Enhanced Emission Performance and Fuel Efficiency for HD Methane Engines

Literature study

Final Report

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ABSTRACT

A literature survey has been conducted in order to define state-of-the-art for methane fuelled engines to be used in heavy duty vehicles. Use of methane can be favourable to increase security of supply and mitigate CO_2 emissions, especially when the methane origins from biomass. Furthermore, methane used as a fuel in heavy duty engines has a potential to reduce toxic exhaust emissions. Historically, use of methane in heavy duty engines has often been hampered by poor efficiency, i.e. high fuel consumption when using the Otto-cycle. However, current generation technology engines might be within 5-10 % of the efficiency of Diesel engine technology. In this context it is worth mentioning that compliance-driven changes for meeting future emission regulations for Diesel engines may have a negative impact on fuel efficiency, thereby narrowing the gap. This may present an opportunity for heavy methane fuelled engines.

The reliability and durability of the exhaust aftertreatment devices for methane fuelled engines has also given rise to some concerns. Some concepts are performing acceptable while others do not meet expectations. This is partly due to difficulties in handling methane in the aftertreatment device and partly to issues in the design of the ignition system. Methane is a fuel used worldwide and has a potential to be an important complement to Diesel oil. There is a great interest to see what efforts have been made to reduce or eliminate the drawbacks of using methane as fuel.

There are two categories of HD methane engines available to end-users: Retrofitted engines, which often include computer controlled retrofit systems developed as “bolt-on” technologies that can be removed if necessary, to resell the vehicle with a normal diesel engine, and those developed specifically for and in conjunction with engine manufacturers and delivered to customers as factory-built engines or vehicles (OEM). Additionally, both these categories can include engines that use the Otto- or Diesel combustion cycles.

When adapting a HD Diesel engine to run on methane there are two options, either to change the combustion system from the Diesel-cycle to the Otto-cycle or to use the Diesel Dual Fuel (DDF) cycle which used a Diesel-like cycle. The Otto-cycle (spark ignited, SI) is the most common option when rebuilding a diesel engine to operate on methane. The Diesel dual fuel-cycle can however offer some benefits since it uses Diesel injection for ignition of the methane/air mixture “like a liquid” spark plug. Additionally, DDF systems can either use the original Diesel injectors together with injection of methane into the air intake, allowing use of methane and/or diesel for more flexibility, or employ a specially designed gas/Diesel injector, incorporating only a small range of Diesel injection which disable operating the engine on 100 % Diesel, but allows for more Diesel substitution by methane over the full operating range of the engine.

The fuel used in methane fuelled engines is biomethane, compressed natural gas (CNG), liquefied natural gas (LNG) or liquefied biomethane (LBM). LNG/LBM is the preferred fuel for long haul trucks since it has significantly higher energy density implying smaller, but different gas cylinders on-board the vehicle. For vehicles operated in a local area, compressed methane gas might be the most suitable alternative. Other combinations of methane fuels could also be used as fuel within the transportation sector such as blends of fuels from fossil and renewable origin and hydrogen enriched natural gas, hythane (HCNG).

For many years, dedicated (only one type of fuel) methane fuelled city buses meeting emission requirements (Euro IV, V and EEV, US Federal and California, Japan) have been offered to the market. Engine in those buses have been either of lean-burn technology or working under stoichiometric operations. Both technologies have their pros and cons. A recent interest for Diesel dual fuel concepts has now appeared among stakeholders as an alternative or a complement to the conventional methane fuelled HD vehicles, underlined by the fact that differences in the actual mode of operation of vehicles will enhance advantages with various engine concepts. A DDF-system does not have the same requirements for infrastructure for the gas filling stations, since some of those systems also can operate on 100% Diesel fuel. Since the working principle of the engine still is Diesel-like this will imply a potential for almost the same fuel efficiency as for a conventional Diesel engine. Additionally, basic engine components do not always has to be modified and there might therefore be a potential for reduction of cost, but this cannot be considered as a general rule. Compared to a SI methane fuelled engine a DDF concept could end up with better fuel efficiency using current engine technology. However, the potential for substitution of diesel with methane would be lower over the full operating range of the vehicle, and emissions performance may impair the ability to fully use the fuel consumption benefits offered by the Diesel cycle.

The challenge for vehicle manufacturer and supplier of DDF-concepts is to reach very low emission levels and at the same time offer cost efficient solutions. However, the European emission regulations are not designed to cope with engines operating on two fuels simultaneously and with a variable mixing rate. This will be an important issue to tackle for the industry. In paragraph 2, engine technology for methane fuelled HD engines is discussed and in paragraph 3.5 the related cost for concepts meeting future emission standards is estimated.

This project has compiled methane as fuel for different HD engine technologies and the associated costs for aftertreatment of exhaust emissions. Additionally, weak points of the DDF system have been identified and also a proposal for a road map for recommended further work is presented.

ACKNOWLEDGEMENTS

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Contribution to the project in the form of task sharing has been other member countries of IEA – AMF such as Austria, Australia, Canada, Denmark and, as observer, the Netherlands by submitting technical reports and other vital information. USA Environmental Protection

Agency as well as the DG ENTR of the European Commission and the informal working group "Gas fuelled vehicles, GFV" under the umbrella of GRPE of United Nations Economic Commission for Europe, has contributed by sharing information about legal requirements.

The work has been carried out by AVL MTC, Sweden

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1 INTRODUCTION

Use of methane can be favourable to increase security of supply and mitigate CO_2 emissions, especially when the methane origins from biomass. Furthermore, methane used as a fuel in heavy duty engines has a potential to reduce toxic exhaust emissions. Use of methane in heavy duty engines are often hampered by poor efficiency, i.e. high fuel consumption when using the Otto-cycle. The reliability of the exhaust aftertreatment devices is sometimes lower than expected. Methane is a fuel used worldwide and has a potential to be an important complement to Diesel oil. There is a great interest to see what efforts have been made to reduce or eliminate the drawbacks of using methane. This report will give answers to some important questions and to serve as a guideline for procurement of vehicles using gas a fuel.

Methane has a very low H/C ratio which results in low CO_2 emissions per energy content. Natural gas as fuel produces in same cases approximately 20 – 25% less GHG on a life-cycle basis than Diesel and gasoline. If instead biomethane is used as energy, the reduction of GHG will be much higher, normally 75 – 90 % on a life-cycle basis. According to the report “Well-to-Wheels analysis of future automotive fuels and powertrains” presented by EUCAR / JRC / CONCAWE, compressed biomethane (CBM) from liquid manure shows the greatest potential for GHG reductions.

Biomethane is typically produced by breakdown of organic matter such as biomass, manure, sewage, municipal waste etc. in the absence of oxygen which is normally referred to as fermentation or anaerobic digestion. The typical composition of “fermentation” biomethane (before upgrading) is methane 50-75%, carbon dioxide 25-50%, nitrogen 0-10%, hydrogen 0-1%, hydrogen sulfide 0-3% and oxygen 0-2%. Biomethane can also be produced from synthesis gas based on biogenic material like surplus from the forest industry. Biomethane from fermentation contains very little energy compared to fossil natural gas and has to be “upgraded” to biomethane before it can be used as fuel in IC engines.

The feedstock and the production of the biomethane are of significant importance and in the Directive 2009/28/EC of the European Parliament and council of 23 April 2009 on the promotion of the use of energy from renewable sources, a table with typical and default values for biofuels if produced with no net carbon emissions from land-use change is presented.

Because of the short carbon chains in methane, methane gas generally also produces low smoke and particulate emissions. DDF combustion systems which are using a combination of Diesel and methane as fuel may in some cases produce unacceptable levels of smoke which may need to be controlled by using a particulate filter. Future European/ECE emission regulation for HD engines will imply limit values both for particle mass emissions and particle numbers. It is verified that methane fuelled engines produce decreased emissions of particles, expressed as mass. There is an uncertainty whether methane fuelled HD engines will increase the small particles and thereby emit higher amount of particle numbers and thereby adding a potential health risk. This issue must be kept under strict observation. Taking all facts into consideration in combination with the widespread availability of methane gas, still make the gas a very interesting fuel for internal combustion engines. However, in order to have the full picture of gas as a suitable and cost effective fuel for the transportation sector the infrastructure for distribution of gas has to be considered.

The work within this project was developed as a first step and will result in a report presenting state-of-the-art in methane vehicles and technologies, while identifying some of the remaining hurdles to be addressed to encourage their adoption, and a proposal for the next step. Focus for the planned second step should be on best solutions based on testing and with recommendations and guidelines to stakeholders.

This project is carried out within the framework of IEA – AMF (International Energy Agency – Advanced Motor Fuels Agreement). The literature survey is financed through the following Member States, on a cost sharing basis, Sweden, Finland and Canada, and on a task sharing base (technical reports and other material to support the project) from Australia, Austria, Canada, Denmark and the Netherlands.

All references, [1-43] have contributed to the content of this report concerning gas engines although all of them are not directly referred to in the text.

2 ENGINE TECHNOLOGY

Natural gas (~ 80-99 mol% methane), upgraded biomethane (~ 99 mol% methane) and LNG (Liquefied Natural Gas) can be used in a similar way as fuel for an internal combustion engine optimized for methane. The difference is that natural gas also contains heavier hydrocarbons such as ethane and propane which to some extent deteriorate the high knock resistance of pure methane. Methane has a high research octane number (RON >120) and a low cetane number which makes it a good fuel for spark ignited engines. Rebuilding a Diesel engine from the Diesel-cycle (compression ignited) to the Otto-cycle (spark ignited) is the most commonly used option.

There are two categories of HD methane engines available to end-users: Retrofitted engines, which often include computer controlled retrofit systems developed as “bolt-on” technologies that can be removed if necessary, to resell the vehicle with a normal Diesel engine, and those developed specifically for and in conjunction with engine manufacturers and delivered to customers as factory-built engines or vehicles (OEM). There are pros and cons to both of theses options, but care must be taken to ensure that only high quality and low polluting technologies are offered to the market to avoid bad reputation to the stakeholders for all the methane fuelled engine offerings.

When rebuilding a HD Diesel engine to run on methane there are two options, either to change the combustion system from the Diesel-cycle to the Otto-cycle including changing pistons and introducing sparkplugs or to use the Diesel Dual Fuel (DDF) cycle. The DDF uses a small Diesel injection to ignite the methane like a “liquid” spark plug.

LNG is the preferred fuel for long haul truck since it has significantly higher energy density. LNG is also the preferred fuel to use for DDF technology since LNG normally has higher knock resistance (due to higher content of methane) than CNG and also allow for extra cooling from the evaporation which is beneficial in DDF engines.

The name Dual Fuel is wide spread when two fuels are used simultaneously where one is used mainly for ignition (Diesel) and the other mainly used for energy supply (methane).

Dual Fuel should not be mixed up with the name Bi-fuel which is commonly used for passenger cars that runs either on gasoline or on gas (methane or LPG)

An overview of the most common gas engine technologies are presented in this chapter.

2.1 Positive ignition

In positive ignited engines there is an electrical ignition source in the combustion chamber to ignite the air/methane mixture. When using a homogenous mixture, a spark plug is used. In direct injected engines, either a spark plug or a glow plug can be used.

Positive ignition methane fuelled engines are using spark plugs. SI (spark ignited) is the most common technology for both passenger cars and heavy duty engines and today also the only technology possible to certify (approve) according to European / ECE emission regulations.

2.1.1 Comparing lean burn and stoichiometric technologies

Two different technologies can be used for operating methane fuelled SI engines, either stoichiometric (λ=1) or lean burn (λ>1) conditions. When operating in stoichiometric conditions, a three-way catalyst (TWC) can be used as an effective and cost efficient aftertreatment system to reduce HC, CO and NO_x. The downsides with stoichiometric engines are lower part load efficiency, higher combustion temperature and higher knock sensitivity compared to lean burn engines. The reason for increased combustion temperature and knock sensitivity is less dilution (with air) compared to lean burn engines. This also leads to a demand for lower compression ratio in a stoichiometric engine compared to a lean burn engine to avoid knocking. For stoichiometric engines, adding an emission reduction system comprising cooled Exhaust Gas Recirculation (EGR) at full load, is an effective way to increase the knock tolerance and decrease combustion temperature. The EGR system could also be used at part load to decrease engine efficiency and thereby making the stoichiometric engine more efficient. In addition, many of the original Diesel engine components (such as cylinder head, exhaust manifold, turbine etc) can be used.

Lean burn engines emits higher tail pipe NO_x emissions compared to stoichiometric engines which benefits from the high NO_x reduction in the TWC that does not exist in oxidation catalysts. Lean burn engines on the other hand emit less engine out emissions of NO_x. This will limit the use of lean burn technology to meet maximum Euro V emission levels if no aftertreatment for reduction of NO_x such as SCR (Selective Catalytic Reduction) is used. The cost and complexity of the SCR aftertreatment system in combination with the oxidation catalyst, loaded with high amount of precious metal, makes the aftertreatment system for a lean burn gas engine meeting Euro VI emission requirement more expensive and complex compared to the stoichiometric engine meeting the same emission requirements.

Another important drawback with lean burn Euro V and Euro VI engines are the high discharge voltage leading to high risk of problems with the ignition system. (Examples such as flash-over, misfire, short lifetime for spark plugs etc.). The high discharge voltage in the lean burn engine origins from late ignition timing to limit the NO_x-emissions, high boost pressure to lean air/fuel (A/F) ratio and thereby limit NO_x and high compression ratio, all leading to very high density in the combustion chamber at the time of spark compared to the stoichiometric engine.

Methane can also be direct injected and burned with diffusion controlled combustion as in a conventional Diesel engine. Because of the low cetane number, an ignition source is needed for the combustion. A spark plug is not the ideal solution, since methane requires very high ignition energy and further, the high cylinder pressure when injecting the gas increases the demands. A more suitable alternative is then to use a glow plug or to use a pilot Diesel injection (see paragraph 2.2 Diesel dual fuel)

Laser-induced plasma ignition can also be an alternative to conventional spark plug ignition in gas engines. Studies regarding laser ignition have been made, but there are not yet any systems commercial available on the market.

2.2 Diesel Dual Fuel (DDF)

In DDF engines, a small amount of Diesel fuel is injected and used to ignite the air/methane mixture like a “liquid” spark plug. This “micro pilot” Diesel injection introduces far more energy than a spark from the spark plug which increases the lean burn capability compared to SI concept.

There are generally two different types of DDF combustion systems, one uses a port injected “premixed” air/methane mixture which is ignited by the Diesel injection and burns with a flame propagation (like the Otto combustion). The second type uses direct injected (DI) methane which burns with diffusion controlled combustion (like the Diesel combustion). The most common DDF system is the premixed concept which is relatively cost effective, simple to install and enable the Diesel engine to operate on “Diesel fuel only” mode with full performance (when the gas tank is empty). The major drawbacks with the premixed system are high levels of unburned methane (methane slip) and knock limited gas substitution over the full operating range of the engine. The direct injected (DI) DDF system has the potential for less methane slip and higher gas substitution but has limited performance in Diesel (only “limp home” mode) when the gas tank is empty. Further, the system is generally more expensive than the premixed DDF system because it demands a complete new fuel system for methane and Diesel, including engine controller, high pressure fuel pumps (methane and Diesel) and specially designed fuel injectors.

