed and calibrated spark ignition engines, running on
dedicated gas, combined with exhaust after-treatment catalysis can minimize methane slip. It also
highlighted how dual fuel, diesel/natural gas engines could be particularly susceptible to methane slip.

The Ricardo-AEA report also noted how methane emissions are regulated via the type approval
process for dedicated gas engines, but not [yet] for aftermarket conversions to dual-fuel operation.
The report estimated that methane emissions higher than about 2.6 g/km would, for the converted
vehicles typically operating in the LCTT, be sufficient to cancel out the reported reductions in CO2
emissions. Furthermore, it highlighted how little research had already been carried out internationally
into the methane slip issue, with previous studies using differing and therefore not directly comparable
approaches to measuring methane emissions, and thus there was a need to develop and use a
representative, standardized test protocol.”
GHG Results Summary – Extract from the LowCVP report (Executive Summary)

“For the dedicated natural gas vehicles, the GHG results are somewhat mixed. When comparing with a substantially higher-powered diesel vehicle (Dedi02), overall savings of 4-8% were measured, but in more like-for-like tests (Dedi01 and Dedi03), the savings were, at best, 5% and, at worst, the dedicated gas vehicle’s emissions were some 15% higher than the diesel comparator. These results suggest that there are quite high efficiency losses under some operating conditions in moving from a compression ignition, conventional diesel engine to a spark-ignition one of similar power output.

None of the dedicated gas vehicles tested were found to emit significant quantities of methane, i.e. there was, for these vehicles, little evidence of any methane slip. The highest levels of methane detected were from the two articulated vehicles when operating under the long haul test cycle, but even under these conditions the quantities involved were of the order of just 0.2 – 0.5 g/km, which on a CO2 equivalence basis only increased the overall GHG emissions by about 1% compared to considering only the CO2 emissions.

For the current-generation dual-fuel vehicles operating on diesel and natural gas, levels of methane slip were found to be substantial under all test cycles (9 – 18 g/km). When considering only tailpipe CO2 emissions, both these retrofit conversions (Dual01 to a Euro VI diesel and Dual02 to a Euro V) showed savings of between 4% and 11%, findings very much in line with those of the Low Carbon Truck Trial. When factoring in the measured methane slip, however, the overall GHG impacts of the dual-fuel vehicles rise by, on average, 26% for the Euro VI conversion and 37% for the older Euro V system, thus turning the CO2 “savings” into overall GHG increases over the diesel-only baselines of around 10 – 35%.”
Future technology developments – Extracts from the LowCVP report

OEM dedicated gas technologies: “While some marginal improvements in overall efficiency are likely as the new, higher-powered engines come to market and other vehicle systems are optimized for dedicated gas engines, it seems unlikely that there will be a radical change in that basic issue. Further testing as and when such technologies become available would be needed to confirm the validity of this premise.”

OEM dual-fuel technologies: “The LCTT involved one OEM dual-fuel technology, as developed by Volvo and applied to Euro V vehicles. The draft LCTT report indicates that this system achieved both low/no efficiency losses and high gas substitution rates (of almost 50%), and overall CO2 savings of around 10% compared to an equivalent diesel vehicle.

This system was not tested as part of the current programme as it is no longer available, so there is no direct evidence on any methane slip. As an OEM system, however, one could reasonably expect little or no methane slip, through a combination of optimized combustion efficiency and effective methane catalysis. The fact there was no efficiency loss is a further indication of low methane slip – as high methane slip would inevitably mean high efficiency losses, too, through not combusting the methane and thus not extracting any usable energy out of it as it passes through the engine.

Volvo are now developing a new dual-fuel system, known as High Pressure Direct Injection (HPDI). Their lead technology partner in this endeavour is Westport. The HPDI system promises to be a radical departure from the previous technology, in that it will achieve very high gas substitution rates (over...
90%) because only a small amount of diesel fuel will be needed, simply to provide the “spark” to ignite the gas. By using the inherently more efficient compression-ignition cycle to combust the diesel, and thus provide the necessary flame to ignite the gas, the system should also achieve low or zero efficiency losses.”

Retrofit dual-fuel conversions: “This test programme has confirmed the indications based on earlier research that retrofit conversions of Euro V diesel vehicles to dual-fuel, diesel and gas (methane) operation are prone to high levels of methane slip. The test programme has further indicated that the only currently available conversion of a Euro VI vehicle also has a propensity to slip methane, typically in slightly lower quantities than the previous versions, but still enough to cause overall GHG increases of around 20%. To appeal to environmentally conscious fleet operators, the retrofit companies recognize that more needs to be done to address this issue. There are two main strategies to do so; improving the in-cylinder combustion of methane and raising the effectiveness of exhaust methane catalyst systems.” Several projects are currently working on these improvements.

Conclusions on Methane & CO2 emissions – Extract from the LowCVP report

“(Note these are based on a limited programme of tests, on a limited number of vehicles, so care is needed if extrapolating the results to a UK-wide level. The data presented are based on actual tailpipe emissions and take no account of the GHG benefits of bio-fuel options)

- The Euro VI dedicated gas vehicles tested through this programme exhibit very low levels of methane slip, typically adding less than 0.5% to the overall GHG impacts of those vehicles compared with the CO2-only case.
- Current generation (Euro VI) dedicated gas vehicles, running on natural gas (rather than bio-methane), are likely to have broadly similar GHG impacts compared to Euro VI diesel equivalents, to within +/- 10%.
- The only after-market dual fuel system currently available, converting a Euro VI diesel truck to diesel and natural gas operation, exhibited high levels of methane slip (sufficient to increase GHG emissions by c. 20%).
- The after-market dual fuel (diesel/CNG) conversion of a Euro V vehicle exhibited high levels of methane slip (sufficient to increase GHG emissions by c. 20-30%).
- Effective catalysis of methane is possible, as is more effective in-cylinder methane combustion. Two current Innovate UK/OLEV-funded projects are developing new retrofit dual-fuel systems. At least one OEM is developing its own dual fuel (diesel-methane) system.”

2.1.1.3.5 UK Low Carbon Truck Trial Evaluation (LCTT – 2016)

The LowCVP (Low Carbon Vehicle Partnership) evaluation analyzed above states that “the Low Carbon Truck Trial, which ran between 2012 and 2016, part-funded industry consortia to purchase and trial around 370 alternatively-fuelled commercial vehicles (most of which were dual fuel, diesel/natural gas aftermarket conversions), and to commission refuelling infrastructure. Nearly all the vehicles trialled (95% of all) were Euro V (with the remaining 5% being Euro VI). Euro VI gas-fuelled trucks were
unavailable until towards the end of the trial period and the project was therefore unable to gather comprehensive evidence on the emissions performance of these vehicles.  

The majority (85%, 315 vehicles) of trial vehicles were tractor units in the 40-44 tonnes gross vehicle weight (GVW) class. Others were 28-38T tractor units and 26T rigid. The LCTT involved only six dedicated gas trucks, all Euro VI and from the same manufacturer.

As mentioned in the LowCVP report, the LCTT final report’s “provisional focus was on CO2 emissions only, as calculated from the measured consumption of fuel and assuming full combustion. Its results do not take account of any emissions of unburnt methane (methane slip) experienced by the trial trucks. Additionally, the LCTT utilized blends of bio-methane and reported overall GHG savings net of these blends.”

