Natural Gas for Road Transport



Freek van Heerden, Cornè Thirion & Jurie Steyn
December 2021

This is the final article in a series of ten on natural gas (NG) and liquefied natural gas (LNG) by OTC specialists and partners.

The series comprises the following articles which have been published on the dates shown:

1. Overview of the LNG industry – September 2020
2. Traditional gas transport modes – November 2020
3. Safe and clean storage of natural gas – January 2021
4. Alternative modes of natural gas transport – March 2021
5. Overview of LNG technologies – May 2021
6. Comparison of inland NG/LNG and imported LNG – June 2021
7. Outlets and applications for natural gas – August 2021
8. Natural gas for power generation – September 2021
9. Small-scale versus large-scale LNG plants – November 2021
10. Natural gas for road transport – December 2021

Natural gas is an excellent transition fuel during the decarbonisation process and subsequent changeover to a hydrogen economy.

Introduction

Natural gas is a fossil fuel consisting primarily of methane (CH_4) and is the cleanest of all hydrocarbon fuels. It generates carbon dioxide (CO_2), a greenhouse gas, upon combustion and is therefore not an ideal fuel for a carbon free future. However, it is an excellent intermediary fuel to use in the migration to a hydrogen-based economy.

Natural gas is suitable for use in most internal combustion engines, either in a compressed state as compressed natural gas (CNG), or in liquid form as liquefied natural gas (LNG). By the end of 2019, the number of natural gas vehicles in the world increased to 28,5 million and fuelling stations to 33 383 (NGV Global, 2020). The majority (72%) of these vehicles are in Asia-Pacific, with only 1% in Africa. Natural gas vehicles represented 2% of the total number of vehicles in the world at the start of 2020.

Decarbonisation efforts, coupled with the lower cost of LNG and CNG as compared to diesel, further stimulates the introduction of natural gas vehicles, especially in the mining and heavy transport sectors. Greenhouse gases in tailpipe emissions are 20 to 30% lower for natural gas-fuelled vehicles. End users can expect to reduce fuel cost by up to 45 %, depending on the cost differential between the delivered price of LNG/CNG and diesel, due to the higher efficiency and lower cost of natural gas.

In this article, we briefly look at the technology of the internal combustion engine, consider natural gas as an alternative for petrol and diesel engines, and discuss the conversion of diesel-fuelled engines to also use natural gas as fuel. The article focuses mainly on heavy diesel trucks and mining machinery.

Internal combustion engine technology

Opening comments

In an internal combustion engine, ignition and combustion of a fuel and air mixture occur inside the combustion chamber of the engine. The combustion chamber is a fixed cylinder with a moving piston. The movement of the piston is caused by an explosion. The engine partially converts the energy from the combustion to work, while a portion is lost as heat. The expanding combustion gases push the piston, which in turn rotates the crankshaft. This rotating crankshaft ultimately drives the vehicle's wheels through a system of gears in the powertrain.

Internal combustion engines are either spark-ignition (SI) engines, or compression-ignition (CI) engines. SI and CI engines differ in how they supply and ignite the fuel in the combustion chamber. This is discussed in more detail in the sections that follow.

Spark ignition engines

The primary fuel used in a spark-ignition (SI) internal combustion engine is petrol, or gasoline. Petrol is a liquid mixture of hydrocarbons in the C_4 to C_{12} range and can include up to 10% ethanol. Petrol typically has a flash point of -42,8 ºC and an autoignition temperature of 257,2 ºC.

SI engines work according to the Otto cycle. A fuel-air mixture is inducted into the cylinder during the intake process. The piston then compresses the fuel-air mixture, whereupon a spark from a spark plug ignites it, causing combustion. The expansion of the combustion gases pushes the piston back during the power stroke. In a four-stroke engine, the following upward stroke pushes out the exhaust gases through the exhaust valve. The complete combustion cycle of a four-stroke engine is shown in Figure 1.