The most common solutions on the market and used for HD truck engines are retrofit applications with DDF capabilities. The retrofitted engines are mostly conventional Diesel engines equipped with special gas injectors in the air intake and a separate control unit for the gas distribution. The important advantage with DDF “premixed” engines are that they can operate also with 100 % Diesel if there is no gas available. Comparatively, direct injected engines like the Westport HPDI system (OEM) will limit the performance in Diesel “limp home” mode since the same injector is used for the injection of both methane and Diesel. This might however be beneficial in some markets where Diesel substitution is important for GHG reduction, and where optimum injection control allows optimization of engine performance and emissions. As mentioned before, “premixed” DDF systems generates high levels of unburned methane which makes them dependent on a highly efficient methane catalyst. They are also sensitive for knocking when using high Diesel substitution at high loads. There are also DDF engines mainly intended for ships and as stationary engines which are specially designed and optimized for dual fuel operation.

The main reasons for methane slip are believed to be poor combustion of methane at part load due to very lean methane/air mixture, unfavourable piston design for flame propagation, blow by of unburned methane during valve overlap and large crevice volumes where the flame can not propagate. This is due to the fact that conventional Diesel combustion system is not designed for premixed flame propagation. Most of the DDF systems can not take full control of the Diesel injections to overcome these problems. One way of minimizing this problem could be to introduce an effective methane catalyst. Another way could be to optimize the combustion control by using the potential of modern common rail Diesel injection systems. Direct injection of methane can however, to some extent overcome these drawbacks but such concepts may instead suffer from high engine out NO_x emissions. The future challenge will be to develop DDF systems without the existing shortcomings. The best opportunities for successful DDF applications will be OEM integrated solutions since it will be difficult and costly to design retrofit DDF applications for engines already in use and at the same time also meet strict emission requirements.

There are several suppliers of DDF systems on the market. Suppliers are focusing both on the retrofit markets, and as suppliers to OEM´s. In Europe there is a trend to focus on retrofit but with various level of OEM involvement, while in North America the focus is almost entirely on OEM integration. Examples of retrofit DDF suppliers are Clean Air Power and the Hardstaff Group while Westport Innovation is an example of OEM application.

As a part of this project, questionnaire was submitted to suppliers asking for comments and other related information. Below is a short summary of the results, but of course confidential information is left out.

2.2.1 Summary from DDF questionnaire

- A common understanding is that lack of emission regulations in Europe for DDF technology has a negative impact of the development work. The rules and regulations give no specific target for development. This also affects the market development in other countries adopting European regulations like China and India.

- Poor infrastructure and especially the lack of LNG filling stations hamper the development of the market. Further, the price considered as high for LNG is another factor that hinders the DDF market. Development of LNG market is essential for market penetration for long haul heavy duty trucks.

- Question is raised whether emission regulations for SI gas engines is sufficient also for DDF concepts since they allow for higher levels of THC. It is believed that classifying the DDF engine as a “Diesel engine” would unfairly punish DDF engines that might reduce GHG emissions, by subjecting them to the same stringent THC limits as Diesel engines. It seems however that the challenge for DDF concepts is to reduce the level of CH_4.

- The common opinion from the survey is that DDF technology could reduce operational costs as well as emissions of GHG compared both to SI gas engines and Diesel engines. As reasons, higher engine efficiency than the SI gas engine and more GHG friendly fuel than Diesel is expressed. However, as SI engine manufacturers exploit the clean burning advantages of methane to close the fuel consumption gap, and with ever more stringent emission requirements this might not always be the case.

- Major suppliers claim that they have the most suitable technical solution.

During the survey it was very difficult to find relevant test results from emission testing. In some cases reference was made to results from steady-state testing, but more interesting should be results from transient emission tests. It is also very difficult to verify specification of the fuel used for testing and the ratio between methane gas and Diesel (Diesel-replacement). However, many of the stakeholders are very interested in actual testing and design of a test program for validation of DDF-concepts.

At a recent event "European Biomethane Fuel Conference, 7-9 September" within the framework of the European project Biomethanemax the following results was presented by the Hardstaff group. How the actual testing was carried out, catalyst status and the specification for test fuel is not fully clear. Please also bear in mind that the results are presented only for steady-state testing and not for gas engines the required transient test (ETC).

Table 1. Emission test result from DDF concept and EU Euro V limit values for HDE

g/kWh	EU Limit values			Tested?
	ESC Euro V diesel	ETC Euro V diesel	ETC Euro V gas	ESC Euro V Hardstaff D/F
CO	1.5	4.0	4.0	0
HC	0.46	0.55	n.a.	n.a.
NMHC	n.a.	n.a.	0.55	0.17
CH_4	n.a.	n.a.	1.1	0.85
NO_x	2.0	2.0	2.0	1.47
Part.	0.2	0.03	0.03	0.03

Source: From presentation by the Hardstaff Group

2.3 Gas injection technology

The methane can be injected by different means by using single point injection, multipoint injection or direct injection. When using single point injection, the gas to all cylinders is injected at one location, normally in front of the throttle, which contributes to a good homogenous mixture between the gas and air. The drawback with this concept is that transient A/F control is more difficult and fuel cut capabilities becomes an issue since the inlet manifold volume contains gas.

When using multipoint injection, there are one or two gas injectors for every cylinder of the engine. This setup provides excellent fuel cut capabilities and transient A/F control, but the mixing of fuel and air can be an issue. Cylinder to cylinder A/F-ratio variation is normally higher when using multipoint injection.

The methane can also be direct injected which means that the gas is injected directly into the combustion chamber with high pressure. Since gas displaces air, the volumetric efficiency and power density will increase with direct injection compared to port injection. One difference with direct methane injection is limited Diesel performance since both fuels normally will be injected by one injector replacing the original Diesel injector.

Example of the design for a state-of-the-art engine control unit for gas engines are presented in Figure 1, below.

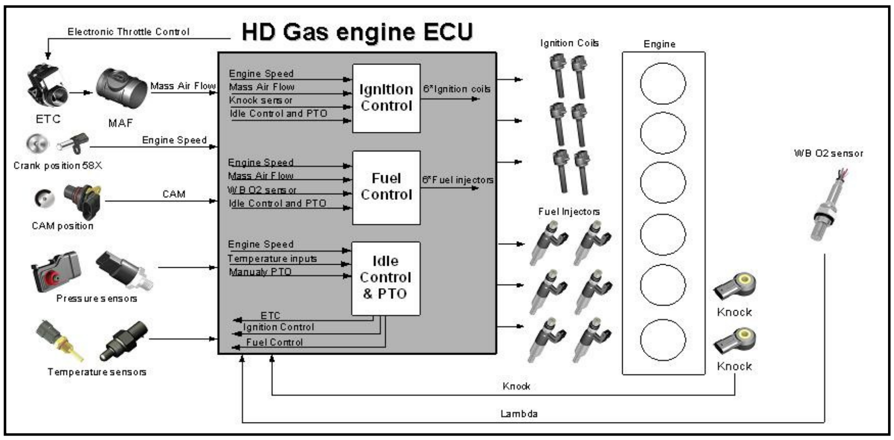

Figure 1. Example of the design for an ECU

2.4 Exhaust Gas Recirculation (EGR)

Cooled EGR (Exhaust Gas Recirculation) at full load is commonly used in modern stoichiometric gas engines to reduce the combustion temperature (dilution with inert gas). The main purpose with this measure is to prevent knocking at full load and to allow for the use of Diesel materials in exhaust manifold and cylinder head. EGR is also used to increase part load efficiency and thereby reduce engine out NO_x. The drawback with too much EGR in methane engines is that it causes unstable combustion which results in higher amount of unburned HC emissions. This problem is more pronounced in the lean burn engine which is one reason for not using EGR in lean burn engines.

3 EMISSION AFTER TREATMENT TECHNOLOGY

Depending on type of combustion used, lean burn or stoichiometric, different types of emission after treatment is used. One of the major problems with methane fuelled engines is that the catalyst loose conversion efficiency over time. This is mainly because that the catalyst is being damaged by misfires due to poor transient control and ignition systems that are not developed accordingly. Aging in the form of sulphur poisoning from the fuel is also an issue.

3.1 Three Way Catalyst (TWC)

When operating a SI methane engine in stoichiometric conditions (λ=1), a three way catalyst (TWC) can be used. The TWC is a passive aftertreatment system which reduces HC, CO and NO_x. The TWC is an effective and cost efficient system to reduce emissions and have been used in light duty gasoline vehicles with good experience for many years. An electronically controlled engine management system is used to keep the engine at λ=1 during various modes of operation which is needed to keep a high conversion rate of all emissions. Figure 2 shows the chemical processes in a three way catalyst.

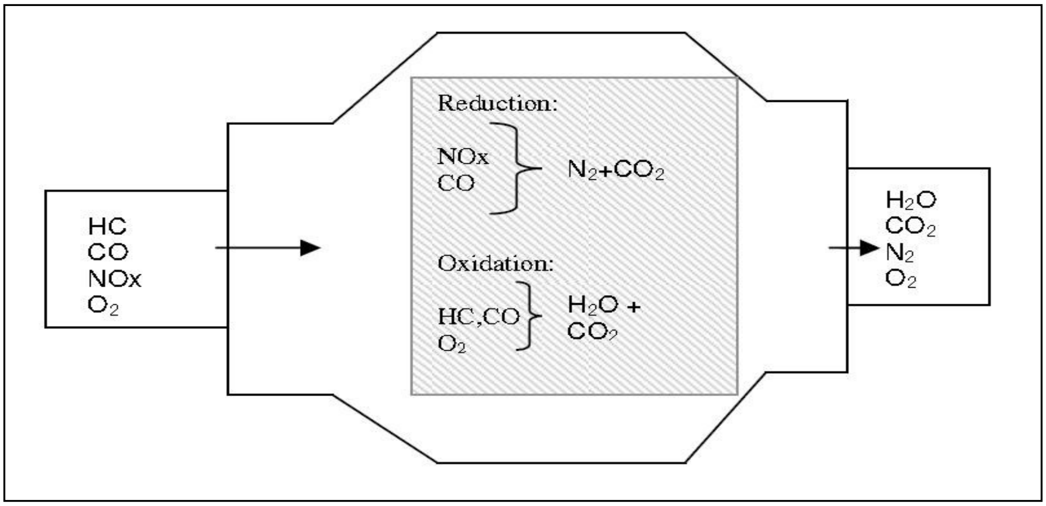

Figure 2. Chemical processes in a three way catalyst [**1**]

Pt (Platinum), Pd (Palladium) and Rh (Rhodium) are the most commonly used precious metals in TWC catalysts. Rh is used to enhance the NO_x conversion, Pt is used for a larger λ-window and Pd for cold start HD reduction. The ratio between Pt, Pd and Rh is normally 1:5:1 but to some degree affected by the market price for the precious metals which is highest for Rh followed closely by Pt. Pd is far less expensive which makes this attractive to use. Rh and Pt as well as Pd are needed to get effective conversion of CO, HC and NO_x.

The loading (amount) of precious metals in a TWC is normally 40-60 g/ft^3 which is much less than the oxidation catalyst (150-250 g/ft^3) making this technology less expensive.

The NO_x conversion can reach over 99% in methane fuelled passenger cars with aged TWC and this should also be possible to reach in HD applications using similar control strategies.

3.2 Oxidation Catalyst (2-way)

When operating a SI methane (or DDF) engine in lean conditions (λ>1), an oxidation catalyst is used to oxidize HC and CO. Reduction of NO_x in lean conditions is only possible using lean NO_x aftertreatment like SCR or NO_x trap which increases cost and complexity. The engine out NO_x from lean burn engines can be reduced down to Euro V emission levels by running very lean and by retard the ignition timing. To reach Euro VI emission levels SCR or NO_x trap is probably necessary.

Methane is a very stable gas and is therefore hard to oxidise in a catalyst. It also has a high light-off temperature (approximately 450 °C). Figure 3, show the light-off performance for an aged (1 000 hours) catalyst. All of this in combination with the fact that methane engines (especially DDF concepts) suffer from high engine-out HC emissions puts high demands on the efficiency and durability of the oxidation catalyst.

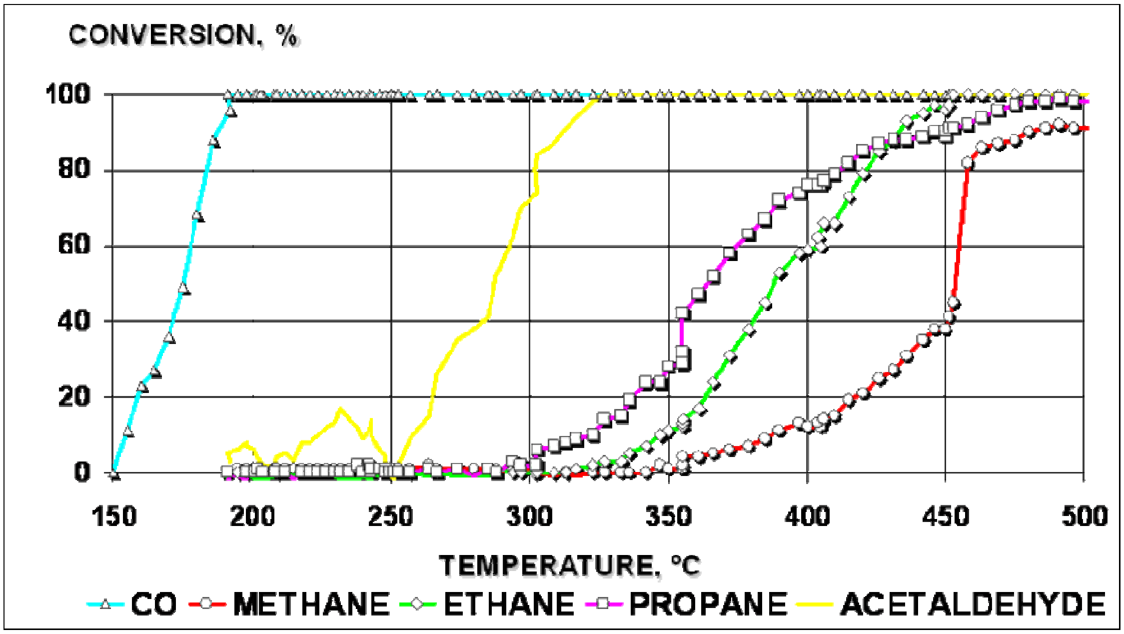

Figure 3. Conversion rate vs. exhaust temperature (Source: Kemira)

In Figure 3, the catalytic conversion rate can be seen as function of exhaust temperature. It is shown that methane has higher light-off temperature compared to other hydrocarbons and carbon monoxide. This might cause increased methane emissions during cold start and idle, especially for lean burn engines which have lower exhaust temperatures than stoichiometric. Lean burn methane engines normally suffer from relatively high levels of misfire which is a major cause for deteriorated catalyst. The high level of misfire is more common for lean burn engines than for stoichiometric engines since they run much closer to the flammability limit. It is very vital to minimize misfire since those are the main reasons for destroyed catalysts and corresponding unaccepted high level of exhaust emissions levels. Malfunction of catalytic converters could sometimes be identified already after very short time of normal vehicle operation. Engine concepts implying advanced closed loop fuel injection control and high voltage ignition system are effective measures to prevent misfiring. Misfire diagnose is a legal demand since many years for passenger cars with Otto engines and will also be introduced for HD/LD Diesel engines. The normal procedure for misfire diagnose is to evaluate engine speed variation from the crankshaft sensor but alternative systems exist using either ion current, cylinder pressure or fast exhaust temperature sensors.