The results from the LCTT were included in the conclusions of the LowCVP evaluation. The LowCVP evaluation indicates that findings of both studies on GHG emissions were in line.

Environmental Performance – Extract from the LCTT report

- “The dual fuel diesel/gas systems showed tank-to-wheel (TTW) CO2 emission savings of up to 12% and well-to-wheel (WTW) CO2 emission savings of up to 9%. The average emission performance across all dual fuel diesel/gas systems resulted in a 3% TTW and 0% WTW emissions saving. This includes an average biomethane blend of 5% which was used by the trial trucks.

- The dedicated gas vehicles showed TTW emissions savings of 11% and WTW emissions savings of up to 10%. This includes a biomethane blend of 15% used by the trial trucks. If this bio-blend were to be removed then the trucks would show an increase in emissions (4% TTW, 3% WTW) mainly due to the reduction in efficiency between the spark ignition dedicated gas trucks and the diesel comparator trucks. However, the trial and comparator vehicles were of different specification (Euro standard, power rating and transmission) meaning this is not a ‘like for like’ comparison.”

2.1.1.3.6 T&E Study “The role of natural gas and biomethane in the transport sector” (2016)

The Transport & Environment (T&E) study is assessing tank-to-wheel (TTW) emissions of heavy-duty natural gas vehicles. This study does distinguish between urban and long haul heavy goods vehicles (HGVs), “urban” being “smaller rigid trucks carrying loads between 3.5 tonnes and 16 tonnes (e.g. Iveco Eurocargo)” with dedicated spark ignited (SI) engine and “long haul” or “long distance” being “large articulated trucks typically carrying up to 44 tonnes (e.g., Volvo FM13 truck chassis)” with dual fuel engine.

The evaluated technologies are those available in the UK market early 2016. In the vehicle category that does correspond to the LNG Blue Corridors’ project vehicles, i.e. HGV long distance, the comparison of tailpipe GHG emissions is based on data for dual fuel LNG vehicles vs. diesel. These dual fuel vehicles are Euro V heavy duty trucks retrofitted to dual fuel, that were not designed do not meet the Euro VI emissions requirements. Moreover, as explained earlier, there are currently no vehicles using this technology homologated to Euro VI and emission results can differ significantly from one technology to another. The data from this T&E study can therefore not be extrapolated to Euro VI vehicles.

The results of tailpipe GHG emissions from this study are shown below (from section 2.2.3.2 in the T&E report). They represent CO2e emissions 6% lower for dual fuel diesel LNG trucks vs. diesel. As stated in the report, these figures assume complete combustion of the fuels, i.e. without accounting for any methane slips.

Methane slips (in section 2.2.3.3 of the T&E report) from these trucks are estimated as follows based on other studies (Ricardo-AEA 2014 and ICCT 2015):

- Currently very variable, ranging from less than 1gCH4/kWh to 10gCH4/kWh, equivalent to 28-280g CO2e/kWh vs. ~600g CO2/kWh for a comparable diesel vehicle.
- For 2020, the study assumes that methane slips will be at the maximum amount allowed by the Euro VI regulation, i.e. 0.5g CH4/kWh, which equates 14g CO2e/kWh.

The Euro VI OEM truck tests as well as some of the other studies analyzed in this report already show that methane slips from spark ignited and HPDI natural gas engines are below this Euro VI limit (see also below section 2.1.1.4 “Euro VI LNG truck test results”). As for dual fuel engines, the assumptions from the T&E study represent a worst case scenario and will need to be revised when such engines become Euro VI tested (e.g. in LNG BC project and HDGAS Horizon 2020 project) and homologated.
2.1.1.3.7 TNO reports “Truck of the Future – CO2 reduction year 2016” (2016) and “The Netherlands in-service emissions testing programme for Heavy-Duty 2011-2013” (2014)

In these studies, TNO has assessed real world CO2 and methane emissions of Euro V and Euro VI dedicated and dual fuel NG HDVs. The vehicles were tested with PEMS.

The 2014 tests feature two dual fuel Euro V trucks, one with a retrofit system (CNG) and the other with an OEM system (Volvo MethaneDiesel LNG). The test results show that the dual fuel trucks:

- Emit less direct CO2 than in diesel operation (~5-10% less);
- Emit substantial amounts of methane, especially for the retrofit conversion system, which lead to up to 50% more CO2e tailpipe emissions vs. diesel (retrofit) and ~10-15% more for the OEM system.

![Figure 2-8 Tailpipe CO2 equivalent emissions of two Euro V dual fuel concepts (Figure 16, TNO report, p.45)](https://www.tno.nl/media/3443/hdv_in_service_testing_tno_2014_r10641.pdf)

As stated in the report, the Euro VI emission legislation and its limits for methane emissions prevent the Euro VI homologation of such solutions and require the OEMs to apply more advanced technologies to reduce methane emissions.

The 2016 TNO report shows similar Euro V results and expects Euro VI dual fuel trucks to provide ~5% (up to 10%) tailpipe CO2e emission savings vs. diesel, including methane emissions. As for dedicated NG trucks, up to 10% tailpipe CO2e emission savings vs. diesel is also reported (for Euro V and Euro VI vehicles), with no details about methane emissions.

https://www.tno.nl/media/3443/hdv_in_service_testing_tno_2014_r10641.pdf Section 4.5 Real world emissions of dual fuel trucks on diesel and natural gas, p.44
2.1.1.3.8 ICCT Assessment of Heavy-Duty Natural Gas Vehicle Emissions (2015)

Like the 2016 West Virginia University study, this study is focused on the US market and GHG emissions of engines compliant with US EPA 2010 emission standards. It is considering two engine technologies: SI stoichiometric and HPDI. Given the US market focus, this study’s results are only partially applicable to the European market, for the same reasons as the West Virginia University study.

Tailpipe methane emissions were estimated from available literature (page 10-11). Some of these data (e.g. tailpipe emissions 0.65 to 0.75 g/kWh for HPDI, from year 2013) exceed Euro VI emission limits, which means that different engine design or calibration are applied to Euro VI engines (even if using the same technologies) and these data are not relevant for Euro VI vehicles.

As for crankcase and fueling system emissions (page 11-12-13), the ICCT report analysis is not relevant for Euro VI engines either for the following reasons:

- For SI engines, the estimated percentage of methane lost to the crankcase vent (between 0.4 and 0.8 percent) is for engines with open crankcase. Since the ICCT report was released Cummins Westport (CWI), the main manufacturer of such engines in the North American market, implemented closed crankcase ventilation for North American as well as European (Euro VI) engines.
- For HPDI engines:
  o The ICCT report expects they will lose little fuel as crankcase discharge because no fuel is introduced into the cylinder until just before ignition, and that fuel does not penetrate the crevice between the piston and cylinder.
  o ICCT does also report about fueling system venting, termed “dynamic venting” of the HPDI system. “It is in the nature of the HPDI fueling system that a small amount of gas may occasionally need to be vented during highly transient operation (sudden shifts in torque and speed) of the engine. This is a result of the dynamic behavior of the fuel rail pressure control system.” Based on numbers from a 2013 study, “the contribution of dynamically vented methane is 1.3 percent of the carbon dioxide equivalent, while tailpipe methane contributes 3 percent of the carbon dioxide equivalent.”
  o Since then, Westport announced HPDI 2.0 and its technology improvements, which include capture of regulator ventilation (i.e. dynamic venting). See also above comment about the 2016 West Virginia University study. Such engine and fueling system emissions will therefore not apply to a Euro VI HPDI engine.