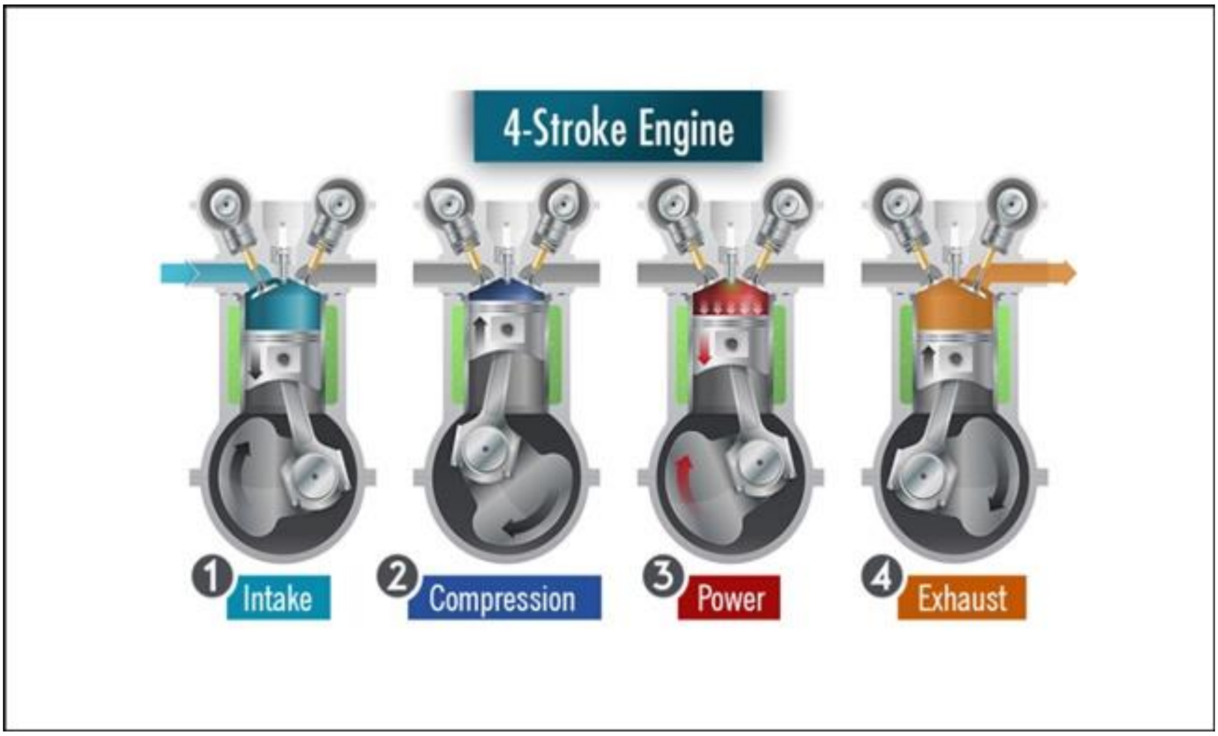

Figure 1: The four-stroke engine cycle (Chainsaw Journal, 2019)

A two-stroke engine is another type of SI engine that does not use valves to allow fuel to enter and exhaust gases to exit the combustion chamber. This simplifies matters and the engine accomplishes the full power cycle in only two strokes. Two stroke engines are more powerful, lighter, and cheaper to maintain. However, two-stroke engines are less fuel-efficient than four-stroke engines, have a narrower power band, lower torque, and are significantly more polluting.

Compression ignition engines

The primary fuel used in a compression-ignition (CI) internal combustion engine is diesel, a liquid mixture of hydrocarbons in the C_8 to C_{25} range. Diesel typically has a flash point of 73,9 ºC and an autoignition temperature of 315 ºC.

CI engines also operate in a four-stroke power cycle according to the Diesel CI engine cycle. In a CI engine, only air is inducted into the combustion chamber during the intake stroke and then compressed in the compression stroke. Diesel fuel is injected into the hot compressed air at a controlled rate, causing it to ignite and combust, and drive the piston down in the power stroke. The following exhaust stroke pushes out the exhaust gases through the exhaust valve.

CI engines are heavier, noisier, and more expensive than SI engines because they operate at higher pressures. However, they tend to be more reliable, more fuel efficient, and produce more torque than an equivalent SI engine.

NG as an alternative fuel for diesel and petrol engines

Opening remarks

Natural gas is the simplest hydrocarbon fuel and consists primarily of methane (CH_4). Natural gas can be used in its compressed form (compressed natural gas, or CNG) or liquid form (liquefied natural gas, or LNG).