TWC and 2-way catalysts (especially Pd based) also suffers from aging by sulphur poisoning which results in drastic reduction of conversion rate of the catalyst over time. Sulphur poisoning (sulphates) can be removed by sulphate regeneration which occurs during rich operation and high temperatures. This operation conditions is easily managed during stoichiometric operation but more difficult during lean burn operation.

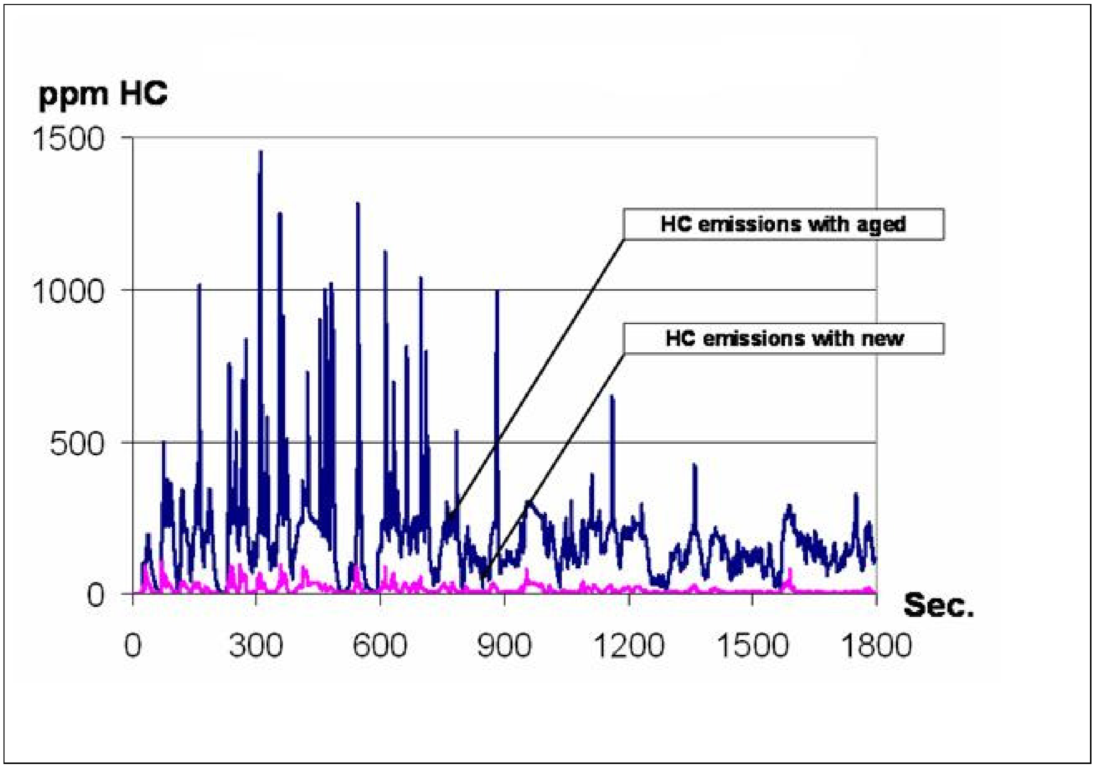

Figure 4. THC emissions with a lean burn engine in the European Transient Cycle (ETC) with a new and a catalyst damaged from misfire. (after 10 executive cycles)

3.3 Selective Catalytic Reduction (SCR)

To reach Euro VI emission levels for NO_x a lean burn engine could use selective catalytic reduction (SCR) which uses urea as reagent to reduce NO_x in lean conditions (implying selective reduction). This is a very effective process which is also used for conventional Diesel engines to reach emission levels specified for Euro VI. The design of the exhaust emission control system is however slightly different since a methane fuelled engine needs a highly efficient oxidation catalyst to reduce methane slip. There are also challenges to reduce ammonia slip and to reach acceptance by the drivers of HDV equipped with SCR systems since there is an extra tank to fill and to keep an eye on.

In addition, the Euro VI emission regulation also requires a sophisticated system for control of vital functions in the exhaust emission control system by the use of on board diagnostic system (OBD). Special concerns are given the operation of the SCR system and the tank with the reagent (urea). As one example, the level of liquid in the tank is supervised as well as the quality of the liquid. In case the system is not working as designed there will be occasions when the engine cannot be started without remedial actions from the driver. Such sophisticated systems will of course result in higher cost for the concept.

3.4 Diesel Particulate Filter (DPF)

Diesel Particulate Filter is used in Diesel engines to remove particulate matter and/or soot. Because of the short carbon chains in methane, it is a “clean burning fuel” which doesn’t produce soot emissions, but attention to a possible increase to total particle numbers must be given as discussed earlier. The soot produced by methane engines is normally coming from lubrication oil that is entering the combustion chamber via the crankcase ventilation system, valve stems or piston rings. Some soot will have it's origin from the process to compress the gas before it is filled in the vehicle. Since the emission limits gets more stringent, some methane engines in the future might also need a DPF to pass certification limits. DDF engines produce more soot than pure methane engines because of the Diesel that take part in the combustion.

3.5 Comparing costs for aftertreatment

The most important factor affecting catalyst prices are the cost for the precious metals.
An oxidation catalyst designed for meeting the Euro V (and EEV) emission limits contains three to five times more precious metal than a TWC. This strongly affects the catalyst price difference between lean burn (incl. DDF) and stoichiometric aftertreatment technologies. To meet Euro VI emission limits there is also a need to use SCR for the lean burn (and DDF) concepts which increase the price difference between these technologies even more. If a DPF is needed for the DDF technology this also adds up to the price differences.

The most cost efficient aftertreatment system for HD gas engines is concept implying a TWC. Oxidation catalysts for the lean burn SI gas engines are 2-4 times more expensive as the TWC when designed to meet Euro V and EEV emission legislation. Oxidation catalysts for DDF engines could be even more expensive than for lean burn SI engines since the DDF engines generally have higher methane slip and lower exhaust temperature than the SI engine.

An even more expensive aftertreatment system is the combination of oxidation catalyst and SCR systems which is believed to be the only way to meet Euro VI and EPA US10 emission requirements with lean burn SI engines (including DDF engines). Some DDF engines may also need DPF to comply with the most stringent particulate emissions demands making this the most expensive aftertreatment system of all.

The stoichiometric engine with TWC have the potential to meet all known emission legislation with a cost effective aftertreatment system but this concept have added costs in other areas such as material upgrade to withstand higher combustion temperatures or application of cooled EGR making the total cost difference compared to lean burn concepts less pronounced.

4 MARKET AND LITERATURE STUDY

There is an increased interest in methane transportation technologies as experiencing significant growth on a global basis with annual growth averaging 30 %. The majority of growth has so far been in the sector for light duty vehicles but for various reasons such as environmental impacts, energy security and increasing complexity of Diesel engine technology the interest for HD methane fuelled vehicles is increasing. A lot of research is going on to verify and validate advantages and disadvantages with different concepts. There are manufacturers all over the world who are marketing dedicated methane engines and solutions for retrofit for methane engines. A summary of the commercial available heavy duty methane engines, field experience and validation of some concepts are presented in this chapter.

4.1 Example of gas engine and system manufacturers

There are a huge number of manufacturers for gas system all around the world. The major part is focusing on retrofit systems for passenger cars where it is relatively cost efficient to convert gasoline engines to bi-fuel engines with a retrofit “master – slave” engine management system for the gas supply. The major part of these manufacturers are located in Italy but there are also companies in countries like China, Brazil, Argentina, Poland etc. where national regulations enables for cost efficient retrofit systems. The cost savings for the end customer is considerable, but low emission performance is not the main priority.

The basic layout of a methane fuelled engine used for HD vehicles is in many cases derived from the design of a conventional Diesel fuelled engine, and it is rare that the engine originally is designed to use methane as the pre-dominant fuel, but of course there are exemptions. Further, there are cases when gaseous fuelled engines are produced on separate production lines rebuilding the original Diesel engine. Whether such engines should be considered as retrofit or not is an open question. The important issue is whether the OEM will take the full responsibility for the modified engine. This special handling of methane fuelled engines is due to a very low production volume and the “manual assembly” of the engine will cease when the volume of engines will increase.

The other possibility is to convert/rebuild engines already in-use. This conversion is rather complicated since the SI gas engine demands a complete new combustion system and new engine management system including spark plugs and throttle which does not exist on the Diesel engine. Most OEM use gas system components and engine control units (ECU) from known suppliers like Bosch or Woodward but some are using their own ECU in order to have full control over the engine including diagnose system, safety and communication to other vehicle control units via CAN.

When retrofitting a HD Diesel engine to gas there are two options, either rebuilt the engine to a SI engine which is complicated, expensive and irreversible since the cylinder head and pistons have to be redesigned. The other option is to use a retrofit DDF (Diesel Dual Fuel) system which by the DDF manufactures is claimed to be more cost efficient and less complicated than the SI conversions. This might be true for “simple” DDF conversions but to reach low emissions and high reliability these conversions have to be very sophisticated with full access to the original (for the Diesel version) installed electronic control unit.

Examples of companies to supply retrofit DDF systems for HD methane engines are the Hardstaff Group and Clean Air Power Ltd. All of them are reported to work in close relation with OEM´s. In a separate Annex (Annex 1) companies offering retrofit solutions are listed.

In Table 2 below, OEM engine/vehicle suppliers are listed offering, on commercial basis, methane fuelled engines/vehicles. Since the definition of manufacturer is somewhat different in Europe compared to USA, it is difficult to have a clear distinction between OEM-applications and retrofit solutions. However, in this context OEM-applications are products offered to the market where the OEM takes the full responsibility for emissions, performance, functionality and durability. It is also important to make the remark that some of the companies listed in Annex 1 as suppliers of retrofit solutions have signed letter of intent with OEM´s listed in Table 2. In those cases it is just a question whether the actual modification of the engine will take place within the premises of the manufacturing plant or at the other side of the fence in order to be classified as an OEM- or retrofit solution.

A further complication related to the classification could be when an OEM in an early stage of development is working together with a supplier of components/system in order to develop a new system.

Table 2. Major suppliers of commercial available HD methane fuelled engines (OEM)

Company	Products	Type of technology	Webpage
Cummins Westport	Gas engines	SI	www.cumminswestport.com
Caterpillar	Gas engines	SI	www.cat.com
Doosan	Gas engines	SI	www.usa.doosaninfracore.co.kr
Iveco	Gas engines	SI	www.iveco.com
M.A.N	Gas engines	SI and Dual Fuel	www.mandiesel.com
Mercedes-Benz	Gas engines	SI	www.scania.com
Scania	Gas engines	SI	www.scania.com
Shanghai Diesel	Gas engines	SI	www.sdeciepower.com
Volvo	Gas engines	SI	www.volvo.com
Westport Innovations Inc.	Gas engines	High Pressure Direct Injection	www.westport.com
Weichai Group	Gas engines	SI and Dual Fuel	www.weichai.com
Yuchai Group	Gas engines	SI and Dual Fuel	www.yuchai.com

Source: US DoE Alternative fuels and advanced vehicle data center – Vehicle/engine manufacturer

Detailed information about products from the suppliers included in the list above is easy accessible through respectively web page and will not be further elaborated in this report. However, mainly DDF concept will be briefly described in this chapter and "conventional" methane fuelled engines of specific interest.

4.1.1 Cummins Westport

Cummins Westport Inc. is a joint venture between Cummins Inc. and Westport Innovations Inc. The company is based in Vancouver, Canada and has offices worldwide. Westport use HD Diesel engines from Cummins as base which is then converted to operate on methane gas. Warranties, service and aftermarket support from Cummins still apply on engines that are converted to operate on methane. More information can be found at the web page Cummins Westport. [4]

A common engine offered by Cummins Westport is the ISL G version. It is a SI methane engine that runs stoichiometric with cooled EGR. By using only a TWC as aftertreatment, it passes U.S. EPA and CARB 2010 emission requirement as well as Euro EEV emission legislations. The engine can operate on CNG, LNG and biomethane.

Table 4. Basic specification for Westport ISL engine

Engine model	Engine power (hp)	Peak Torque lbs. @rpm
ISL G 320	320	1000 @ 1300
ISL G 300	300	860 @ 1300
ISL G 280	280	900 @ 1300
ISL G 260	260	660 @1300
ISL G 250	250	730 @ 1300

Especially high-lighted by the manufacturer is the maintenance intervals expressed as:

- Oil and filter — 6 months/7 500 miles/500 hours
- Fuel filter — 12 months/15 000 miles/1000 hours
- Coolant filter — 6 months/7 500 miles/500 hours
- Spark plugs — 18 months/22 500 miles/1500 hours
- Change coolant — 24 months/30 000 miles/2000 hours
- Adjustments of valves — 24 months/30 000 miles/2000 hours

More detailed information about the engine can be found at the webpage of Cummins Westport [7].

4.1.1.1 Westport GX - HPDI

Westport Innovations Inc. which is a separate company from Cummins Westport Inc., has a patented DDF system working with the principle of high pressure direct injection (HPDI). Methane and Diesel is direct injected at the end of the compression stroke from the same injector which reduces methane slip and the risk of knocking (No premixed fuel). Since Diesel and gas is injected by the same injector the performance when running on Diesel is very limited. Figure 5 shows the principal lay-out of the injector.