Even though no specific data are available about crankcase and fueling system emissions of Euro VI engines, these emissions should not be seen as a major issues as they are included in the Euro VI emission limits. OEMs are therefore obliged to reduce them to the minimum in order to get their engines Euro VI homologated.

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2.1.1.3.9 JEC Well to Wheel analysis version 4a (2013)

For the present analysis, no relevant data can be taken from JEC report 4a for the following reasons:

- It is focused on passenger cars. All simulations were based on a common model vehicle, representing a typical European compact size 5-seater sedan. The TTW data from this report are therefore not applicable to trucks (different duty cycles, different engine technologies, etc.).
- It is outdated (published in 2013, analysis based on Euro 5 vehicles). Version 5 is underway to be prepared soon.

2.1.1.4 Euro VI OEM LNG truck test results

Test results for specific Euro VI LNG trucks are published by each OEM. Some of these results are available in other LNG BC project deliverables (D2.2 to D2.5) for the vehicles developed in the project.

For vehicles using spark ignited (SI) engine technology, Iveco Euro VI LNG trucks are demonstrating 90% less NMHC and 88% less CH4 emissions than Euro VI limits and 10% to 15% CO2 emissions reduction vs. diesel (Iveco Stralis LNG NP, report on testing in Poland, August 2016)\(^\text{28}\).

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\(\text{Figure 2-9 Iveco Stralis Euro VI LNG Emissions (Iveco)}\)

---

Very low NOx and particulate emissions to protect our health

<table>
<thead>
<tr>
<th>LNG vs. DIESEL Euro VI</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx emissions</td>
<td>-54%</td>
</tr>
<tr>
<td>NO2 emissions</td>
<td>-96%</td>
</tr>
<tr>
<td>CO2 emissions</td>
<td>-10%</td>
</tr>
<tr>
<td>External costs (2009/33 EU)</td>
<td>-4 885 € (-14%)</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>-15% (kg vs L)</td>
</tr>
</tbody>
</table>

PORTABLE EMISSION MEASUREMENT SYSTEM (PEMS)

Figure 2-10 Iveco Stralis Euro VI LNG PEMS Test Results (Iveco)

For MAN Euro VI CNG buses (SI engine), the emission results presented in the table below show emissions significantly lower than Euro VI limits: -87% for NMHC, -72% for methane.

![Figure 2-11 MAN CNG Buses Emission Results (MAN)](image)

For Euro VI vehicles using high pressure direct injection (HPDI) technology, approx. 18% to 20% tailpipe GHG emissions reduction vs. diesel is expected, including all methane emissions from the

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2.1.1.5 Real life vehicle tests from the LNG Blue Corridors project

A PEMS test was carried out in the LNG Blue Corridors project for the only truck which is available on the market and, in turn, available in the project, namely, the 400 hp LNG Stralis.

It is foreseen that the same PEMS test will be done for a diesel version, in order to get comparable data. As the time of this writing, the test on diesel truck is not yet available, but it will be when the project ends.

A summarized description of this test is explained below beside the final emissions results.

The goal was to test one heavy-duty vehicle in order to analyse the vehicle's behaviour differences regarding emissions and gas consumption.

Two types of equipment were used in order to analyse the emissions and gas consumption:

- OBS – One: for measuring the emissions of the engine
- Micromotion: for measuring the gas consumption

2.1.1.5.1 Emissions measurement equipment (OBS-One)

The Portable Emissions Measurement System (PEMS) used during the test allows the emissions of CO, CO₂, NOₓ, THC and CH₄ to be measured in real conditions.

This equipment has two main components: the gas analyser equipment (main body) and the exhaust measurement system type Pitot (exhaust flow and temperature). A GPS system was also used in order to acquire speed signal and GPS position.

The PEMS equipment measures the concentration of the pollutant gases and exhaust flow rate. Using these data, it is possible to calculate the quantity of grams that the vehicle emits in different driving conditions.

The following table shows the characteristics of the test PEMS equipment:

<table>
<thead>
<tr>
<th>PEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal identification number / Model number</td>
</tr>
<tr>
<td>Brand / Type</td>
</tr>
</tbody>
</table>
2.1.1.5.2 Flowmeter measurement equipment

The following table shows the characteristics of the test gas consumption equipment:

<table>
<thead>
<tr>
<th></th>
<th>Gas flowmeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal identification number / Model number</td>
<td>12524 / CMF025</td>
</tr>
<tr>
<td>Brand / Type</td>
<td>Micromotion / Coriolis</td>
</tr>
<tr>
<td>Date of calibration</td>
<td>September 28th, 2016</td>
</tr>
<tr>
<td>Serial number</td>
<td>14269076</td>
</tr>
</tbody>
</table>

2.1.1.5.3 Vehicle characteristics

The table below shows the vehicle characteristics:
### Truck

<table>
<thead>
<tr>
<th>Model</th>
<th>Iveco AS440T</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIN</td>
<td>W5NN1VRH60C354647</td>
</tr>
<tr>
<td>Engine</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Iveco</td>
</tr>
<tr>
<td>Capacity/ Max power</td>
<td>8,7 l / 400 HP @ 1,700Nm</td>
</tr>
<tr>
<td>Fuel</td>
<td>LNG</td>
</tr>
<tr>
<td>Tyres - Pressure (bar)</td>
<td>1\textsuperscript{st} and 2\textsuperscript{nd} axle: Michelin Multiway 315/70 R22,5 156/150 - 8,5</td>
</tr>
<tr>
<td>Initial / final mileage (km)</td>
<td>354,0</td>
</tr>
<tr>
<td>Test weight (kg)</td>
<td>40,023</td>
</tr>
</tbody>
</table>

### Trailer
2.1.1.5.4 Test procedure

Emissions and gas consumption measurements were performed following the next steps:

- Installation of the emissions and gas consumption equipment.
- Performance of the emissions and gas consumption in five different steady-state speeds, starting at 50 km/h and increasing the vehicle speed every 10 km/h up to maximum speed.
- Performance of the emissions and gas consumption tests following the route IDIADA – Fraga – IDIADA, described above.
- Uninstallation of the emissions equipment on the first vehicle.