As a fuel for vehicles, natural gas is suitable for use in both SI and CI internal combustion engine technologies. Although capable of working in either type of engine, CNG is mostly used with petrol engines, while CNG or LNG is used with diesel vehicles. LNG is the preferred fuel for heavy duty diesel engine applications such as long-distance trucking and mining equipment.

Compressed natural gas

CNG is made by compressing natural gas to a pressure of 200 to 250 bar, thereby reducing the volume to less than 1% of the volume it occupies at standard atmospheric pressure. This allows for large volumes of gas to be stored in CNG cylinders. The pressure of CNG cylinders on vehicles is normally limited to 200 bar.

The volumetric energy density of CNG is about 42% of that of LNG and 25% of that of diesel fuel. This implies that the volume of CNG cylinders on vehicles is more than twice that for LNG tanks and four times more than diesel tanks. A key factor limiting the use of compressed natural gas in trucks has been the question of range. Vehicle CNG cylinders must be robust because of the high-pressure requirement and are therefore heavy. Examples of back-of-cab and frame-mounted CNG cylinders as used on heavy duty vehicles are shown in Figure 2.

Figure 2: Back-of-cab and frame-mounted CNG fuel cylinders

Gas supply to CNG fuelling stations is generally by pipeline and compressed on site. Refuelling is done from a CNG filling station, like a diesel/petrol filling station and the filling time is about the same.

Liquefied natural gas

LNG is produced by cooling natural gas to -162 ºC at which point it liquefies. LNG occupies a volume 600 times smaller than natural gas at atmospheric pressure. LNG can be economically transported across long distances, thus making natural gas available at end-users or filling stations.

The energy density of LNG is approximately 58% of that of diesel, which means that LNG tanks must be 72% larger than diesel tanks for a comparable range. Figure 3 shows examples of after-market and original equipment LNG tanks. Modern LNG-powered trucks can reach up to 1 700 km between refuelling.

Figure 3: LNG tanks on heavy duty trucks

LNG is delivered to filling stations and other users by LNG tankers and stored on site in cryogenic LNG tanks. These tanks are designed to keep the LNG at its liquefaction temperature of -162 ºC but cannot provide perfect insulation against warming. Heat slowly affects the tanks, which can cause boil-off of some of the LNG inside. Boil-off allows the LNG to remain at the liquefaction temperature. Boil-off gases can be compressed to supplement the CNG supply at the filling-station.

An example of a natural gas filling-station for trucks is shown in Figure 4. LNG is pumped from the storage tank to the liquid filling points as well as to an atmospheric vaporiser and compressor from where natural gas is also provided to filling points for CNG vehicles.

Figure 4: A Shell natural gas filling station in Amsterdam (Tinham, 2015)

Natural gas engines

Natural gas engines fall into one of the following three categories:

- **Dedicated natural gas engines:** These are engines specifically designed to run on 100% natural gas.
- **Bi-fuel engines:** These are engines designed to run either on natural gas or on petrol. It includes petrol engines converted to run on natural gas.
- **Dual-fuel engines:** These are engines designed to run on a combination of natural gas and diesel. It includes diesel engines converted to run on a mixture of gas and diesel.

An engine designed to run on 100% natural gas, must be an SI engine because of the high autoignition temperature of natural gas. Bi-fuel engines are also SI engines and can run on petrol or natural gas, whatever is available. This allows the added advantage of running on petrol if natural gas filling stations are not available on specific routes. SI natural gas engines for heavy transport applications operate primarily on LNG, and to a much lesser extent on CNG, thereby maximising engine efficiency due to only one type of fuel, natural gas, being used.

Natural gas engines cannot operate as CI engines unless a small amount of diesel is added as a pilot fuel, to facilitate ignition. This is referred to as a dual-fuel engine because both natural gas and diesel are required. The amount of diesel replacement by natural gas depends on the load factor of the engine. During idling, 100% diesel is consumed, but up to 85% diesel replacement is achieved at high engine loads. The engine can revert to full diesel fuel if the natural gas supply is depleted during a trip. The replacement of diesel with natural gas contributes to substantial savings and up to

45% fuel cost savings can be achieved, depending on the diesel/natural gas price differential.