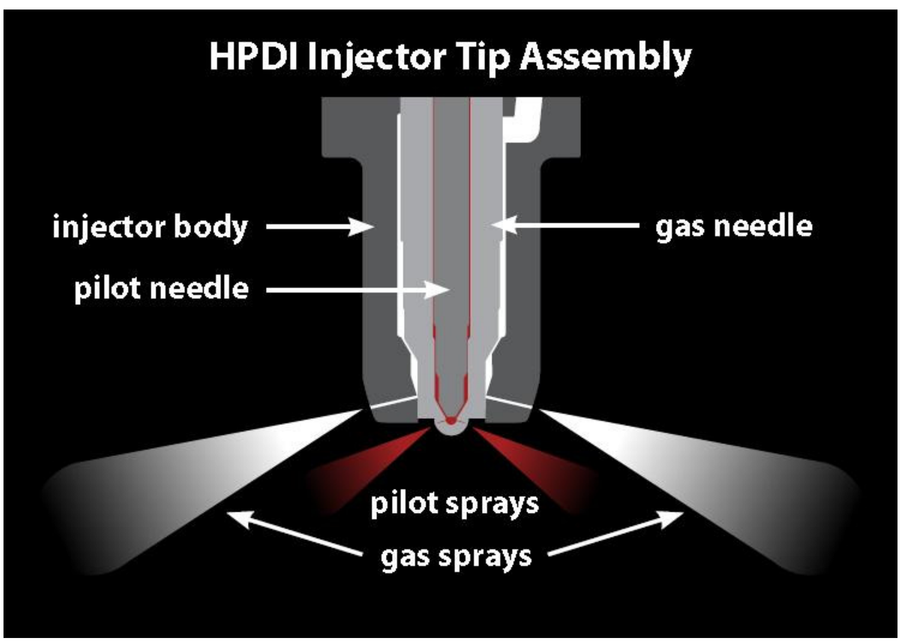

Figure 5. Westport Innovation HPDI injector [4]

The Westport GX is currently (04/2009) available for some vehicle models marketed by Kenworth and Peterbilt as OEM applications. Available engines with main characteristics are listed in Table 3. The engines are meeting emission standards for California (Executive orders A-343-0004/5) and are the only engines approved in California using the DDF technology [5].

Table 3. Available HPDI engines from Westport

Engine model	Engine power (hp)	Peak Torque lbs. @rpm
GX 450 ST	450	1550/1750 @ 1200
GX 450	450	1650 @ 1200
GX 400 ST	400	1450/1650 @ 1200
GX 400	400	1450 @1200

The warranty periods are expressed as follows [6]:

- Base engine excl. HPDI fuel injectors: 24 months/250 000 miles/6 250 hours[1)]
- HPDI injectors & LNG pump: 24 months/125 000 miles/3 125 hours[1)]
- LNG Tank: 24 months/250 000 miles/6 250 hours[1)]

[1)] **whichever occurs first**

This technology might also be used in the future by manufacturer in Europe and Asia since business agreement is signed with the purpose of jointly development of new concept. However, according to our knowledge, no HPDI system is approved in Europe due to lack of legal possibilities for approval within the EU/ECE emission regulations

4.1.2 Clean Air Power

Clean Air Power Ltd. (CAP) was founded in UK 1991 with the main activity to supply DDF retrofit conversion kits to customer world wide. Most of the conversions are to modify Euro III Diesel engines to meet Euro IV emission requirements. CAP has developed a system called Passive, clean and cold EGR (PACCOLD) system which uses a particulate filter and low pressure cooled EGR to reduce PM and NO_x. The PACCOLD system is shown schematically in Figure 6.

CAP has also developed a system called Secondary Inter Cooler (SIC) to enable high load DDF operation in warm climate without engine knocking. SIC system uses the flow of LNG to the engine as a cooling media. LNG is passed through a heat exchanger (HEX) in order to vaporize LNG to CNG. The principle of the SIC is to use the LNG vaporization process to cool the charge air to the engine. The SIC system is shown schematically in Figure 7.

More detailed information about the company is found on the webpage [8].

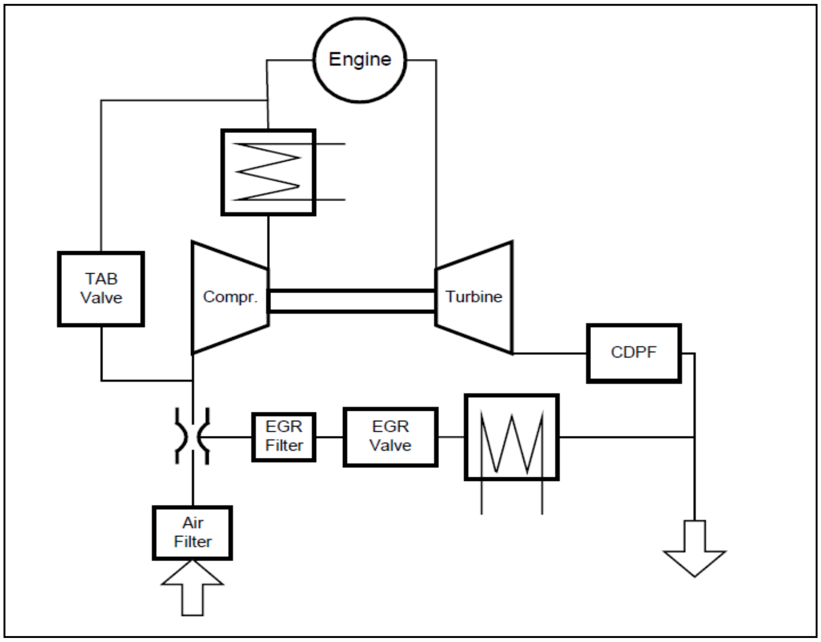

Figure 6. Basic lay-out of PACCOLD-EGR system

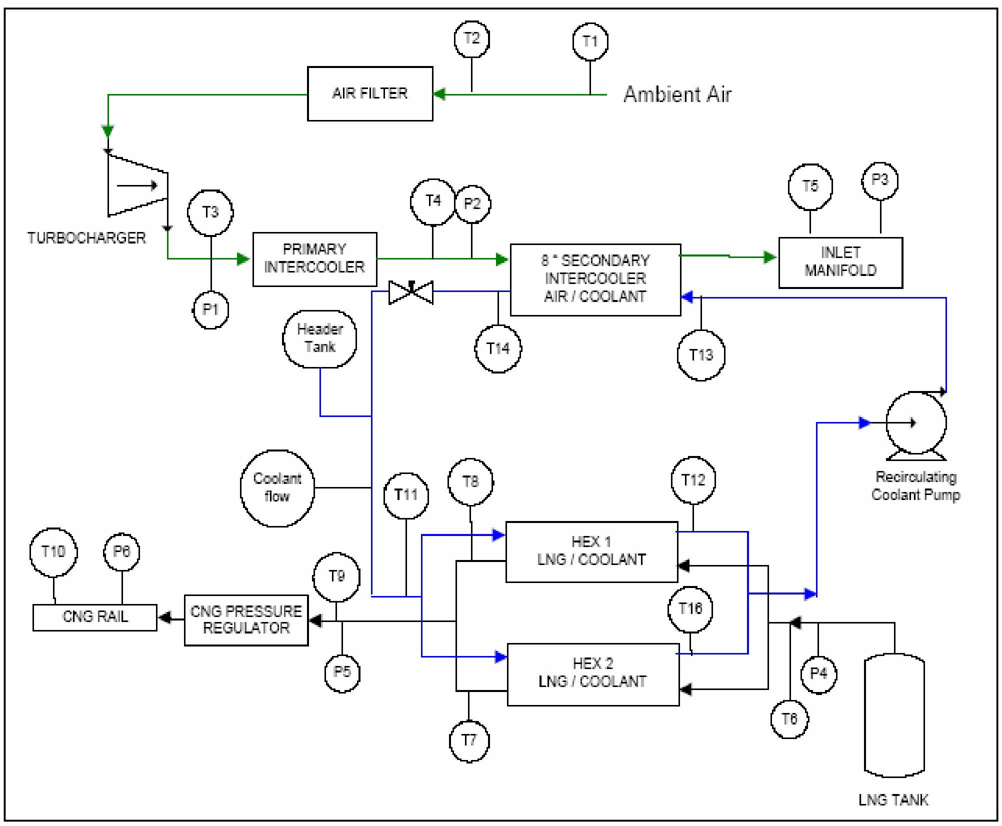

Figure 7. Basic lay-out of SIC system with parallel HEX arrangement

In 2007, Clean Air Power developed together with Volvo trucks, a dual fuel demonstration vehicle. The truck (Volvo FM9) has since then been presented at a number of events and exhibitions around the world. In February 2008, Volvo Powertrain and Clean Air Power together developed a second demonstration vehicle, a Mack Pinnacle with a 13 liter DDF engine which was presented at Washington international renewable energy conference, USA.

According to Clean Air Power a letter of intent has been signed with Volvo to modify conventional heavy duty Diesel engines to operate in dual fuel mode [9]. The intention is a closer cooperation with Volvo Trucks, and to have Clean Air Power technology fully interfaced with the Volvo engine management system applied to Volvo's D13 engine. The plan according to Clean Air Power is to introduce the first commercial product in late 2009 or early 2010.

Clean Air Power has signed letter of intent also with other major global truck manufacturer.

4.1.3 The Hardstaff Group

The Hardstaff Group located in Nottingham UK have been working with methane engines for more than 10 years and presented in 2006 the second generation of a retrofit Diesel dual fuel system called Oil Ignition Gas Injection (OIGI). Hardstaff has also a patented catalytic temperature control system. More detailed information of the Hardstaff Group is found on the webpage [10].

4.1.3.1 Hardstaff OIGI

The Hardstaff OIGI® is a dual fuel system developed to substitute natural gas for Diesel in light and heavy duty engines.

A separate electronic control unit (ECU) is used for the natural gas fuel, providing a full closed loop feedback system that monitors existing variables alongside the Diesel electronic control unit and thereby controls the gas injection based on the feedback from the various engine sensors. The system can also handle on board diagnostics.

Diesel is required as the ignition source in dual fuel engines. With the system the engine will use 100 % Diesel at idle and gas injection and Diesel reduction commences when engine speed increases from idle. A principal lay-out of the system is presented in Figure 8.

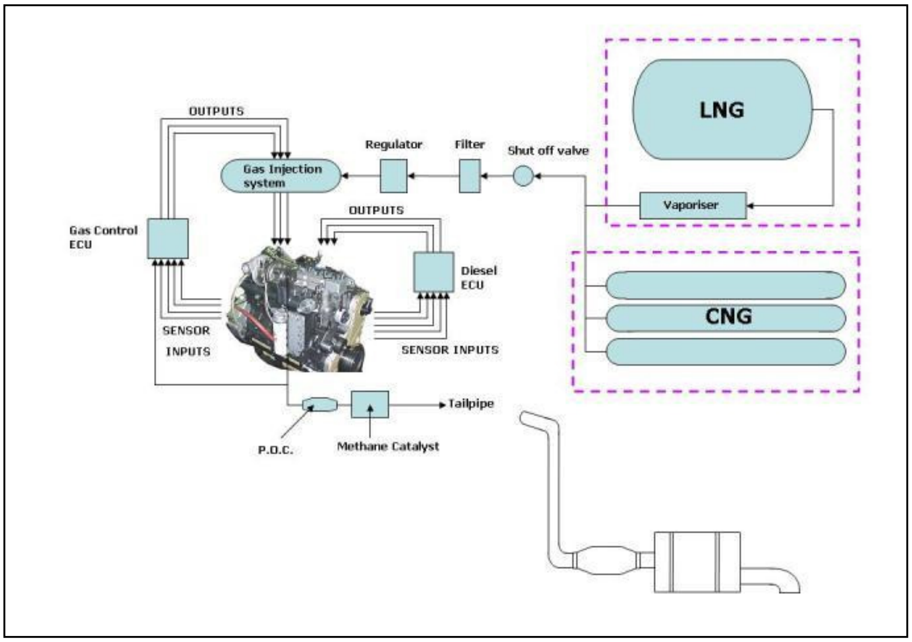

Figure 8. Hardstaff OIGI Diesel dual fuel system

In order to control emissions within a dual fuel system a Particulate Oxidizing Catalyst (POC) is required as well as a methane catalyst. This in combination with Hardstaff's patented catalytic temperature control system ensures that only sufficiently hot exhaust gases pass through the methane catalyst, thus retaining temperature for optimum performance. The basic lay-out of the system is presented in Figure 9.

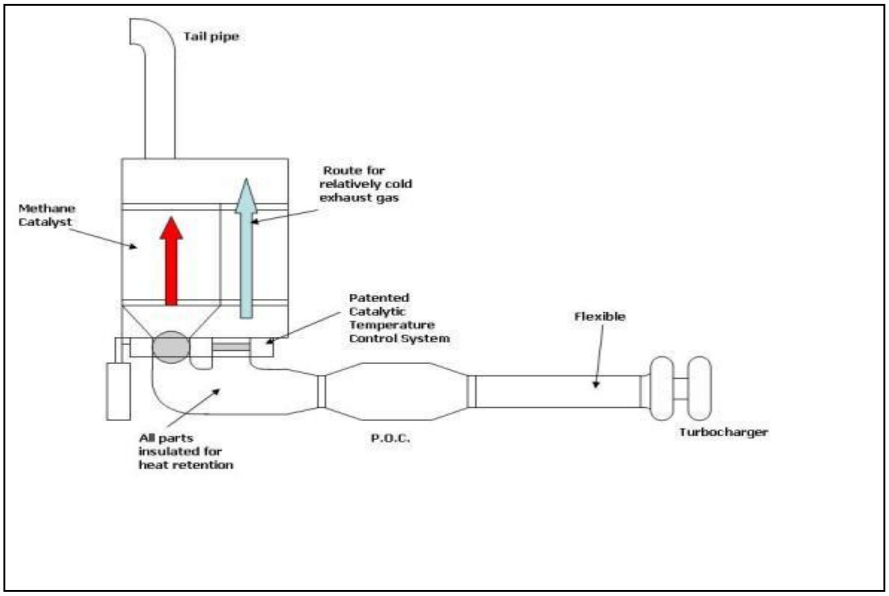

Figure 9. Hardstaff patented catalytic temperature control

The Hardstaff DDF system is claimed to meet emission requirements specified according to Euro III and Euro IV requirements and is available for different engines from different manufacturer.

Other advantages with Hardstaff exhaust technology listed by the supplier are:

- 98 % reduction in CO
- 3dB(A) reductions in noise levels
- 65 % reduction in NO_x
- Particulate emissions meet Euro IV and V regulation

Emission results have been presented by the supplier according to steady state test procedures, but no information about the test fuel is mentioned. In addition, nothing is found in literature about reduction of HC for the Hardstaff OIGI system.

4.1.3.2 Hardstaff / BAF Technologies

BAF Technologies, a US based provider of methane fuelled vehicles as aftermarket conversions, has entered into an exclusive distributorship agreement with the Hardstaff Group to retrofit in-use heavy duty vehicles to dual fuel operation. [11, 12]

4.1.3.3 Hardstaff / Howard Tenens Services Ltd

UK based logistics provider Howard Tenens Services Ltd is introducing dual fuel technology for their fleet of heavy duty vehicles in order to reduce the emissions of CO_2. The technology used will be the OIGI dual fuel system developed by the Hardstaff Group [13].

4.1.4 Bosch Heavy-Duty Natural Gas Dual-Fuel Conversion Kit

Bosch is in the phase to develop an aftermarket methane dual-fuel conversion kit for heavy duty Diesel vehicles in Brazil. The system is called GD Flex and is based on technology originally developed by DieselGas in New Zealand.