2.1.1.5.5 Routes characteristics

The table below shows the theoretical characteristics of the tested route:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test duration (s)</td>
<td>12.000</td>
</tr>
<tr>
<td>Distance (km)</td>
<td>240.0</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>75.0</td>
</tr>
<tr>
<td>Maximum altitude (m)</td>
<td>573.0</td>
</tr>
<tr>
<td>Minimum altitude (m)</td>
<td>87.0</td>
</tr>
</tbody>
</table>

*Table 1 Characteristics of the route*

The picture below shows the route IDIADA-Fraga by using Google Earth tools:
2.1.1.5.6 Emissions results and gas consumption results in IDIADA-Fraga-IDIADA route tests

The table below shows the Fraga route characteristics:

<table>
<thead>
<tr>
<th>Test date</th>
<th>March 23\textsuperscript{rd}, 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test start (UTC)</td>
<td>09:00</td>
</tr>
<tr>
<td>Total test duration</td>
<td>s 11.546,0</td>
</tr>
<tr>
<td>Distance</td>
<td>km 237,1</td>
</tr>
</tbody>
</table>
The table below shows the emissions and gas consumption results obtained (test performed without air-conditioning) in the IDIADA-Fraga-IDIADA route.

<table>
<thead>
<tr>
<th>Gas</th>
<th>CO</th>
<th>CO₂</th>
<th>THC</th>
<th>CH₄</th>
<th>NOx</th>
<th>Gas consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>g</td>
<td>314,73</td>
<td>216,905,6</td>
<td>22,36</td>
<td>13,146</td>
<td>40,77</td>
</tr>
<tr>
<td></td>
<td>g/km</td>
<td>1,327</td>
<td>914,80</td>
<td>0,0943</td>
<td>0,0554</td>
<td>0,1720</td>
</tr>
</tbody>
</table>

The vehicle started in cold conditions the route.

During the motorway phase, the vehicle run at its maximum speed.

The following figures show the behavior of the emissions for each measured gas during the route.

CO emissions

Figure 2-17 CO emissions FRAGA route
CO2 emissions

![CO2 emissions Fraga route](image1)

*Figure 2-18 CO2 emissions Fraga route*

THC emissions

![THC emissions Fraga route](image2)

*Figure 2-19 THC emissions Fraga route*
NOx emissions

Figure 2-20 NOx emissions Fraga route

2.1.1.5.7 Summary of the emissions and gas consumption results

As a summary, the following table shows the emissions and gas consumption results obtained in the different tests described above.

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Gear</th>
<th>Engine speed (rpm)</th>
<th>CO (g/km)</th>
<th>CO₂ (g/km)</th>
<th>THC (g/km)</th>
<th>CH₄ (g/km)</th>
<th>NOₓ (g/km)</th>
<th>Gas consumption results (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>11ᵗʰ</td>
<td>1.174,5</td>
<td>0,0000*</td>
<td>523,21</td>
<td>0,0018</td>
<td>0,0000*</td>
<td>0,0001</td>
<td>207,4</td>
</tr>
<tr>
<td>60</td>
<td>12ᵗʰ</td>
<td>1.094,0</td>
<td>0,0040</td>
<td>535,48</td>
<td>0,0080</td>
<td>0,0047</td>
<td>0,0076</td>
<td>211,2</td>
</tr>
<tr>
<td>70</td>
<td>12ᵗʰ</td>
<td>1.273,3</td>
<td>0,0007</td>
<td>589,53</td>
<td>0,0044</td>
<td>0,0033</td>
<td>0,0104</td>
<td>234,8</td>
</tr>
<tr>
<td>80</td>
<td>12ᵗʰ</td>
<td>1.452,1</td>
<td>0,0000*</td>
<td>666,99</td>
<td>0,0039</td>
<td>0,0020</td>
<td>0,0119</td>
<td>265,3</td>
</tr>
<tr>
<td>89</td>
<td>12ᵗʰ</td>
<td>1.610,0</td>
<td>0,0000*</td>
<td>757,19</td>
<td>0,0055</td>
<td>0,0006</td>
<td>0,0154</td>
<td>302,5</td>
</tr>
</tbody>
</table>
2.1.2 Off-engine emissions

Off-engine emissions from LNG vehicles can consist of the following main types of emissions:

- Venting due to LNG boil-off in the tank: This would happen if a truck was out of service for far longer than the tank design hold time. The pressure inside the tank would rise until it reaches a certain pressure (determined for each system) at which the safety device “pressure relief valve” (PRV) would open. The tank could then lose a high fraction of its fuel unless the fuel in the tank was recovered e.g. before parking the vehicle.
- Manual venting of LNG vehicle tanks to atmosphere: It was observed in some cases in North America that some drivers manually vent their tank to atmosphere before refueling in order to avoid venting back to the station.
- Vehicle fuel system leaks: Even though there could also be methane emissions from leaks, they are usually considered negligible as storage and vehicle systems are designed to avoid leaks as per UNECE R110 regulation.

2.1.2.1 Vehicle technology comparison

The different off-engine systems – or LNG fuel systems – of Euro V LNG trucks were already described in LNG BC D2.1 “Euro V final technical solutions”, section 3 (starting page 35). As explained in LNG BC D2.6 “Other LNG vehicle technologies”, section 2.2.3, the same solutions have the potential to be used in Euro VI LNG trucks. A summary of the Euro VI solutions is presented here.

The current Euro VI LNG trucks featuring SI engines are all equipped with passive LNG systems. These vehicles need to be fueled with saturated LNG (i.e. pressurized to ~ 8 bars) and rely on the tank pressure to feed the engine. All Euro V LNG trucks with SI and dual fuel engines operating in Europe are using passive LNG systems.

Euro VI LNG trucks featuring HPDI engines will be equipped with active LNG systems as described in section 3.2 of LNG BC D2.1. The HPDI off-engine system includes a hydraulically driven cryogenic LNG pump integrated in the LNG tank that pumps LNG to 350 bar, as needed for the HPDI engine. These vehicles can be fueled with unsaturated LNG (i.e. “cold” LNG at ~-160°C, 1-3 bar).

Active LNG systems for SI and dual fuel engines are currently commercialized in other parts of the world but not in Europe yet. One is being developed in the EU funded Horizon 2020 project “HDGAS”. Similarly to the HPDI system, the vehicles using such systems can be fueled with unsaturated LNG.

All these LNG fuel systems are capable to vent LNG back to the station, either with a dedicated vent line (like all current LNG trucks in Europe) or through the fill line (for HPDI).
When fueled with unsaturated LNG, active LNG systems used in SI vehicles improve LNG tank hold time by approx. 5 days compared with passive systems fueled with saturated LNG. They also reduce the need to vent back to station before refueling because the tank pressure drops while driving.\(^{31}\)

### 2.1.2.2 Euro VI requirements

The off-engine part of LNG vehicles and their specific components are regulated by the UN ECE regulation No. 110 (referred to as “R110 regulation”), Addendum 109, Revision 3\(^{32}\) and its amendments 1 to 4. This revision focused on CNG and LNG vehicles entered into force in June 2014. All LNG vehicles and their components commercialized in the EU must comply with this regulation. See also LNG BC D4.1 for more details about LNG vehicle regulations.