Most existing diesel engines can be retrofitted with an after-market dual-fuel system supplied as a kit, as is discussed in the following section. The kit can also be removed, with the original engine and engine management systems intact.

Conversion of diesel engines to dual-fuel engines

Opening remarks

In a dual-fuel system, a CI internal combustion engine operates on a combination of diesel and natural gas, supplied from separate fuel tanks. Dual-fuel engines allow natural gas to substitute up to 85% of diesel fuel in the combustion process of CI engines without any loss in performance. Small volumes of diesel are required for the diesel pilot injectors to initiate combustion in a dual-fuel engine.

In dual-fuel mode, natural gas is introduced into the engine's intake system. The air-natural gas mixture is then drawn into the cylinder, just as it would be in a spark-ignited engine, but with a leaner air-to-fuel ratio. Near the end of the compression stroke, diesel fuel is injected and ignites due to the heat of compression, causing the natural gas to combust.

A diesel engine converted to dual-fuel operation, can run on 100 % diesel fuel or the substitution mixture of diesel and natural gas, whilst delivering the same power density, torque curve and transient response as the original diesel engine. Seeing that diesel is used for start-up and idling, diesel substitution by natural gas typically averages between 50% and 70%.

Dual-fuel conversion kits

Many companies are developing and optimising natural gas conversion systems for diesel engines, which allow the conversion of existing diesel engines to a dual-fuel supply. There are also kits available from Omnitek, and others, for converting diesel engines to run on 100% natural gas. This necessitates the installation of a spark ignition system and a reduction in the compression ratio of the engine.

Original equipment manufacturers like Caterpillar offer dual-fuel engine solutions where there are no changes required to the basic diesel engine when their after-market conversion kits are fitted. Some additions are required, such as a gas injection system, an additional engine control unit, a display unit in the cab, and LNG fuel tank. Caterpillar offer a dual-fuel conversion kit specifically developed for the Cat® 785C mining truck using Dynamic Gas Blending™ (DGB) technology which automatically adjusts to changes in incoming fuel quality and pressure. The kit uses natural gas in the form of LNG. The Caterpillar 785C mining truck is shown in Figure 5.

Figure 5: The Caterpillar 785C mining truck

The Cat® DGB system was developed with the key goal of maximising diesel substitution at loads ranging from 20% to 90%. When in dual-fuel mode, diesel fuel injection timing is adjusted and optimised automatically to maintain durability and performance of the engine while maximising diesel substitution. In addition to monitoring detonation, exhaust temperatures, and emissions, the Cat® DGB system is designed to not exceed peak cylinder pressures within the engine. Gold Fields are currently conducting a trial on four dual-fuel 785C trucks at its Tarkwa open-pit gold mine in Ghana (Gleeson, 2020). It is estimated that from five to six trucks can be converted for the cost of one new similarly sized 100% natural gas SI engine, or approximately US$180 000.

Dual-fuel conversions of diesel engines can be completed in a matter of days. The kit can also be removed from the vehicle and installed in another vehicle if the owner wants to dispose of the original vehicle.

The Cat® DGB system is only one example of several similar dual-fuel conversion kits on the market, but it is one that has been thoroughly evaluated in real-world applications.

Scope of a dual-fuel conversion

The scope of a typical dual-fuel conversion is discussed based on the simplified schematic of the system supplied by DieselGas (2021), shown in Figure 6. We divide the conversion process into five principal areas, namely additional fuel supply, engine management, gas injection system, operator-machine interface, and safety measures.