The Diesel fuel is estimated to be substituted by gas up to 90% depending upon engine operation. Development engineers have been working for more that 2 years to finalize the system. Currently the system is suitable for a small number of engines but more engines is planned to be added in the near future.

The basic lay-out of the system is shown in Figure 10 and emission results are shown in Figure 11. Please note that only result from NMHC (Non Methane Hydrocarbons) measurement is shown in the figure, and the references are against the Euro II emission requirements. In the European emission regulation for Euro II, the limit values are specified for THC (including methane), and most probably emission requirement for Euro II as implemented in Europe will not be met with this system.

More information about the system is found on webpages [14, 15]

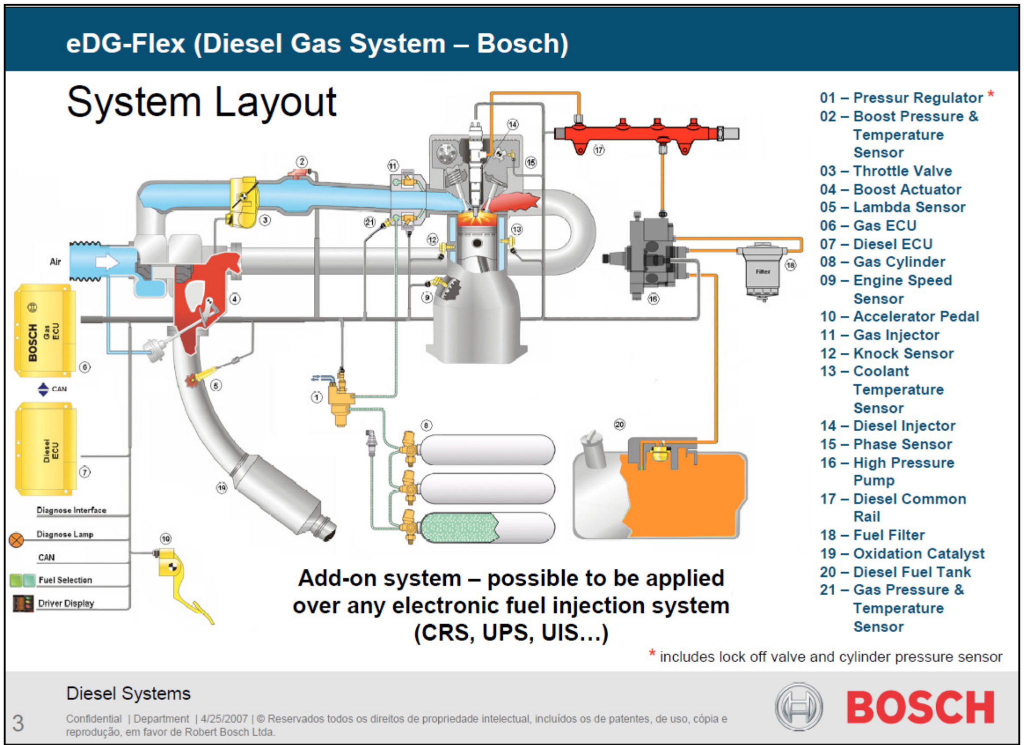

Figure 10. Bosch Dual Fuel system eDG-Flex (Source: Bosch Brazil)

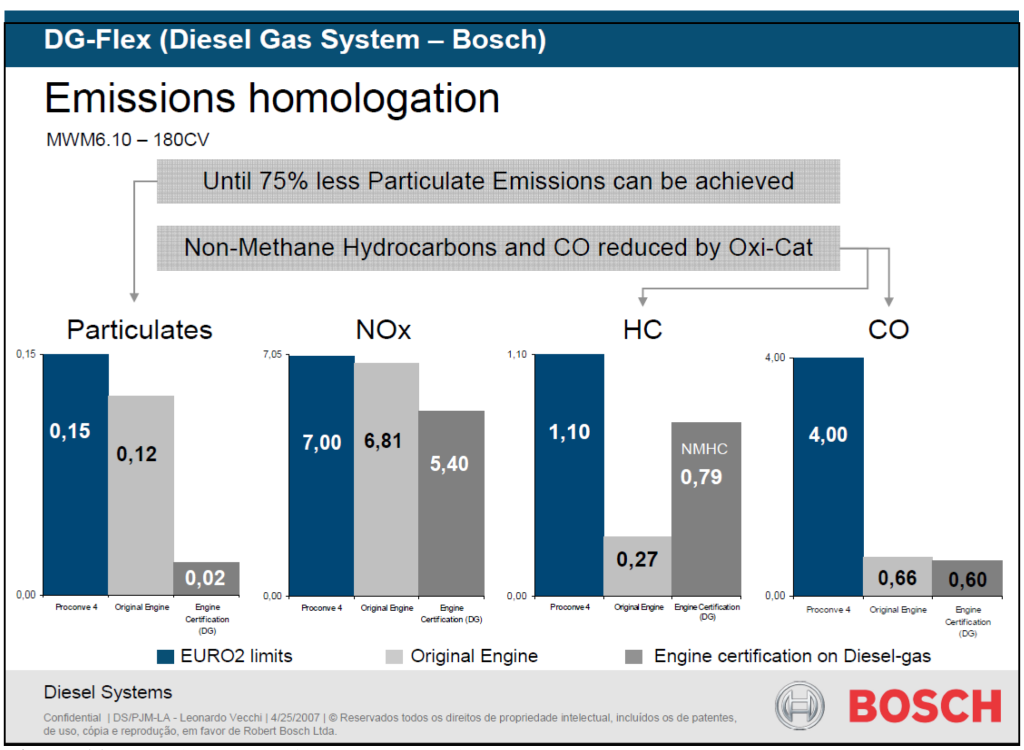

Figure 11. Emission results from Bosch Dual Fuel system eDG-Flex (Source: Bosch Brazil)

4.2 Field experience

Methane fuelled engines are known to have the weak points related to durability of catalysts and ignition parts such as spark plugs and ignition coils. Some of the engines and aftertreatment systems mentioned in previously chapters have been tested and analysed a "long" time after production. Conclusions from these tests are presented in this chapter.

4.2.1 Cummins Westport Inc. C-Gas Plus vs. diesel in HD trucks

Cummins Westport Inc. released the latest version for production of the C8.3G natural gas engine, the C Gas Plus, in July 2001. Two pre-production C Gas Plus engines installed in tractors were operated in a Viking Freight fleet for 12 months as part of the U.S. Department of Energy's Fuels Utilization Program. The engines are certified according to US EPA and CARB emission requirement 2.0 g/bHp-h low NO_x-emissions. In-use exhaust emissions, fuel economy, and fuel cost were collected and compared with similar 1997 Cummins C8.3 Diesel engine installed in tractors. A test program was designed to simulate the Viking Freight fleet duty cycle from in-service data collected with data loggers. Emission tests were carried out using the West Virginia University heavy-duty transportable chassis dynamometer and emissions laboratory. The Viking Freight C Gas Plus tractors demonstrated significant reductions in CO, NO_x, and PM emissions on the Viking Freight test cycle. The natural gas tractors also had an advantage in fuel cost per mile when fueled at the on-site natural gas fueling station. [16].

As a summary from the program the following can be high-lighted:

- Monthly mileage varied from 500 to 2 000 miles
- Nine gas cylinders, with total capacity of 49.8 Diesel gallon equivalent (DGE) for a driving range of over 200 miles, were used to store the gas on the tractors.
- Cumulative fuel consumption of the natural gas vehicles was on average 5.17 mpg DGE, versus 6.73 mpg for the Diesel vehicles. This results in a 23.2 % fuel economy penalty for the natural gas vehicles.
- Fuel operating costs were 31 % lower for the natural gas tractors compared to the Diesel units when fuelled at Viking's in-house station, and 94 % higher when fuelled at a public station.
- Chassis dynamometer emissions testing showed that the natural gas tractors significantly reduced NO_x (24 % and 45 % for UDDS respectively the Viking cycles) and PM (greater than 90 %) emissions relative to their conventional Diesel counterparts.

The oxidation catalyst efficiency and emissions of HC and CO is not demonstrated in the report.

4.2.2 Caterpillar C10 DDF engine in commuter buses

In the report "Demonstration of Caterpillar C10 dual fuel natural gas engines in commuter buses" [20], results from validation of three commuter buses of model year 1997 over a 12 months period are presented. The engines were certified according to CARB alternative low NO_x 2.5 g/bHp-h emission standard.

The project evaluated the retrofit costs and process, performance (torque, engine power and acceleration), reliability, fuel economy, operating costs, and emissions of the C10 dual fuel natural gas engines compared to a standard C10 Diesel engine.

During 94,000 combined service miles, performance, reliability and durability of the dual fuel buses were similar to the Diesel fuelled buses. Emission test was carried out on chassis dynamometer using three typical driving cycles representing normal operation of the buses. Compared to the Diesel fuelled buses, the C10 engines operating in the dual fuel mode had 27 to 60 % lower emissions of NO_x. The PM and CO_2 emissions was reduced by 14 to 19 % during all measured driving cycles. CO and NMHC emissions were higher than expected, but areas for improved emission performance were identified. The use of natural gas was two-thirds of the expected level and could be improved. Fuel economy was within 11 percent of the Diesel fuel economy.

More field experience in a wider range of applications is needed to assess fully the capabilities and potential benefits of dual fuel engines compared to the Diesel versions.

In Figure 12, the difference between the exhaust emissions from the dual fuel engine operating in DDF mode or in the Diesel mode compared to the original Diesel engine are shown for each of the driving cycles used for the emission tests.

	CO	NO_x	THC/NMHC**	PM	MPG
Central Business District (CBD) Cycle					
DFNG buses in **dual-fuel mode** vs. diesel buses	860% increase	27% reduction	861% increase	58% reduction	----------
DFNG buses in **diesel only mode** vs. diesel buses	1% reduction	1% increase	14% reduction	31% reduction	3% increase
Urban Dynamometer Driving Cycle (UDDC)					
DFNG buses in **dual-fuel mode** vs. diesel buses	653% increase	31% reduction	1718% increase	64% reduction	----------
DFNG buses in **diesel only mode** vs. diesel buses	2% reduction	3% reduction	18% reduction	42% reduction	1% increase
55 mph Steady-State					
DFNG buses in **dual-fuel mode** vs. diesel buses	634% increase	60% reduction	444% increase	54% reduction	----------
DFNG buses in **diesel only mode** vs. diesel buses	2% reduction	6% reduction	18% reduction	25% reduction	3% increase

* The differences in the shaded boxes are statistically significant at the 95% confidence level.

** THC for diesel tests and NMHC for dual-fuel tests.

Figure 12. Emissions from Diesel Dual Fuel concepts for various mode of operation compared to the diesel fuelled version

During the timeframe for the validation, the buses using DDF technology averaged 5.34 miles per gallon, which is 11 percent less than the C10 Diesel fuel economy of 6 mpg. An estimated fuel economy calculation suggests a potential fuel economy penalty of up to 20 % relative to the C10 Diesel engine. The buses operated 57 % of the time in the dual fuel mode. When in the dual fuel mode, the engines used approximately 86 % methane gas and 14 % Diesel. However, primarily due to less operating time in the dual fuel mode, overall CNG use was 56 % of total fuel used during the demonstration. Failure to refuel with methane gas, down time at gas filling station and unexpected switching to Diesel only mode was underlying causes.

However, those drawbacks could be worked on in different manners to improve the usage of gas.

Potential clean air or emission reduction benefits from dual fuel engines are directly related to dual fuel operating time of the vehicles. In this demonstration, the C10 DDF engines operated about 57 % of the time in dual fuel mode, and 43 % of the time in Diesel mode. Lower dual fuel operating time affects the total use of methane gas and also the emissions. The low use of gas can reduce the potential emission reduction, but eliminating the causes to achieve the desired substitution rates can help realize the expected emission reductions and associated clean air benefits. Suitable measures could be education of the driver or to improve the engine management system.

Operating costs for the dual fuel buses were nearly twice the cost for the Diesel bus due to the higher costs of CNG components, lower fuel economy and refueling costs. The difference of the operational cost can be eliminated over a longer operating period if CNG prices are less than Diesel fuel prices.

The C10 DDF buses cost about $ 0.20/mile more to operate than the conventional C10 Diesel bus. This cost difference attributable to the cost of the CNG components could be recovered within three to seven years if CNG prices are lower than Diesel prices. The recovery period depends on the quantity of CNG used and the price difference between the Diesel fuel and a CNG Diesel-gallon-equivalent. Furthermore, the cost difference could be reduced or eliminated in cases where government grants or other economic incentives such as emission reduction credits pay for the CNG conversion cost and on site CNG is used and Diesel is purchased at retail.

4.2.3 Fleet operators

A survey has been carried out by fleet operators and transport associations mainly in Sweden. However, some of the fleet operators are working on the international arena and have activities in many countries throughout Europe. One of the operators has the largest feet of methane fuelled buses in Europe. To summarize the experience from fleet operators they would like to high-light the following:

- Infrastructure for gas supply is general speaking weak (also outside Sweden)
- A general problem (regardless manufacturer) for urban buses is overheating of the engine, this problem has not yet been taken serious enough from manufacturer
- Service intervals for methane fuelled vehicles are about 50 % shorter than for a comparable Diesel fuelled vehicle, thereby the operation costs are increased.
- A common opinion is that methane fuelled buses is mainly put into operation because of requirement in procurement.
- A general understanding among operators is that the methane fuelled busses not yet are fully developed and manufacturer does not pay sufficient interest in methane concepts.

Manufacturer of buses, however, clams that the market still is very limited and thus it is difficult to offer buses in accordance will all requirements from the market.

In the US, the market for methane fuelled vehicles are more mature than in Europe and therefore the experience is more extensive and can not at all be compared with the situation in Europe. The number of fleet operators in U.S. using methane fuelled HD vehicles in their fleets is huge compared to European situation. On the web site of US Department of Energy many testimonies related to usage of NGV´s can be found. Below are just some examples from testing of HD NGV´s (CNG or LNG) versus HDV´s fuelled with Diesel.

Transit buses used by Washington Metropolitan Area Transit Authority and equipped with model year 2004 CNG engines produced 49 % lower nitrogen oxides emissions and 84 % lower particulate matter emissions versus transit buses equipped with model year 2004 Diesel engines.

In a study of CNG and Diesel fuelled delivery trucks operated by United Parcel Service (UPS), the CNG trucks produced 75 % lower carbon monoxide emissions, 49 % lower nitrogen oxides emissions, and 95 % lower particulate matter emissions than Diesel trucks of similar age.

City of Los Angeles Bureau of Sanitation LNG Heavy-Duty Trucks recorded a 23 % reduction in nitrogen oxides emissions from dual-fuel LNG refuse trucks compared with Diesel trucks. In another evaluation of freight trucks, CNG trucks produced 24-45 % lower nitrogen oxides emissions and more than 90 % lower particulate matter emissions compared with Diesel trucks.