The R110 regulation does include a number of requirements to prevent methane emissions from LNG vehicles:

- 18.3.4.4. “The LNG system shall contain the following components: LNG pressure relief valve; LNG venting system; LNG valve (manual)”. These components are mandatory for safety reasons.
  - “4.23. “Pressure relief valve (discharge valve)“ means a device that prevents a pre-determined upstream pressure being exceeded.”
  - “4.46. “Venting system” means a system that controls the release of natural gas from the LNG storage system.”
  - “4.22. “Manual valve” means a manual valve rigidly fixed to the cylinder or tank.”
- Annex 3b - 2.7. “Vehicle LNG tank(s) shall have a design hold time (build without relieving) minimum of 5 days after being filled net full and at the highest point in the design filling temperature/pressure range.”
- Annex 4O – LNG fuel pump 2.6.3. “The pressure control device is not allowed to vent natural gas to atmosphere during normal function.”
- The LNG system shall be tested for leakage. A number of other mandatory tests (e.g. drop test, durability test, vibration resistance test, corrosion resistance test, etc.) are also meant to ensure proper resistance of the LNG system without leakage.
- Annex 3b - 2.1.3. Periodic requalification – “Recommendations for periodic requalification by visual inspection or testing during the service life shall be provided by the tank manufacturer on the basis of use under service conditions specified herein. Each tank shall be visually inspected at least every 120 months after the date of its entry into service on the vehicle (vehicle registration), and at the time of any reinstallation, for external damage and deterioration, including under the support straps.” 2.1.4. and 2.1.5. – Tanks that have been involved in a vehicle collision or in fires shall also be re-inspected.

The main requirement preventing boil-off from the LNG tank is the minimum 5 days hold time without relieving gas.


\(^{32}\) Accessible from [https://www.unece.org/trans/main/wp29/wp29regs101-120.html](https://www.unece.org/trans/main/wp29/wp29regs101-120.html)
In addition to these regulatory requirements, off-engine methane emissions from LNG vehicles should be avoided by proper operation of the vehicles. Such operative requirements are not included in vehicle regulations.

2.1.2.3 Literature analysis

So far very few studies have characterized off-engine methane emissions from HD NGVs.

The ICCT 2015 report on NG HDV emissions assessment\(^{33}\) does address this topic but doesn’t make any assumption on the magnitude and frequency of these emissions due to data limitations. The French Equilibre Project has measured tailpipe HC emissions on several trucks. Based on these data and other available data and input from OEMs, the recently published European Greenhouse Gas Intensity of Natural Gas study has estimated CH4 emissions of Euro VI natural gas trucks.

2.1.2.3.1 European “Greenhouse Gas Intensity of Natural Gas” report (2017)

In this study, the assumption that the actual CH4 emissions are half of the Euro VI regulatory limit of 0.5 g CH4/kWh was used as an approximation for both types of Natural Gas HDV (SI and HPDI). The report states that this is a conservative estimate, since some of the HDV manufacturers achieve CH4 emissions that are considerably below the assumed value, which can lead to corresponding reductions of the overall GHG emission.\(^{34}\)

2.1.2.3.2 French “Projet Equilibre” preliminary results (2017)

In August 2016, the Equilibre project published a first report summarizing tailpipe HC emissions measured on four natural gas trucks, light and heavy duty, all using SI engines (report in French)\(^{35}\).

Measured emissions were below 0.25g/kWh on average (all types of routes and vehicles). Only one vehicle had emissions close to the 0.5g/kWh limit on highway use. Other measures were all below 0.25g/kWh.

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34 Section 6.2.3, page 76 of the report
The West Virginia University study “Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector” (2016) does address these emissions, as mentioned in the previous section. Tank venting is explained in the following extract of the article:

“A truck out of service for far longer than the tank design hold time would lose a high fraction of its fuel unless the fuel in the tank was recovered. LNG storage tank boil-off, PRV venting and manual venting of on-board LNG vehicle tanks by drivers prior to fueling were observed during the study. Vehicle tanks may also be vented prior to maintenance.”

- Tank venting: Boil-off “venting emissions from in-use LNG tanks could not be characterized directly in the field because of the intermittent nature of events.” These emissions were estimated based on laboratory observations and modeling.
- Manual venting of LNG vehicle tanks to atmosphere: The study estimated “the vent mass from ten observations of manual venting of vehicle LNG tanks” at 4.2% of the tank fuel mass on average for the vehicles that were manually vented, illustrating “that this practice could be a significant contributor to overall methane emissions from LNG vehicles”. However “the statistical frequency of how often tank venting incidents occur throughout the PTW sector was not determined”. “While complete statistical data on manual venting was not collected, it was observed that a large majority of trucks did not vent their tanks at the station prior to fueling.”
- Vehicle fuel system leaks: “Leak audits were performed on all vehicles included in the emissions study. No continuous leaks were found from CNG vehicles while a single leak identified on an LNG vehicle that was below the quantification limit of 0.24 g/h.”

36 Accessible from http://pubs.acs.org/doi/full/10.1021/acs.est.5b06059
According to this study, vehicle manual vent methane emissions represent 0.6 g/kg fuel (4.4% of PTW methane emissions from HG NGVs) and vehicle fuel tank methane emissions (boil-off) represent 0.5 g/kg fuel (4.0% of PTW methane emissions from HG NGVs).

2.1.3 Summary of current GHG emissions for Euro VI vehicles

<table>
<thead>
<tr>
<th>Emission Type</th>
<th>Euro VI limit</th>
<th>Spark Ignited Euro VI</th>
<th>HPDI Euro VI</th>
<th>Dual Fuel retrofit (not Euro VI compliant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-engine - exhaust</td>
<td>NMHC 0.16 g/kWh CH4 0.5 g/kWh</td>
<td>CO2 (excluding CH4) -5% to 10% vs. diesel CH4 very low &lt;0.5 g/km (at least 50% less than Euro VI limit) GHG -5% to 10% vs. diesel (+10% to 15% worst case)</td>
<td>CH4 &lt;0.2% of total fuel flow GHG -18% to 20% vs. diesel</td>
<td>CO2 (excluding CH4) -5% to 10% vs. diesel CH4 high 9 to 18 g/km GHG ~+20% to 30% vs. diesel (up to +50%)</td>
</tr>
<tr>
<td>On-engine - venting</td>
<td>Included in above limit</td>
<td>Avoided if closed crankcase, included in above value</td>
<td>Captured, included in above value</td>
<td>No information available, not included in exhaust value</td>
</tr>
<tr>
<td>Off-engine – LNG tank boil-off</td>
<td>5 days min. LNG tank hold time</td>
<td>Negligible in good operating conditions 0.5 g/kg fuel (NA study)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off-engine – manual venting</td>
<td>Emergency use only</td>
<td>Negligible in good operating conditions No evidence of manual venting in Europe 0.6 g/kg fuel (NA study)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other – leaks, etc.</td>
<td>N/A</td>
<td>Negligible</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-23 Summary of current GHG emissions for Euro VI vehicles
2.2 Solutions for further improvement

This section provides suggestions for further reduction of methane (CH4) emissions from LNG vehicles. Solutions for further reduction of CO2 emissions from LNG vehicles are not addressed here – even though this important topic is also being addressed by the industry – as they are outside of the scope of this report and directly related to engine technologies.

2.2.1 Combustion strategy

With the solutions implemented on Euro VI vehicles (such as closed crankcase ventilation / capture of dynamic venting), methane slips from the engine are avoided, as per Euro VI regulatory requirement.

Combustion strategies such as direct injection (non-premixed combustion), late-cycle injection, tighter control over the injection event, optimization of combustion temperatures and others can be applied to help improving the in-cylinder combustion of methane and therefore reducing unburned methane emissions when needed. Such solutions are already being implemented (e.g. HPDI engines) or developed e.g. in the EU funded HDGAS project mentioned earlier and are expected to become more widely available in the next few years.