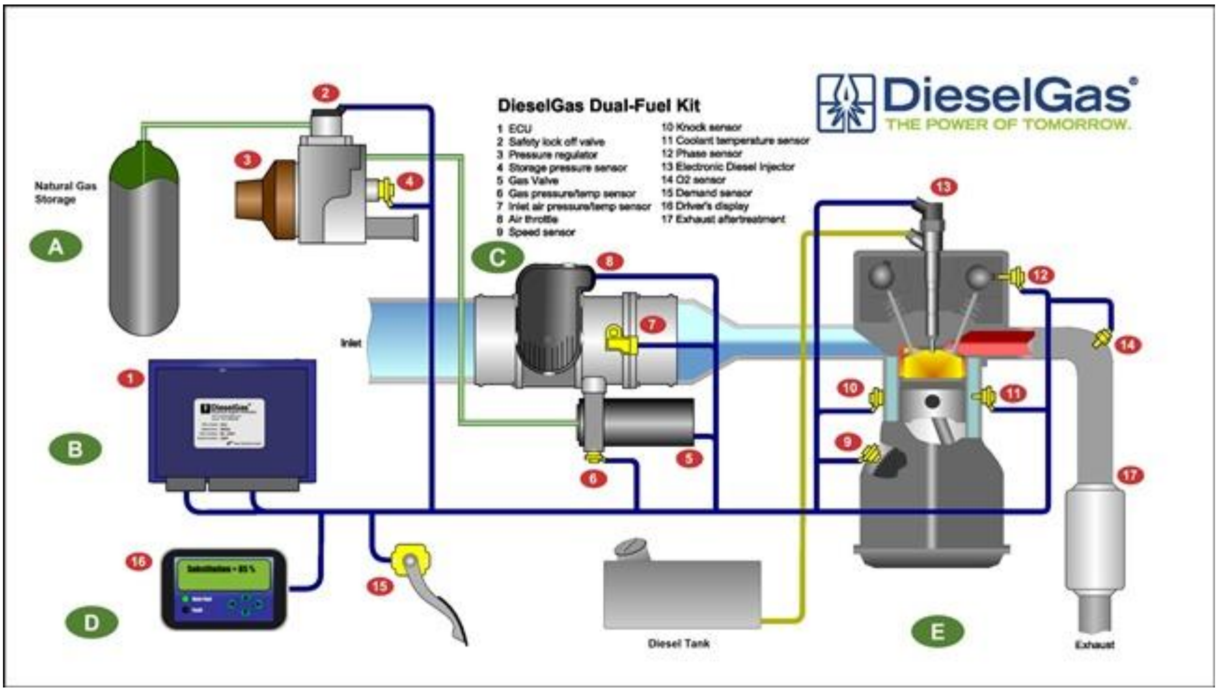

Figure 6: Schematic of a dual-fuel system (DieselGas, 2021)

Additional fuel supply

This discussion refers to the area marked as A (in a green oval) in Figure 6. A dual-fuel system for a motorised vehicle requires an additional container for the natural gas to be used. If the natural gas is supplied as CNG, it will require a gas cylinder, or set of cylinders, rated up to 250 bar. If the natural gas is supplied as LNG, it will require a cryogenic gas holder with a vaporiser. The natural gas supply system will require a filling mechanism, fuel filters, regulators, and shut-off valves. Back-of-cab, and chassis-mounted natural gas containers are available.

Engine management system

A revised engine management system or electronic control unit (ECU) is required to properly integrate the additional equipment of a dual-fuel conversion kit with the original diesel engine, as indicated in the area marked B in Figure 6. On dual-fuel systems for diesel engines with electronic diesel injection systems, a second ECU interfaces with the diesel engine's electronic sensors and original ECU but the original ECU is not modified. Any additional sensors that may be required form part of the conversion kit.

Gas injection system

The gas injection system includes all equipment required to inject the natural gas into the inlet air stream, shown as area C in Figure 6. The typical approach is to employ single point admission of gas into the air intake through mixers installed upstream of the turbocharger (not shown in Figure 6). The DieselGas (2021) high pressure single point injection system delivers the natural gas into the inlet air between the aftercooler and the inlet manifold. On low-speed engines, fuel is injected through individual valves on each cylinder in a concept referred to as multi-point admission.

Operator-machine interface

An interactive, cabin-mounted driver's display (see area D) informs the driver regarding natural gas inventory levels, percentage diesel substitution, system functionality, and to indicate any special service requirements. Technicians may use the display to access fault codes and other technical data.

Safety measures

Safety measures can include on-board methane detectors and shut-off valves to monitor and prevent gas leaks, fire suppression systems effective with natural gas, and effective safety training and operating protocols.