The U.S. Environmental Protection Agency calculated the potential benefits of LNG versus Diesel based on the inherently cleaner-burning characteristics of natural gas, summarized in Clean Alternative Fuels:

- Produce half the particulate matter of average Diesel vehicles
- Significantly reduce carbon monoxide emissions
- Reduce nitrogen oxide and volatile organic hydrocarbon emissions by 50 % or more
- Potentially reduce carbon dioxide emissions 25 % depending on the source of the natural gas
- Drastically reduce toxic and carcinogenic pollutants
- Increase methane emissions (not a benefit)

The list should be looked upon just as examples related to emissions. More information at: http://www.afdc.energy.gov/afdc/vehicles/natural_gas.html

The experience from fleet operators is general comments for all types of methane fuelled HD vehicles.

4.2.4 Transport associations

A transport association is an authority responsible for public transport in a larger geographic area. Such an association is in many cases very close related to a municipality and thereby other requirements are applicable as for a fleet operator. Experience and visions from a transport association differs significantly from those of a fleet operator. The future challenge is to merge those positions.

When making a survey among transport associations in Sweden also the future vision became very important. The general position is that the share of conventional (fossil) fuels used for public transport should be decreased and be substituted with renewable fuels. One target mentioned is that the share of renewables should be at least 10 % at 2020. Since biomethane is one of the fuels with the highest potential to reduce CO_2, the use of this fuel will be very important in procurement documents. Methane fuelled city buses will therefore play an even more important role in future city traffic. The municipalities also declare that asking for methane fuelled vehicles will form the base for local production of biomethane and related investments. Introduction of biomethane fuelled vehicles for public transport will also create a base for long term supply of fuel, which can be used also for other types of vehicles.

The traffic associations also mention some drawbacks with existing technology and should appreciate efforts to reduce the downside with renewable fuels. Those disadvantages could be expressed as follows:

- Energy consumption is theoretical 25 % higher for biomethane fuelled city buses compared with conventional Diesel fuelled buses. However, the practical experience shows a difference of up to 40 %. This is considered to be too much and thereby increase the operational cost for a bus. Comparing the energy consumption between a hybrid bus and a methane fuelled bus ends up in a difference of about 50 %.
- The maintenance cost for biomethane fuelled city buses is up to 1 Eurocent per kilometre higher than for a conventional Diesel bus. This is considered to be an issue when a fleet operator is putting monetary terms in his offer.
- Some larger biomethane fuelled buses experience unexpected malfunctions requiring immediate actions (which cost money and create lack of confidence)

The public transportation industry can of course cope with increased cost but the cost has to be known in advance. The extra cost for investing in a methane fuelled city bus (12 m) is in the range of 30 000 – 35 000 Euro. The total cost for operating a biomethane fuelled city bus is higher than for a corresponding Diesel bus. The cost is however to some extent balanced with differences in fuel cost, cost for maintenance and vehicle taxation. Since the cost for fuel, labour forces and system for taxation is different between countries, the total operational cost will of course be different when comparing between countries.

The summary of the survey can be expressed as the main targets for transport associations is to phase out fossil fuels and reduce the energy consumption per passenger kilometre travelled. Finally, they consider the development of low emitting Diesel dual fuel concepts as essential, since this will meet the set targets.

The experience from transport associations is general comments for all types of methane fuelled HD vehicles.

4.3 Validation in emission laboratories

Some reports presenting validation of emission performance from dual fuelled methane engines in laboratories were found. There are only a few reports mentioning results from measurement of THC and CH_4. Most of the reports indicate a strong increase for those components for DDF concepts compared to Diesel and SI methane gas engines. Further, emission measurements according to transient test cycles are very rare. Some reports related to this study are presented below.

4.3.1 Clean Air Power Dual Fuel Caterpillar engine

In the report "Chassis dynamometer emission measurements from refuse trucks using Dual-Fuel™ natural gas engines" [18], 10 refuse trucks equipped with Caterpillar C10 engines were measured on West Virginia University's (WVU) transportable emissions laboratory. Basic engine and vehicle parameters are shown in Table 5 below. All engines used a commercially available dual fuel natural gas system supplied by Clean Air Power Inc. Some were also equipped with catalyzed particulate filters (CPF), also supplied from Clean Air Power.

Before the tests, the trucks were verified to be in good running order with no engine diagnostic error codes. The test program and the actual emission testing were carried with low sulphur Diesel fuel (less than 10 ppm sulphur).

Table 5. Basic engine/vehicle parameters

	Diesel Trucks	DFNG Trucks
Chassis		
Manufacturer	Peterbilt	Peterbilt
Model Year	2000-2001	2000-2003
GVWR	51,000 lbs	51,000 lbs
Curb Weight	32,077 lbs	32,077 lbs
Test Weight	40,600 lbs	40,600 lbs
Engine		
Manufacturer	Caterpillar	Caterpillar/DDF
Model	C10	C10
Model Year	2000	2000-2002
Displacement	10.3 L	10.3 L
Peak Power	315 hp	315 hp
Torque	1050 ft-lbs	1050 ft-lbs

Emissions measurements on DDF trucks, both with and without catalyzed particulate filters revealed statistically significant lower NO_x emissions (in the range 17 – 35 % for the selected driving cycles) than the Diesel trucks equipped with catalyzed particulate traps. Differences in fuel consumption due to differences in specification between the reference fuel and the fuel used for testing might also have contributed to the reductions of NO_x. However, no information about actual figures from measurement of fuel consumption could be found in the report.

Measurements of particle emissions revealed no statistically significant difference between the DDF trucks equipped with catalyzed particle filter compared with the Diesel fuelled trucks equipped with "conventional" Diesel particle filter (Engelhard DPX). Depending upon the driving cycles used for test, small differences of the particulate emissions could be observed, but on a very low level. The report pointed out that more accurate measurement techniques for these low PM levels are needed to accurately assess the differences.

The emissions of CO were substantially reduced both for the Diesel vehicles using DPX particulate filter and the methane fuelled vehicle with the DDF system. The CO_2 emission was lower for the truck using the DDF-system compared to the Diesel fuelled truck, mainly because the main fuel used in a DDF concept has a lower content of carbon.

Overall, the tested DDF technology reduces NO_x and CO_2 compared to their Diesel counterparts and can maintain a similar duty cycle while significantly reducing petroleum use. The use of the catalyzed particulate filters on the low sulfur fuelled Diesel trucks result in virtually the same particle emissions as the truck equipped with Diesel dual fuel system.

4.3.2 Cummins Westport HPDI

Direct injection of natural gas in a modern four-stroke Diesel engine can provide NO_x emissions reduction by nearly 45 % compared to the 1998 EPA emissions requirement with little deterioration in fuel efficiency. These results are consistent with previously reported work on two-stroke engines. By optimizing the gas injection timing and pressure at every engine speed/load point it is possible to achieve highest cycle NO_x reduction without an appreciable impact on cycle thermal efficiency (<3 % change in BSFC) while maintaining Diesel baseline performance.

In the report "Direct injection of natural gas in a heavy-duty Diesel engine" [19], results of transient tests were consistent with steady-state data prediction obtained over an AVL 8 mode cycle. The HPDI engine achieved a combined NO_x + NMHC emissions of 2.38 g/bhp-hr during official US EPA certification tests according to FTP cycle for heavy duty Diesel engines. Emissions of NO_x, NMHC and PM were reduced by 45 %, 85 % and 71 % respectively, compared to the 1998 EPA emissions requirement for heavy duty Diesel engines.

5 POSSIBILITIES FOR APPROVAL

In order to push manufacturer to present new technology to be used in vehicles, introduction of more severe (emission) regulations might be the most important driving force. Other driving forces can be different financial incentives or special requirements for procurement of vehicles. In addition, there might also be companies looking for enhanced environmental profile. During the long process to introduce new technology on the market, manufacturer must be given the possibility to test vehicles extensively in normal operation on the road. This is normally possible by including special vehicles in pilot projects, in which a manufacturer is allowed to operate vehicles not meeting all requirements in contradiction to a series produced vehicle that have to meet the requirements. Normally, pilot projects are allowed during a specified time period and with specific and well identified vehicles.

Another possibility within the European Union is that national Governments have the power to approve vehicles based on national regulation not as detailed as the European Directives. Vehicles approved according to national regulations are not subjected to the possibility of free movement of goods between European member states.

When a technology is mature enough to live on its own merits and is introduced in mainstream production, it should be possible to have the new technology approved according to a standardized procedure. In the case of HD methane fuelled engines this is possible as long as the fuel is Diesel, methane gas or ethanol and the type of engine is either SI or CI. When a combination of fuels are used there will be some problem, since DDF concepts, using a combination of Diesel and methane gas in a variable percentages of blend depending upon the mode of operation of the engine.

During survey for this report it is obvious that there is an interest for introduction of methane fuelled heavy duty vehicles from manufacturers as well as from transport associations. As mentioned above there are no problem for manufacturer to apply for approval/certification of conventional methane fuelled engines, but no certification scheme exist for DDF concepts. The text below is therefore focusing on DDF concepts since no procedure is yet defined.

European Commission (EU)
Today, it is not possible to approve Diesel dual fuel concepts according to the European emission requirements. For the very moment there is no plan from the Commission to implement dual fuel concepts in the emission requirements for Euro VI. However, if there is an increasing demand it might be possible to reconsider the situation, but today this is not the main priority of the Commission. Since emission limit values are defined based on the working principle of an engine, the limit values for engines operating according to DDF principle should be the same as for Diesel engines since the same working principle is used (CI). The detailed regulations and requirements must however be designed accordingly. As example, question that must be solved is what fuel to be used for certification tests, whether it should be Diesel, gas or the mix of Diesel and gas? The viewpoint of the Commission is that DDF concepts will be more frequently used as retrofit systems as OEM applications, therefore the recommended starting point for development of a regulatory system should be via GRPE. The Commission also expressed an interest to follow the future development of DDF concepts.

United Nations Economic Commission for Europe (UNECE)
Question whether to include Diesel duel fuel concepts in the regulatory system have been discussed in the informal group gas fuelled vehicles (GFV) within the working party on pollution and energy (GRPE). In the UN ECE/R115 regulations (Specific compressed natural gas retrofit systems to be installed in motor vehicles for the use of CNG in their propulsion system) retrofit of Diesel dual fuel systems are excluded. However, at recent meetings in Geneva and in related protocol, Diesel dual fuel is mentioned as a “place holder” for the future. During discussions with members of the group, a clear interest for the DDF concepts is expressed, but so far no thorough report has been presented showing emission performance meeting Euro V and Euro VI requirements for modified engines. The requirements in UN ECE/R115 are incomplete for dual fuel systems and are not acceptable for certification of a Diesel dual fuel system. Methods to deal with are the change of fuel mix during the tests as well as the HC ratio for calculation of the results has to be elaborated. The GFV- group is most interested to follow the development and will take proper actions when technology is mature enough. The recommendation for introduction of DDF concepts is to use the possibility for Member States to allow for national approvals such as in the UK.

Australia
This information is collected from the Department of Infrastructure, Transport, Regional Development and Local Government (DITRDLG), who is responsible for the Australian Design Rules (ADR). Diesel dual fuel/natural gas engines are in a grey area under rules as the

Euro standards adopted in ADR80/02 (2005/55/EC, “Euro IV”) do not explicitly recognise dual fuelled heavy vehicle engines. If someone wish to gain certification for a dual fuel engine DITRDLG would have to consider it on its merits and decide whether it would be tested as a Diesel or gas engine or some combination of both. This would have an impact on what test cycles to use since Diesel requires two test cycles (ETC and ESC) while natural gas requires ETC only. There would also be different emission limits and types that would apply - for example only Diesels are subject to PM limits, gas engines subject to NMHC limits. No one has tried to import a dual fuel engine at this time, so this is all untested. According to information, Westport HPDI fuel system (LNG) adapted to the 2008 Cummins ISX engines is approved according to requirements 2008 ADR 80/2 and ADR 30/1 (Smoke emission control for diesel vehicle) in Australia.

USA (EPA)

The US EPA regulations do not specifically discuss Diesel dual fuelled engines. Since CNG and Diesel fuel engines are regulated by EPA, the approach is the possibility of approving a system which uses both fuels. Prior to 2007, EPA has been approached by manufacturers for approval of such systems.

Beginning with the 2007 heavy duty engine standards, dedicated CNG engines do not have significant differences in CO, NMHC, NO_x and PM emissions compared to Diesel engines. It is doubtful a request to certify new engines with a DDF system will be submitted to EPA.

EPA has been approached by a number of companies to retrofit older, pre-2007, engines with systems which inject CNG into the air intake system and displace some of the Diesel fuel. EPA has not such a system but it maybe only a matter of time. There is strong interest to use CNG because it is a locally available fuel but so far no actual data to determine if there are any emissions benefits has been presented.

6 METHANE AS VEHICLE FUEL

Methane based fuels (CNG, LNG, CBG, LBM) has been used as a substitute for gasoline or Diesel for many years. The major market drivers for using this fuel are:

1) Environmental concern (less emissions of PM and NO_x compared to “old” Diesel technologies, less GHG than Diesel and gasoline).
2) Economical reasons (lower production costs and/or financial incentives/taxes to significantly reduce the price at the gas filling stations compared to the prices for gasoline and Diesel)
3) Political reasons (secure national resources for energy and less dependency of imported oil)

The most common type of methane fuel is fossil based CNG which contains not only methane but also other hydrocarbons as well as nitrogen and carbon dioxide. This makes CNG a demanding fuel to handle for the engine control system, since it has large variations in energy content and knock sensitivity. LNG (Liquefied Natural Gas) and refined/upgraded biomethane normally has less variation in energy content and knock sensitivity compared to CNG.

Because of the short chains of hydrocarbon in methane, methane gas produces low smoke and particulate emissions. These advantages together with the widespread availability make methane gas an attractive alternative fuel in internal combustion engines.

6.1 Methane compared to other vehicle fuels

Methane has very low H/C ratio compared to gasoline and Diesel which results in lower CO_2 emissions per energy content. Natural gas as fossil fuel produces approximately 20-25 % less GHG than Diesel and gasoline. If instead biomethane is used, the reduction of GHG will be much higher.

The major differences between CNG and liquid fuels (gasoline and Diesel) are:

1) Methane has higher octane number (knock resistance)
2) Methane has higher ignition temperature (650 ºC compared to gasoline 350 ºC and Diesel 250 ºC)
3) Methane has lower cetane number (need aid for ignition)
4) Methane is a gas and therefore more “spacious” than liquid fuels (10-20 % loss of performance)
5) Cooling from fuel enrichment not possible (leading to high combustion and exhaust temperatures)
6) Burns without soot (low PM emissions but also increased wear on valves and valve seats from lack of lubricity)

The most important differences compared to other vehicle fuels can be seen in Figure 12.