2.2.2 After-treatment system

As mentioned earlier in this report, the current methane catalysts are not effective in capturing unburned methane emissions from lean burn systems, which is particularly an issue for dual fuel vehicles. New methane oxidation catalysts would be required to enable dual fuel vehicles to comply with Euro VI emissions requirements. Such developments are underway e.g. in the above mentioned HDGAS project.

2.2.3 Active LNG system

Keeping LNG as cold as possible is the best way to minimize venting. As mentioned in section 2.1.2.1., active LNG systems, i.e. LNG tanks with integrated pump, enable LNG trucks to be fueled with very cold, unsaturated LNG (e.g. ~-160°C). Using cold LNG at 1-3 bar instead of warm, saturated LNG at ~8 bar provides approx. 5 days of additional hold time for a full truck tank. The total hold time of at least 10 days achieved with cold LNG is then sufficient to avoid methane venting from the tank to the atmosphere even in most cases of long parking.

2.2.4 Use of boil-off gas

Low pressure LNG systems (e.g. those of current SI trucks, which feed the engine with NG <15 bar) have the ability to directly use boil-off gas from the LNG tank to feed the engine. With the current trend of improving engine efficiencies and performance by increasing the LNG system pressure (e.g. to ~50 bar for SI direct injection engines and >300 bar for HPDI), this direct use of boil-off gas becomes...
impossible as its pressure is not sufficient to feed the engine. For such medium and high pressure systems, other solutions aiming at using boil-off gas on the vehicle could be implemented; some are already being investigated or developed by industry players.

2.2.5 Training

In addition to the regulatory requirements, off-engine methane emissions from LNG vehicles should be avoided by proper operation of the vehicles. This requires thorough training of the truck drivers, maintenance engineers, station operators and monitoring of their behavior.

Operators should be well aware of the consequences of methane venting (safety, environmental and financial), trained on best practices (including e.g. procedure to be followed before long parking periods) and be rewarded for applying best practices related to LNG truck operation including no methane venting to atmosphere. Such instructions could be provided by OEMs, station operators as well as truck operators themselves.

As manual venting does not seem to be an issue in Europe, there is currently no need to put much emphasis on this topic. However it is important to ensure manual venting does not become a common practice by proper behavior’s monitoring.

2.2.6 Information

In order to help the operator making the right decisions to avoid methane emissions, it is important to provide him with accurate information.

For example, providing real time hold time information to the fleet operator and driver is expected to facilitate refueling planning and further help avoiding venting.

2.2.7 Inspection

If deemed necessary, regular inspection procedures of LNG vehicles could be strengthened to include additional leak detection operations. However, according to the present analysis, such leaks are considered negligible and very infrequent, especially given the R110 regulatory requirements on tank and system design and inspection. Therefore additional inspection procedures are not recommended at this stage.
3 Design solutions on the station

3.1 Introduction

The introduction of LNG stations on the main transport corridors is one of the goals of the LNG Blue Corridors project, and an essential step for the introduction of LNG as an alternative transport fuel.

LNG is a clean, low-carbon and climate-friendly fuel, but the environmental performance of LNG is depending on the management of the entire LNG supply chain in terms of methane leakage.

LNG stations are also a potential source of methane leakage if not managed properly. There are little accurate date available, but it can be estimated that – depending on the station design and practices on the station – up to 5% of the LNG that is delivered to the stations is emitted to the atmosphere.

A study on the state of the LNG stations worldwide revealed that 44% of the stations have no BOG-management system.  

In this chapter, we are highlighting the different technologies and practices that are available in order to avoid boil-off being released from the LNG stations and allowing zero-emission LNG stations.

3.2 Insulation

LNG is typically delivered to a station at temperatures of -155°C to -140°C.

As the new generation Euro VI trucks are designed to be fueled with LNG at max. -120°C, it is critical to insulate the storage tanks and the equipment of the station against the ambient temperatures, and to avoid the temperature of the LNG rising above -120°C.

3.2.1 Piping

The heat leak at an LNG station is for an important part related to the design of the piping.

One of the parameters is the presence and type of insulation.

Vacuum insulated piping is the most expensive, but will give the best result. This kind of insulation may have a heat leak that is up to 5 times lower than foam insulated piping.

This piping is especially important between the pump and the dispenser, as this is very frequently used, this is, by every refueling of a vehicle. The insulation in the filling pipe of the storage tank is obviously much less important in this respect.

Vacuum insulation is also available for flexible piping and for underground piping. Vacuum monitoring is also an available option.

37 A review of liquefied natural gas refueling station designs. Amir Sharafian, Hoda Talebian, Paul Blomerus, Omar Herrera, Walter Mérida  
Clean Energy Research Centre, The University of British Columbia, Vancouver, BC, Canada V6T 1Z3
Foam insulation of the cryogenic piping is an alternative, less expensive option. It can be a solution for small, short piping at the pumps, where vacuum insulation would be too expensive. There is also a foam insulation with metal jacket possible. This is a more robust solution than mere foam insulation.

Apart from the vacuum insulation, also the length of the piping is an important parameter. Crucial in the heat management of the station is the distance between storage tank, pump, and dispenser. It may be a challenge, especially when an LNG installation is to be added to an existing fuel station, to keep this distance to a minimum. 10 to 15 meter can be managed, but more may become critical.

Finally, there is also the matter of the connection of different pipes. The number of screwed connections should be minimized. This connection (2 flanges connected with screws) adds mass to the piping, and this mass will increase the heat input each time is to be cooled down.

3.2.2 Pumps

Depending on the station design, the LNG pump can be an integral part of the station, necessary to feed the LNG into the fuel tank. This pump is usually installed in a sump, submerged in LNG. Despite vacuum insulation, there is a heat leak at the pump.

Therefore, stations without this pump have one source less of heat inleak. On the other hand, this station design forces to pressurize the gas phase of the storage tank, which could also affect the holding time of the LNG. This technology could also be unsuitable to supply LNG to multiple dispensers, or if the throughput of the station becomes very high.

3.2.3 Storage tank

The storage tank of an LNG station is one of the main components. The design and sizing is essential for the pressure build-up and holding time of the LNG.

The state of the art LNG storage tanks for small scale LNG applications consist of an inner stainless steel vessel, and an outer carbon steel jacket. In between, there is usually vacuum insulation and perlite grains.

In the Journal of Natural Gas Science and Engineering, Amir Sharafian calculated that the holding time of LNG in tanks with LCI (Layered Composite Insulation, similar insulation value than vacuum insulation with perlite) offers 8 to 10 times the holding time of tanks using polyurethane insulation.
Most commonly, the tank is installed in vertical position. This position reduces the used space, allows thermosyphon design and accurate level measurement. It is also easier to empty the tank to a lower level, and thus using the maximum capacity of the tank. However, also horizontal position is possible.

Also the size of the LNG storage tank matters. Even if – from a logistics point of view – bigger tanks are interesting, oversizing will generate more boil-off. This is because bigger tanks have a bigger surface area, and thus more boil-off generation.