Benefits of dual-fuel engine conversions

Some after-market dual-fuel systems perform better than others, but in general the following will be true:

- **Low capital outlay:** Keep your existing diesel engine but add a dual-fuel conversion kit to benefit from using natural gas.
- **Saving on fuel cost:** Although the price of natural gas and diesel fluctuate all the time, diesel is generally more expensive than gas. The more natural gas is used, the higher the saving.
- **Fuel flexibility:** If natural gas is unavailable on the routes you travel, interrupted full diesel operation is available instantly.
- **Consistent performance:** Retain the full original power and torque characteristics of the engine, whether running on dual-fuel or diesel.
- **High efficiency:** Nearly all dual-fuel engines have better efficiency than SI natural gas engines due to the higher compression ratio.
- **Service intervals:** Diesel pilot fuel provides lubrication to valves and rings, which, when combined with clean natural gas, should extend service intervals.
- **Less harmful emissions:** Exhaust emissions, specifically nitrogen oxides (NO_x), carbon dioxide (CO_2), and particulates (PM_{10}) are reduced by up to 30%.
- **Fail safe operation:** If a problem develops with the natural gas supply system, full diesel backup is instantly available.
- **Longer engine life:** The use of natural gas generates less oil contaminants, leading to a longer lasting engine, possibly by a factor of two.

- **Warranty:** No changes should be made to your standard engine warranty, especially if the conversion kit comes from the original engine supplier.

There, are obviously some disadvantages of using a dual-fuel engine, although these are relatively minor. We list them here to give a complete picture:

- **Diesel is essential:** Whilst you can operate a dual-fuel engine without natural gas, unfortunately the same is not true for diesel. Dual fuel engines require diesel for ignition. Run out of diesel and you stop.
- **CO emissions:** Dual-fuel engines have higher emissions of carbon monoxide (CO) than an engine running on diesel fuel. This can be addressed by fitting a catalytic converter.
- **Higher complexity:** You now have two fuel systems to maintain. However, CI systems require less maintenance than SI systems and the gas control system is mostly maintenance free.

Payback

Owners of vehicles and trucks are always looking for ways to optimise total cost of ownership of their vehicles and running cash costs. The contribution of fuel cost as a percentage of total cash cost varies and can be as high as 52% for long distance transport trucks in South Africa, and up to 40% of mining operating expenditure.

A payback period of typically between 1,5 and 2,5 years can be achieved for the installation cost of the dual-fuel conversion kit only, depending on the price difference between gas (LNG or CNG) and diesel. This is based on mining trucks covering at least 120 000 km per annum.

Greenhouse gas emissions

The overall greenhouse gas (GHG) reduction benefit of transport trucks running on LNG instead of diesel depends on how efficient the LNG liquefaction process is as well as how effectively fugitive methane emissions are managed along the value chain. These include GHG emissions during production, processing, storage, transport, and filling operations at LNG/CNG filling stations.

GHG emissions reduction of less than 10% is on average being achieved when comparing Well-to-Wheel (WTW) emissions (Mottschall, Kasten & Rodriquez, 2020). The fact that LNG trucks have lower CO_2 tailpipe emissions is reversed by CH_4 emissions along the Well-to-Tank (WTT) value chain. The accuracy of WTT calculations has a wide range, as natural gas can be from various sources with a different CH_4 footprint (e.g., biogas vs. natural gas) and the efficiencies of various LNG technologies can differ by up to 30%. The findings of Mottschall et al (2020) are reflected in Figure 7.