		Diesel	Gaso-line	Metha-nol	Etha-nol	LPG	CNG	DME
Chemical Formula	(-)	$C_{15}H_{28}$	C_7H_{15}	CH_4O	$C2H_6O$	$C3H_9$	CH_4	C_2H_6O
Molecular Weight	(-)	208	99	32	46	45	16	46
Carbon Content	(%m)	86.1	84.9	37.5	52.2	80.0	75.0	52.2
Hydrogen Content	(%m)	13.9	15.1	12.5	13.0	20.0	25.0	13.0
Oxygen Content	(%m)	0	0	50.0	34.8	0	0	34.8
Density Liquid at 20°	(kg/l)	0.840	0.740	0.795	0.790	0.540	-	0.668
Lower Heating Value	(MJ/kg)	42.7	42.5	19.7	26.8	46.0	47.7	28.4
Heat of Evaporation	(kJ/MJ)	≈6.0	≈8.0	56.4	33.8	8.6	-	14.4
Octane Rating RON	(-)	-	95	>110	>100	≈100	≈130	-
Cetane Number CN	(-)	45-55	-	-	-	-	-	>55
CO_2 Emission	(g/MJ)	74.2	73.3	70.0	71.5	63.8	57.7	67.5

LPG: Liquified Petroleum mGas (50%gew. C_3H_8 + 50% C_4H_{10}

CNG: Compressed Natural Gas (mainly Methane CH4)

DME: Dimethylether

Figure 12. Properties of different vehicle fuels.

6.2 Differences in methane quality and specification

There are large differences in fuel quality and specifications for methane based fuels around the world. The differences manly depend on different production sources, fuel storage and filling equipment at refuelling stations (compressors etc). Different fuel standards around the world also contributes to unwanted differences which puts high demand on quality validation for the manufacturers of gas systems and engines.

The methane fuel quality differences could be divided in the following categories.

1) Differences in energy content (manly effecting the A/F ratio leading to increased emissions and/or increased level of misfire)
2) Differences in content of longer HC chains (i.e. ethane, propane, butane, manly effecting knock resistance leading to engine durability problem)
3) Contamination (i.e. oil, dirt etc. manly effecting fuel system functionality and durability. Injector and/or pressure regulator clogging is typical problems)

Examples of methane fuel specification is shown in Figure 13 where commercial available CNG is compared with G_{20} and G_{25} which is the two methane gases used during the emission certification tests. G_{20} and G_{25} are used for passenger car certification tests. G_R and G_{23} (H range) or G_{23} and G_{25} (L range) is used for certification (Euro V) of engines to be used in HDV. For Euro VI emission certification the proposal is to use G_R, G_{23} and G_{25}.

AVL MTC	TEST FUEL SPECIFICATION				
Description	**Unit**	**CNG (1)**	**G20**	**G25**	**Gasoline (2) (CEC RF-02-03)**
Density (0°C, 1013 mBar)	**kg/m3**	0,835	0,720	0,792	763
Specific calorific val.	**MJ/kg**	47,8	49,6	39,0	42,2
A/F$_{stoch.}$		16,4	17,0	13,4	14,7
Relative fuel corr.		0,89	1,00	1,15	---
CH4 (Methane)	%	87,64	99,50	86,00	---
C2H6 (Ethane)	%	6,79	0,00	0,00	---
C3H8 (Propane)	%	2,85	0,00	0,00	---
C4H10 (Buthane)	%	1,01	0,00	0,00	---
C5H12 (Penthane)	%	0,20	0,00	0,00	---
C6H14 (Hexane)	%	0,05	0,00	0,00	---
N2 (Nitrogen)	%	0,33	0,50	14,00	---
CO2 (Carbon dioxide)	%	1,13	0,00	0,00	---
S (Sulphur)	%	0,00	0,0035	0,00	---

1) AGA 20031023
2) Haltermann RF12513AD0

Figure 13. Properties of commercial available CNG compared to CNG used for certification. (Source: AVL)

Both energy content and types of hydrocarbons can affect drivability and emissions since they also influence the A/F ratio as seen in the Figure 14. An advanced engine management system including knock control, closed loop A/F control and fuel trim is recommended to avoid these problems.

There are several indicators of energy content in the methane gas.

- Higher heating value
- Lower heating value
- Wobbe index.

The higher heating value is defined as the amount of heat released by a specified quantity of gas when it is combusted and the products have returned to the starting temperature of 25 °C.

The lower heating value is defined as the amount of heat released by combustion of a specified quantity of gas and returning the temperature of the combustion products to 150 °C This means that the lower heating value take into account that the water component still is in vapour state at the end of combustion as opposed to the higher heating value that take into account the condensation of all water.

The Wobbe index is defined as the higher heating value/(square root of gas specific gravity) The gas specific gravity is the ratio between the density of the gas and the density of air. The Wobbe index is used as an indicator for the interchange ability of gases with different composition when used in a burner with fixed orifice. If two fuels have identical Wobbe indexes, then for given pressure and valve settings the energy output will also be identical.

The most common indicator for energy content of methane for internal combustion engine is the lower heating value since the combustion gases includes water vapour but also the higher heating value is commonly used.

Methane number is often used to define the knock resistance in methane based fuels. Methane number 100 is close to 120-140 RON for liquid fuels. Methane with high methane number has high content on inert gases and low content of longer HC chains which also leads to low energy content (heating value).

Figure 14 shows how the methane number and higher heating value of natural gas differs between different parts of the world [21]. As can be seen in the figure, the gas quality differs much, even when the gas comes from the same region. This has a negative aspect on the engine efficiency since the engines have to be calibrated for worst case scenario.

6.2.1 Standardization of methane gas

As mentioned above, the gas used for certification tests is well specified, and to assure accepted emission performance and drivability when different quality of the gas is used during the test procedures. However, the situation for commercial available gas is not as complete as for conventional fossil fuels. When the content of methane in the gas differs, the vehicle will react differently. Many engine management systems have a built in ability of self-adaption for considering gas quality and will adjust engine performance within 10-15 minutes.

Since the number of OEM´s offering methane fuelled engines has increased, the demand for a standard is growing. When designing an engine meeting low emission standard a narrow tolerance for the gas specification is required. The standard most used today for NG engines is ISO 15403, but the standard is relative broad and most related to water content. Efforts in Germany to introduce a new standard, DIN 51624 for CNG quality is said to threat the industry due to very narrow values for content of methane, sulphur, oil and water.

Biomethane upgraded to biomethane for vehicle applications can however be manufactured to a consistent methane content.

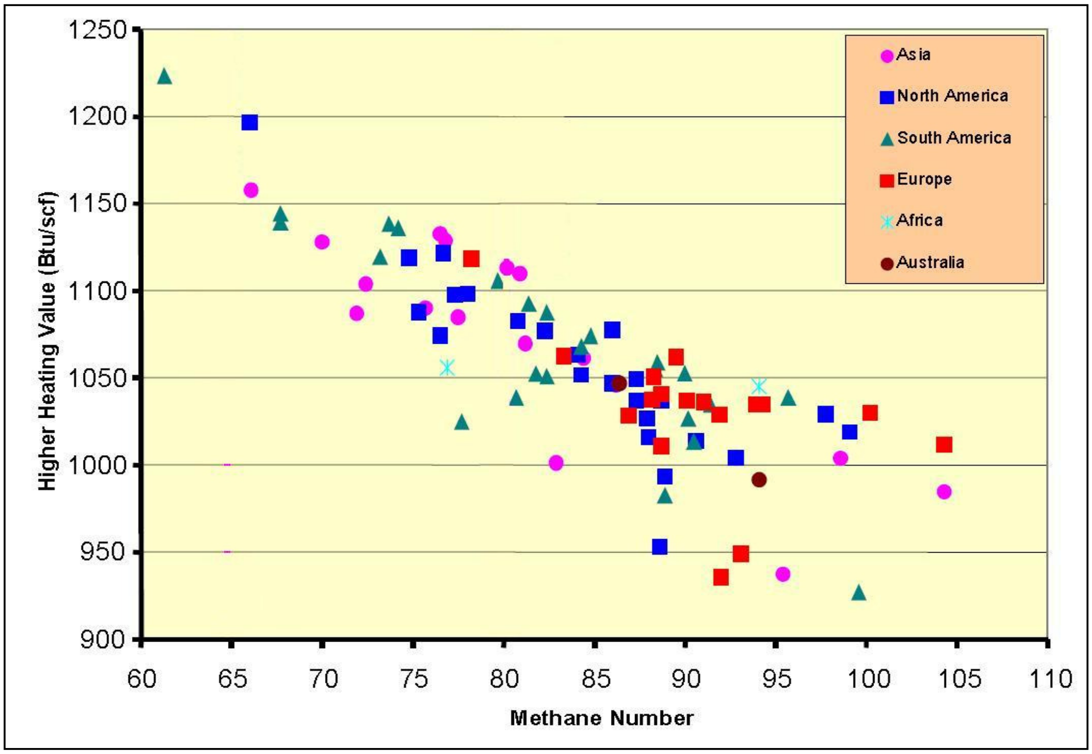

Figure 14. Methane number and higher heating value of natural gas differs between different parts of the world

6.3 Diesel (and Gasoline) fuel quality

It is well known that emission performance will change depending upon the specification for fuel. The quality of fuel must work together with the engine technology in order to use the full benefit of the combination, and it is therefore essential to introduce worldwide standards both for fuel used for certification tests as well as the commercial worldwide available fuel. The specifications for Diesel fuel for testing purposes are well defined and are to be found in corresponding regulations. An initiative to achieve worldwide fuels harmonisation is presented in the document “Worldwide Fuel Charter”. The document is a joint initiative from the vehicle industry represented by European Automobile Manufacturers Association (ACEA), Alliance of Automobile Manufacturers, USA (Alliance), Engine Manufacturers Association, USA (EMA) and Japan Automobile Manufacturers Association (JAMA). The objective is to define proper fuel for various engine technologies.

Fuels are differentiated in different categories such as:

Category 1: Markets with no or first level of emission control based primarily on fundamental vehicle/engine performance and protection of emission control systems (ex. Euro I).

Category 2: Markets with stringent requirements for emission control or other market demands (ex. Euro II/III, US Tier I).

Category 3: Markets with advanced requirements for emission control or other market demands (ex. Euro III, US/Cal LEV/ULEV, JP2005)

Category 4: markets with further advanced requirements for emission control to enable sophisticated NO_x and particle matter aftertreatment technologies. (US EPA 2007/2010, Euro IV, V).

Lately, the Worldwide Fuel Charter Committee has addressed the need for more information about renewable fuels. This has resulted in two additional documents, Biodiesel guidelines and Ethanol guidelines. Those guidelines introduce recommended limits for 100 % biodiesel blend stock intended for blending with petroleum-based Diesel fuel to make a blend containing a maximum of 5 % biodiesel by volume suitable for use in vehicles with compression ignition engines and for anhydrous 100 % ethanol blend stock intended for blending with petroleum-based gasoline to make a blend containing a maximum of 10 % ethanol by volume suitable for use in vehicles with spark ignition engines.

To summarize, the situation for international harmonization of fossil fuel is more successful than for methane gas. This is partly due to the fact that crude oil is refined at special production plants for worldwide distribution, while methane gas is more used on a local or national level, and long distance operation (including crossing of borderlines) of vehicles fuelled by methane is not yet that common.

7 SUMMARY OF REPORTS FROM MEMBER STATES OF IEA – AMF

This literature study was financed through Member states of IEA – AMF. Both cost sharing and task sharing activities was included. In the task sharing activity, countries have submitted technical reports and other relevant material to support the project. The conclusions of the reports are presented in this chapter. Information of how to find the full reports can be found in the “list of references” below.

7.1 Australia

A report was submitted “An investigation of heavy duty engines efficiency”, prepared by Orbital Australia PTY Ltd, September 2007 [22]. The report presents available combustion technology for heavy duty engines and the possibilities to reduce GHG emissions in the heavy duty vehicle fleet. The technology is undergoing rapid development and deployment in the market and the actual benefit offered is unclear, making the choice of technology somewhat subjective. This study summarises the basic aspects of alternative combustion systems with particular focus on relative efficiency.

The three heavy duty combustion systems reviewed in the report are as follows:

a) Diesel compression ignition (CI),
b) Dedicated spark ignited (SI) compressed natural gas (CNG), and
c) Dual-fuel compression ignition (manifold injected CNG with Diesel pilot injection).

From the summary the following main conclusions can be listed

1. Brake efficiency increases as a function of engine load.
- CI Diesel has the highest brake efficiency and typically in the range 35~45 %.
- CI dual-fuel can match or exceed CI Diesel at high load, but is less at part load.
- SI CNG at 25~38 % is typically below the efficiencies achievable with CI systems.

2. Operating cost was determined at 50 c/litre for LNG and 110 c/litre for Diesel, and is expressed in relation to engine work done to indicate relative vehicle costs.
- CI Diesel is in the range of 25~32 c/kWh.
- CI dual-fuel is in the range of 20~33 c/kWh.
- SI CNG is in the range of 22~34 c/kWh.

3. GHG tailpipe emissions are reported as a CO_2 equivalent, and expressed in terms of engine work done.
- CI Diesel is in the range of 600~780 g/kWh CO_2e.
- CI dual-fuel is in the range of 510~820 g/kWh CO_2e.
- SI CNG is in the range of 570~860 g/kWh CO_2e.

7.2 Austria

Due to IPR regulations in almost all studies, no results could be provided to third parties such as IEA – AMF. A report “Emissions and fuel consumption of clean city bus concept” presented by technical university in Graz, Austria [23] was submitted. The report present test results from emission testing of city buses. Included in the report are results from methane fuelled buses meeting emission requirements for Euro IV and EEV. All methane fuelled buses were equipped with dedicated gas engines.

7.3 Canada

National Resources Canada has made a contribution of two reports and a fact sheet dealing with methane fuelled HD vehicles.

One of the comprehensive reports "Natural gas vehicle research roadmap" [25] is prepared by the California Institute for Energy and the Environment and prepared for the California Energy Commission. The roadmap provides an analysis of NGV R&D needs, primary and supporting activities, and setting of priorities. This roadmap is only a benchmark, since time passes and circumstances change. However, it provides a solid foundation for regular review and updating in light of changing needs, R&D results, and specific opportunities that cannot yet be predicted. The report is focusing on three main areas such as:

- Engine development and vehicle integration
- Fueling infrastructure and storage, and
- Technical and strategic studies

The following areas are high-lighted as priorities and where gaps in strategic research, development, demonstration and deployment (RDD&D), in California, are listed:

- *Integrate Natural Gas Engines into More Models and Applications by OEMs (All Classes)*
Gap: Need to integrate, demonstrate, and deploy additional natural gas vehicle models of all classes, as OEM vehicles. This includes HDV applications such as goods-movement (e.g., port drayage) trucks; MDV applications such as shuttle buses, street sweepers, utility trucks, and pick-up and delivery trucks; larger passenger vehicle (LDV) applications, such as SUVs.