### 3.3 LIN cooling

LIN (Liquefied Nitrogen) has a boiling point of -196°C, which is lower than the boiling point of LNG (-162°C).

This makes LIN a suitable coolant for LNG, because it can cool down the gas phase of the LNG in the storage tank, re-condensing the gas, and lowering the pressure inside the storage tank.

As a consequence of this process LIN will boil-off. Nitrogen is an inert gas, non-explosive, non-harmful for the environment and with no direct climate effects.

LIN cooling is possible by the installation of specific equipment on the station. The main components are a (cryogenic) LIN storage tank, a pump and a heat exchanger (coil).

This equipment can be installed on a temporary basis, in order to keep the boil-off under control at the station start-up, when the throughput of the station is insufficient to avoid excessive pressure build-up. When the number of trucks is growing, boil-off could be under control due to a better management of logistics and higher output volume.

Apart from the cost of the equipment, there is also the cost of the LIN consumption to be considered. In worst conditions, the consumption of LIN can be in the range of 1kg LIN for 1 kg of LNG supplied to the vehicle.

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38 A. Sharafian et al. / Journal of Natural Gas Science and Engineering 36 (2016) 496e509
3.4 Saturation-on-the-Fly

When a new LNG delivery is supplied to a station, due to the low temperature of the ‘fresh’ LNG, the pressure inside the storage tank will collapse, and it will take some time before the pressure will rise to a critical, close to the maximum allowable pressure. At the end of the cycle, short before the refill, the pressure will usually be high, unless the delivery of LNG is consumed in very short time.

Boil-off management intends to increase the holding time of the LNG, this means keeping the LNG at a lower temperature and pressure during a longer time.

In this respect, it would be advantageous not to condition the LNG to the saturation pressure which is required by most of the vehicles (6 to 7 bar, approx. -130°C) but to leave it in the condition as it is after the refilling.

This is possible by using a saturation-on-the-fly system. This system will saturate only the LNG which is required for the actual refueling of a truck, instantaneously, or ’on the fly’. The bulk LNG load is not conditioned.

This system allows the LNG to remain cold for a longer time, compared to the bulk saturation system.

3.5 Micro-liquefaction

A relatively new solution to manage the condition of the LNG is the use of a micro-liquefaction unit.
This unit will actively cool the boil-off gases, and transform them into liquid LNG by using a compressor, refrigerant circuit, heat exchangers and electrical power. The liquid LNG is the returned to the storage.

The unit can be stand-alone, and could even be removed in case that the throughput of the station increases, allowing to run the station without it.

Using this liquefier, the holding time could be without any limitation, and without changing the gas composition, but it will involve some power consumption (15kW max. absorbed power), and of course additional capital cost, which is estimated around 200.000€.

### 3.6 Gas phase pressure control

Following methods of boil-off gas management are intended to make use of the boil-off gas rather than venting it to the atmosphere. As mentioned, vented gas is harmful, and has significant global warming effects. By using the gas for other applications, the BOG is finally burned, and thus converted to CO₂ and H₂O, which has much less global warming impact. On top of that, the energy from the BOG is used efficiently, and has a positive contribution for station operator.

One important aspect of gas phase methods, is that high quantities of BOG may be removed from the storage tank, the gas composition will change over time. The Boil-off gas consists mainly of the lighter fractions of the LNG (methane and nitrogen). So, over time, there will be an overconcentration of the heavier hydrocarbons (ethane, propane). This will be equivalent to a lower Methane Number of the LNG. This phenomenon is also known as ageing of the fuel.

Especially on the first generation Dual Fuel trucks (e.g. Volvo Euro V) the engines may be sensitive to low Methane Number, since this can lead to knocking of the engine, and consequent damage.

Care should be taken not to withdraw too much BOG, and to empty from time to time as much as possible from the storage tanks, to get rid of the old, aged LNG.

#### 3.6.1 Gas injection in grid

If a local gas grid is available to accept the boil-off gas, than it can be a good solution to avoid venting the gas.
This solution is depending on some criteria that should be considered:

- The grid is a local, private one, and not a public one. It is not likely that public gas grids will accept boil-off gas.
- The pressure in this grid should be lower than the set point for BOG-venting to that grid. E.g., if it is chosen to vent BOG to a grid from 8 bars onwards, then this grid cannot be operated at 8 bars. Some pressure difference is necessary to have a proper flow.
- Sufficient flow in this grid. If there are longer periods without any gas consumption through this grid, there will be no possibility to inject BOG in the grid, and the MAWP could be reached anyway, resulting in BOG venting to atmosphere. If the grid is used for heating during winter season, problems may be expected during the summer season, when BOG issues are the biggest.
- Conditioning of the BOG:
  - It will be necessary to control the temperature of the gas. A gas heater is advisable.
  - If the grid is operated with odorized gas, odorisation of the BOG may be necessary.
  - Attention should be drawn to the Wobbe index of the grid gas and the BOG.

### 3.6.2 Cogeneration

There is little information available about such application, but nevertheless it could be evaluated – on a case by case basis – to consume the BOG using cogeneration (production of heat and electricity through a thermal engine).

Correct sizing of the unit in relation to the expected BOG volumes will be crucial.

Again, as in previous solution, it must be considered if there is sufficient demand for power and heat at all times, in order to consider this system as good BOG management system.

One could even consider the BOG feeding fuel cells to produce electrical power. This technology is under development.

### 3.6.3 CNG production

A more common practice is to add a compressor to the station, which will recompress the BOG to a high pressure CNG storage. This can be connected to a CNG dispenser, and the BOG can be sold to drivers of CNG vehicles.

Since most stations are anyway public stations, CNG can also be offered publically, and this practice will help to boost the CNG market along the LNG market.

Care should be taken to the legal requirements for CNG fuel. Most countries will not allow the use of non-odorized gas, so an odorizer will be required.

Again, if there are not enough cars refueling at the station, once the storage of CNG is full, it will not allow further pressure reduction in the storage tank, and gas may be vented anyway. In that case, it could be considered to transport the gas to a daughter station. See mobile CNG pipeline concept, as described in 4.1.3
On the other hand, there is a risk to take too much BOG from the LNG storage, if the CNG sales are successful. As mentioned before, this could have a negative impact on the Methane Number of the LNG. An L-CNG pump will also produce CNG, but from the liquid phase of the tank, rather than from the gas phase. This will not change the gas composition.

Therefore, a combination of a (small) compressor for the gas phase BOG and an L-CNG pump could be the best solution, avoiding BOG venting, but also avoiding ageing of the fuel and allowing high sales of CNG.
4 Good practices

LNG is a great fuel only if it is handled properly. Keeping LNG as cold as possible is the best way to minimize venting. Further improvement of LNG station and vehicle system technologies should be considered but will not replace proper handle of LNG by operators. Therefore some good practices to help station and vehicle operators minimizing LNG boil-off and venting are suggested in this section.

4.1 Increase throughput of the station

4.1.1 LNG base volume

The golden rule for the start-up of an LNG station, is to have the base volume guaranteed. An operator should be sure to have a minimum turnover in order not to face big costs for boil-off gas management.

Therefore, upfront teaming up with partners (fleet operators) is a must, and will prevent a lot of stress in the start-up phase of the project.