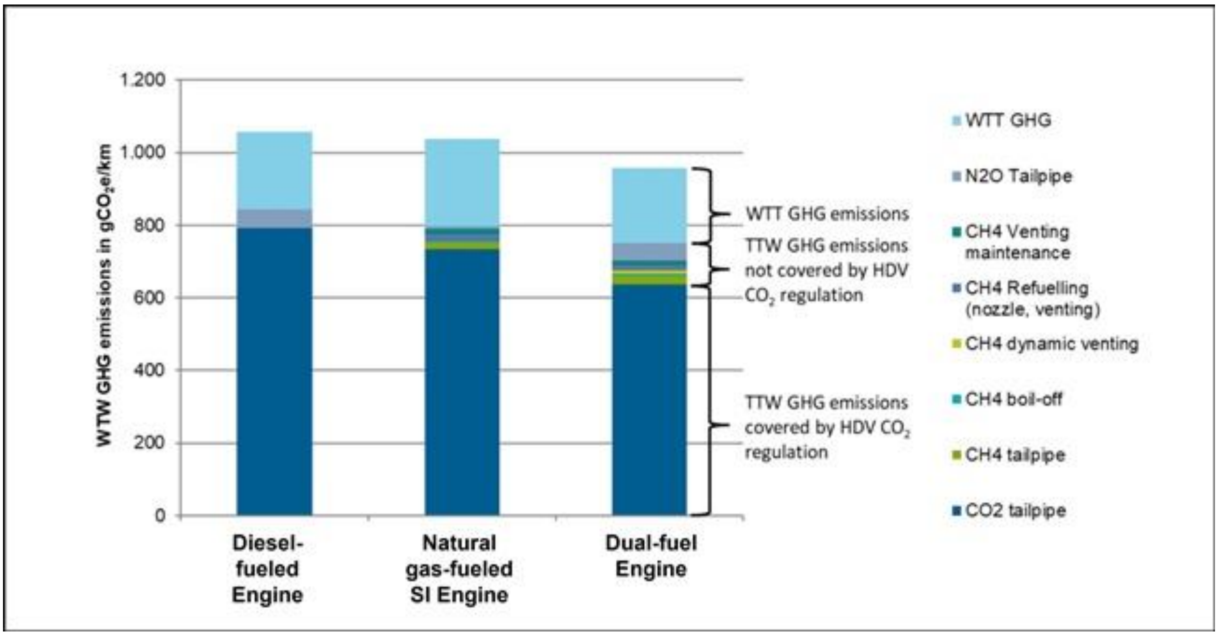

Figure 7: GHG emissions for various engines (adapted from Mottschall et al, 2020)

To improve the environmental benefit of using natural gas for transport, there must be increased focus on the reduction of fugitive CH_4 emissions along the LNG value chain.

Closing remarks

The financial and environmental benefits of switching to natural gas-fuelled vehicles provide a clear case for change and this change is accelerating globally. The required technologies are all commercially proven and globally available from various suppliers. The business case for the partial replacement of diesel with LNG by converting a diesel engine to a dual-fuel engine is discussed in this report, but the total value chain should be analysed on a case-by-case basis to ensure an accurate assessment of the viability of such a step.

In African countries where natural gas is being produced or LNG is available (Nigeria, Ghana, etc.) conversion to natural gas vehicles is accelerating. Southern Africa is lagging the rest of Africa because of the shortage of gas in the region. The advent of LNG becoming available in the first quarter 2022 from Renergen's Tetra4 facilities in Virginia will provide the first impetus for change. It is also expected that LNG will become available from LNG imports via Matola or other SA ports, as well as from regional gas fields where exploration and commercial testing are in progress.

References

Chainsaw Journal (2019) 2-Stroke vs 4-stroke engines – What's the difference? Available from 2-Stroke vs 4-Stroke Engine — What's the Difference? - Chainsaw Journal. Accessed on 17 December 2021.

DieselGas (2021) Dual-fuel systems for diesel engines. Available from Products | DieselGas. Accessed on 23 December 2021.

Gleeson, D. (2020) Gold Fields to trial Caterpillar dual-fuel solution on haul trucks at Tarkwa mine. Available from Gold Fields to trial Caterpillar dual-fuel solution on haul trucks at Tarkwa mine - International Mining (im-mining.com). Accessed on 22 December 2021.

Mottschall, M., Kasten, P. & Rodriquez, F. (2020) *Decarbonization of on-road freight transport and the role of LNG from a German perspective*. Available from Decarbonization of on-road freight transport and the role of LNG from a German perspective (theicct.org). Accessed on 20 December 2021.

NGV Global (2020) *Current natural gas vehicle statistics*. Available from http://www.iangv.org/current-ngv-stats/. Accessed on 14 December 2021.

Tinham, B. (2015) *Shell opens third truck refuelling station*. Available from Shell opens third LNG truck refuelling station (transportengineer.org.uk). Accessed on 20 December 2021.