Below graphs shows the example of a station with unsaturated LNG, with 3 scenarios: 5, 10 or 20 vehicles per day. It shows that with 10 or 20 vehicles (roughly 1600 or 3200kg/day), the MAWP will not be attained. However, with only 5 vehicles/day (approx. 800kg), the MAWP is reached after about 18 days. The second graph shows that at that time (after 18 days), the tank is not empty yet. In this condition, in order to avoid methane venting, it will be necessary to refill the tank partially and collapse the vapour pressure, or find an alternative way to decrease the pressure (e.g. LIN cooling, recompressing to CNG, ...).

![Figure 4-1 LNG pressure in relation to fuel delivery rate](image)

39 Source: Amir Sharafian, Ph.D., University of British Colombia, Assessment of Boil-off Gas Management in Liquefied Natural Gas Refueling Station Designs
4.1.2 L-CNG production

As mentioned in previous chapter, CNG production from the gas phase can be an effective solution to prevent the emission of BOG to the atmosphere.

If reasonable sales of CNG are expected, it can be a good idea to install an L-CNG pump. This reciprocating pump is much more efficient in terms of output per KWh electrical power, because there are no pump losses. This technology will not affect the gas quality compared to the gas compressor, since it takes the liquid phase of the tank to produce its CNG.

Most L-CNG pumps have a big output, in the range of 500 kg/h, which make them suitable to supply a big fleet of vehicles, including commercial vehicles (light and heavy duty), or a big public CNG station. Consequently, the CNG sales will help to increase the frequency of LNG refills, and to shorten the filling/emptying cycles of the station.

On the other hand, each time the L-CNG pump has to be started, it requires to be cooled down, and this cooling down is generating BOG. It is important to make sure that the CNG storage is big enough to allow less restarts of the L-CNG pump for a given CNG quantity.

4.1.3 Supply to daughter station

It is true that the share of CNG on a combined LNG/CNG station may represent up to 50% of the throughput. This is a very effective way to manage BOG, but it many cases, the CNG sales will be much lower, because the location for LNG stations (e.g. in logistic, industrial areas) may not be the ideal sales location for CNG.

In order to make use of the L-CNG capacity on a station, it could be worth considering selling the CNG on a more suitable location, for example near a city. The CNG can be stored on CNG trailers, and up to 7 tons or more of gas can be transported to a daughter station. This station is not connected to the gas grid, but instead uses a booster to empty the trailer with CNG and to supply it to vehicles.

Ideally, 2 trailers are used. One is emptied at the daughter station, while the other is filled at the mother L/CNG station.

The efficient way of producing CNG from LNG, with the L-CNG pump, is allowing to transport the gas to a remote location, while still being economically competitive. Moreover, the quality of gas
originating from LNG is in many cases higher than the gas from the grid in terms of purity (absence of oil, water) and calorific value (allowing vehicles to make more mileage per refueling).

### 4.2 Management of LNG logistics

#### 4.2.1 Frequency of supply

Every LNG refilling of cold LNG will manage to drop the pressure inside the storage tank, and will create some time before the pressure will raise back to a critical level.

Even if the LNG level in the tank is not requiring a refill, it could be useful to order a refill of e.g. 50% of the tank, just to have the LNG back in the right condition, and to collapse the pressure in the vapor phase of the tank.

Of course, refilling just a part of the tank will lead to increased logistic costs for the operator of the station. On the other hand, this method of controlling the pressure and temperature does not require expensive investments in liquefiers or LIN-cooling. Especially if the LNG terminal is not too far, more frequent (partial) refills could be a cost-effective alternative.

It could also be considered to share a truck load of LNG over 2 (or more) stations. One truck load is typically 20 tons, so each station could take a share of this 20 tons load in order to have better BOG control at a moderate logistical cost. Even if the stations are from a different operator, there is a win-win situation if they collaborate to share the truck loads.

#### 4.2.2 LNG level in the station’s tank

Another practice which can help to keep the temperature low over time, is to keep the level of LNG inside the tank to a high level.

If the level of LNG is on the low side, the heat in leak will have a bigger impact on the totality of the LNG mass, than if the level is high.

So, in case that the tank is refilled partially anyway, it is better to refill from half to full than from empty to half.

Care should be taken if the BOG is removed rather than conditioned, because the LNG could age, and then it could be a good idea to empty the tank to a lower level from time to time.
4.3 Management of truck refueling

Even if the station is designed to have the lowest possible BOG generation, there could be another source of BOG: the trucks.

Depending on the state of the fuel upon arrival at station, the vehicle tank will need to be vented prior to or during the refueling:

- If the LNG is warm, the pressure from the station will not overcome the vehicle tank pressure, and venting to the station is necessary. This requires also the pressure of the station tank not to be too high.
- If the LNG is cold, or not too warm, the pressure from the station will be able to overcome the vehicle tank pressure, and the BOG in the vehicle tank will be condensed. In that case, the vent line of the station should even not be connected.

4.3.1 Avoid hot tanks

LNG vehicle tanks are designed to hold their product for a longer time, even in case of longer periods of non-use.

However, the LNG will eventually increase in temperature and pressure, and hot tanks will need to be vented to the station in order to refill them properly.

Following precautions can be considered, to minimize the inconvenience of hot tanks:

- For a short period of inactivity: refill the tank upfront. A full LNG tank will have a longer holding time.

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40 Amir Sharafian, University of British Columbia, Assessment of Boil-off Gas Management in Liquefied Natural Gas Refueling Station Designs
• For a longer period of inactivity: empty the tank upfront, in order to avoid product loss and ageing of the fuel. In case of dual fuel truck, or truck with CNG back-up, the truck will remain mobile anyway. For mono-fuel LNG trucks: some residual gas will remain in the tank, to cover a short trip to the filling station.

• In case of high tank pressure after a period of non-use: before refilling, use the truck for some mileage, in order to lower the pressure. The economizer on the tank will use the BOG first, to supply the engine.

As a general rule, hot tanks can be avoided by organizing the frequent use of the trucks, and avoiding longer periods of non-use.

4.3.2 Concentration of refueling events

For each refill, the complete circuit between storage tank and dispenser will need to be cooled down. If the time between two refills allows it, ambient temperature will warm up this circuit, and the heat will enter the system.

If the operations of the station and its customers allow it, it’s a good idea to concentrate the refueling events on a short time during the day, for example in the morning hours. This could avoid the repetitive heat ingress due to the cooling of the dispenser circuit for each refill. If all the trucks refill one after the other, there will be just one complete cooling-down.

Obviously, this is not easy to manage on a public station, but it could be worth considering in a start-up phase, when there are few customers, and when boil-off issues are more important.

4.3.3 Small vehicle tanks vs. big vehicle tanks

On LNG trucks, the tank configurations vary from one small tank (around 90 kg capacity) to big, double tanks (nearly 400 kg LNG capacity).

On one fill-empty cycle, considering 16 tons of LNG, this could mean a variation of about 60 refueling up to 175 refuelings, and potential cool-downs.

It is preferable to limit the number of cool-downs, and thus it is obvious that double-tank vehicles, in the end, generate less boil-off issues for the station operator.
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