- *Develop a Broader Range of Heavy-duty NGV Engine Sizes for More Applications*
Gap: Develop, demonstrate, and deploy larger horsepower/displacement (e.g., 400-600 HP range, 12-16L displacement) natural gas engine offering(s) suitable for heavy-hauling and/or off-road applications such as waste transport, coal hauling, and semi-tractor trailer applications; this would allow NGVs to serve more high-fuel-consuming transportation markets.

- *Improve HDV Engine Economics, Efficiency, and Emissions*
Gap: Develop a broader range of heavy-duty NGVs with improved cost-effectiveness, engine thermal efficiency, and emissions.

- *Exhaust Emission Reductions*
Gap: Methane emissions from NGVs are currently unregulated (in the US), but as GHG emission standards are rolled in, methane will be very important to control.

- *Develop, Demonstrate, and Deploy Hybrid Natural Gas Heavy-duty Vehicles*

Gap: Managing the power density, developing the system, and lowering technology cost of hybrid NGVs. There may be synergy with hybrids developed for conventional fuel applications, but ultimately, the controls will need to be tailored to the load profile/power management needs of the NGV and its application.

- Develop Engine Technology Optimized for Hydrogen-CNG Blends

Gap: Develop hydrogen-natural gas blend options that increase vehicle fuel efficiency and reduce emissions from legacy fleet. This may incorporate an engine retrofit and/or engine control reprogramming.

- Develop NGV HCCI Engine Technology

Gap: Homogeneous charge compression ignition (HCCI) is a low temperature combustion technology utilizing compression ignition of well-mixed air fuel mixture.

Compression ignited methane fuelled engines have been given special attention in the report since such engines could hold great advantages over SI engines in terms of fuel efficiency and performance. Because they would use Diesel-like engine systems, they also could allow engine manufacturers to produce only one engine platform type (versus today's two). This could improve the economies of scale in manufacturing, reduce the cost of methane gas engines and promote greater resale compatibility in the marketplace.

A further contribution from Environment Canada is a presentation by the California Energy Commission related to the investment plan for the alternative and renewable fuel and vehicle technology program presented Jan. 14, 2009 at the natural gas vehicle technology forum [26].

Within the program, three different fuel/vehicle categories have been established based on their GHG emissions reduction potential:

1. Super-Ultra-Low Carbon (SULC) - fuel/vehicle technologies that are theoretically capable of reducing lifecycle emissions by up to 80 % compared to today such as hydrogen fuel cell vehicles and full electric vehicles.

2. Ultra-Low-Carbon (ULC) - fuel/vehicle technologies that can reduce lifecycle emissions by up to 60 % in the future such as biomethane-powered natural gas vehicles and cellulosic E85 vehicles.

3. Low-Carbon (LC) - fuel/vehicle technologies that can reduce lifecycle emissions by up to 20 % now such as propane and natural gas vehicles.

This program is an $840 million, 7 year initiative focused on helping the state achieve its climate change goals. Proposed funding allocations among these three categories are 35 % SULC, 13 % ULC, and 23 % LC with remaining funds to be allocated to related initiatives identified in the presentation.

Second report "Greenhouse gas emissions from heavy-duty vehicle" [43] is a paper summarizing GHG emission measurements obtained during several recent studies conducted by Environment Canada. The report can be found at atmospheric Environment 42 (2008). A variety of HDV and engines operating with biodiesel, CNG, hythane and LNG and with different advanced aftertreatment technologies were studied by testing on chassis dynamometer, engine dynamometer and on-road. Vehicles operated on CNG and hythane show decreased GHG emission by 10-20 %. At the tailpipe when compared to Diesel. Emission factors proposed/developed for CH_4 and N_2O are substantially lower than those recommended for use by IPCC methodologies for developing national inventories. Results from the study show that for HDV´s without aftertreatment CH_4 emissions account for between 0-0.11 % and N_2O emissions account for between 0.16-0.27 % of the CO_2-equivalent GHG emissions.

The fact sheet “Freight Transportation Case Studies” [42] presents the project “Clean Air Corridor”. Westport Innovation installed their HPDI system on five heavy duty trucks and testing was conducted May 2005 – June 2006 on routes normally served by Diesels fuelled vehicle of same size. The gas company Enbridge provided LNG for the vehicles. The vehicle weight during the test period was for two of the vehicles either empty or fully (110 000 pounds) loaded. For the remaining three vehicles the load did vary between curb weight up to fully loaded 140 000 pounds. During the test period the vehicles accumulated 726 000 km. Summary of test result from two of the five trucks found that emissions of NO_x was reduced by 40-50 %, particles by 80 % and total GHG by 20-25 %. Nothing is however mentioned about how theses emission results was created and no emission results from standardized test methods are presented.

The following additional comments are highlighted:

- No significant difference in fuel consumption was identified for the HPDI equipped vehicles (compared to Diesel fuelled trucks)
- Time for LNG fuelling about 20 minutes/day. Diesel tank topped up once/week
- Availability for the HPDI equipped trucks was 96.5 % (slightly lower than the baseline truck)
- Driver’s rated perceived safety and performance very similar to the baseline truck
- Diesel replacement was 90 % during the test period

7.4 Denmark

A report titled “Faster CHP gas engine start with loss emission” [27] was submitted from Denmark. However, since the report mainly covers engines built for power plant use, it will not be further elaborated in this report.

7.5 The Netherlands

Three reports from the Netherlands were sent to support this project. The first report “VDL Ambassador Diesel EEV bus: emission measurements and comparison with other buses”, TNO, 2007-11-07 [28], presents the difference in emissions between Diesel and methane fuelled buses.

Summaries from the other two reports “Brandstoffen en Emissies, TNO” [29] and Emissions and Fuel Consumption of Clean City Bus Concepts, TU Graz, Austria [30], will not be elaborated further since those reports already have been discussed.

VDL Bus & Coach produce buses with light weight chassis, about 20 % lighter (for the Ambassador model) than conventional chassis. The model Ambassador SB 220 meeting EEV emission requirement has been tested on a transient chassis dynamometer and the results are compared with those of heavier state-of-the-art Diesel buses (measured in 2006) and three CNG buses measured in 2004. Testing has been carried out at VTT emission laboratory in Finland.

From the test report, the following can summarized:

The CO_2 emission is for the Ambassador SB 220 bus around 860 g/km and around 740 g/km for typical city bus application and typical regional bus application. This is lower than methane fuelled buses meeting EEV emission levels (in the range of 1 040 – 1 440 g/km for city application). It is also lower than other (heavier) Diesel buses (in the range of 990 -1 020 g/km for city application).

The measured particulates emission is respectively 0.004 – 0.005 g/km and 0.003 g/km for typical city bus application and typical regional bus application. This is lower than tested methane fuelled buses (usually 0.01 – 0.02 g/km for city application) and it is much lower than conventional Diesel buses without wall-flow filter. The number of fine and ultra fine particles and the particle size distribution of the Ambassador bus are comparable with those of tested methane fuelled buses.

The emissions of NO_x are around 4.6 g/km for typical city bus application and around 2.8 g/km for typical regional bus application. For city application the figure of the Ambassador bus is the same (4.6 g/km) and no values are available for regional bus application. For methane fuelled city buses meeting EEV emission requirements, tested buses are in the range of 2.1 – 4.5 g/km. The NO_2 emission of the Ambassador bus is relatively high (35% to 42% of the NO_x emission).

8 CONCLUSIONS

An increasing interest for introduction of methane fuel HD engines is apparent both from the vehicle industry, governmental agencies and from transport sector. One of the main reasons is to meet agreed targets for reduction of green house gases. During the process of the report the following main conclusions could be drawn:

- The drivers for using methane are different in different countries but main reasons are mitigations of CO_2 emissions, mitigation of toxic emission and access to low cost fuels.

- The general trend for OEM might be towards stoichiometric engines with TWC. One alternative technology pathways is lean burn engines either SI or DDF with sophisticated (and thereby also expensive) aftertreatment of the exhaust.

- The main advantage of using DDF is a potential for better fuel efficiency than the traditional SI-engine, due to the Diesel-like process.

- Further development of methane fuelled engines has to be carried out in order to meet future emission regulations (Euro VI). Especially the part of regulations specifying limit values and durability.

- Exhaust aftertreatment systems for dedicated methane fuelled HD vehicles have to be further developed to minimize the degradation, normally caused by "poor" design of the converted Diesel engine.

- Conversion from Diesel to Diesel dual fuel (DDF) is very attractive for vehicles operating in long haul operation but DDF concepts have to be developed further to be able to meet stringent emission and durability requirements.

- European emission regulations must be further adopted in order to cope with engines using two fuels simultaneously at various mixing rate. Cooperation with the informal group for gas fuelled vehicles (GFV) within the GRPE (UNECE) is recommended. Items to discuss are test procedure, methods for calculations of emissions, test fuel to be used and limit values for DDF-concepts.

- Development of procedures for verification of emission performance of methane fuelled HD vehicles in real life operation is essential for assuring proper function of the complete exhaust control system during the life time of the vehicle

- Since advanced emission control and engine management system is required to meet latest emission requirement, the gas application should be designed as a complete system and not only as a stand alone unit. We identify difficulties to meet these requirements without a close cooperation between OEM and suppliers of gas systems

- A sustainable principle for setting the price for methane must be introduced giving stakeholders long term schedule for further development of methane fuelled vehicles. The main objective should focus on methane fuelled vehicles as a cost efficient alternative as well as a vehicle with low level of exhaust emissions during the useful life.

- A common position about methods for calculation of CO_2 equivalent GHG reduction from different methane based fuels should be adopted to enable the most cost efficient methods for future production of methane fuel and engine technologies.

9 ROAD-MAP FOR RECOMMENDED FURTHER WORK

Based on the work so far with this project, the following general measures is our recommendation for the future work, listed just as bullet points:

- Continue the dialog with supplier of DDF-concepts and OEM´s
- Enhance the communication with countries approving DDF-concepts on a national level
- Verify present status fuel efficiency for commercial available DDF concepts

- Design a proposal for a certification system for DDF-concepts
- Verify present status of emission performance for commercial available DDF concepts
- Benchmarking – After initial testing (DDF & SI) propose areas for improvement
- Include operational and maintenance cost in the literature survey
- Development of proposal for verification of emission performance during the life time of the vehicle (I/ M)
- To place IEA – AMF in the front seat for coordination of information about development of methane fuelled HD vehicles.

10 ABBREVIATIONS

ADR	Australian Design Rule
A/F Ratio	Air / Fuel Ratio
BSFC	Brake Specific Fuel Consumption
CAN	Controlled Area Network
CAP	Clean Air Power Ltd.
CARB	California Air Resources Board
CH_4	Methane
CI	Compression Ignited
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPF	Catalyzed Particle Filter
DDF	Diesel Dual Fuel
DGE	Diesel Gallon Equivalent
DI	Direct Injection
ECU	Electronic Control Unit
EEV	Enhanced Environmental friendly Vehicle
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency (U.S)
ESC	European Steady-state Cycle (test cycle)
ETC	European Transient Cycle (test cycle)
g/bhp-h	Gram/brake horsepower-hour
GFV	Gas Fuelled Vehicles
GHG	Green House Gases
GRPE	Working Party on Pollution and Energy
HC, THC	Hydrocarbons, Total Hydrocarbons
H/C	Hydrogen to Carbon ratio
HCCI	Homogeneous charge compression ignition
HD	Heavy Duty
HEX	Heat Exchanger
HPDI	High Pressure Direct Injection
IEA – AMF	International Energy Agency – Advanced Motor Fuels
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
MDV	Medium Duty Vehicle
Mpg	Miles per Gallon
NG	Natural Gas
NGV	Natural Gas Vehicle

NMHC	Non-Methane Hydrocarbons
NO_x	Oxides of Nitrogen
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
OIGI	Oil Ignition Gas Injection
PACCOLD	Passive, Clean and Cold EGR
Pd	Palladium
PM	Particulate Matter
POC	Particulate Oxidizing Catalyst
Pt	Platinum
RDD&D	Research, Development, Demonstration and Deployment
Rh	Rhodium
RON	Research Octane Number
SCR	Selective Catalytic Reduction
SI	Spark Ignited
SIC	Secondary Inter Cooler
SUV	Super Utility Vehicle
TWC	Three Way Catalyst
WVU	West Virginia University

11 ANNEX 1

List of major suppliers offering components and systems used for retrofit of HDE´s to operate on methane gas. Please observe that some of the suppliers below are developing the concepts in close cooperation with vehicle manufacturer and therefore it is sometimes difficult to have a clear distinction between OEM-application and retrofit solutions.

Company	Products	Type of technology	Webpage
Alternative Fuel Systems	Gas system components	SI	www.afsglobal.com
BAF Technology	Gas system components	SI	www.baftechnologies.com
Baytech Corporation	Gas system components	SI and Dual Fuel	www.baytechcorp.com
Bosch	Gas system components	SI and Dual Fuel	www.bosch.com
Clean Air Power	DDF systems	Dual Fuel	www.cleanairpower.com
Diesel/Gas Australia	Gas system components	Dual Fuel	www.dieselgasaustralia.com.au
DieselGas International Ltd.	Gas system components	SI and Dual Fuel	www.dieselgas.co.nz
Emission Solutions Inc	Gas system components	SI	www.emissionsolutionsinc.com
Energy Conversions	Gas system components	SI and Dual Fuel	www.energyconversions.com
GSPK Multifuel Tech	Gas system components	Dual Fuel (Diesel/LPG)	www.multifuel-technology.co.uk
The Hardstaff Group	DDF systems	Dual Fuel	www.hardstaffgroup.co.uk
IMPCO	Gas system components	SI	www.impco.ws
US Energy Initiatives Corporation	Gas system components	Dual Fuel	www.usenergyic.com
Westport Innovation Inc.	DDF systems	Dual Fuel	www.westport.com
Woodward	Gas system components	SI	www.woodward.com

List of references

[1] Internet homepage of EcoCat. www.ecocat.com 2009-08

[2] George, Michael W.. "Commodity Report: Platinum-Group Metals". United States Geological Survey USGS. http://minerals.usgs.gov/minerals/pubs/commodity/platinum/mcs-2008-plati.pdf. Retrieved on 2009-08-03.

[3] SAE paper 2008-01-1550. Development and Test of a New Catalytic Converter for Natural Gas-Fuelled Engine Publication Date: 06-23-2008

[4] Internet homepage of Westport http://www.westport.com/news/index.php?id=305 2009-08

[5] "Guide to Available Natural Gas Vehicles and Engines", www.ngvamerica.org 2009-08

[6] WPTHD datasheet collected at www.westport-hd.com 2009-08

[7] Homepage of Cummins Westport www.cumminswestport.com 2009-08

[8] http://www.cleanairpower.com/dualfuelCasestudies.php?libraryId=1

[9] www.**cleanairpower**.com/admin/doc/109.pdf

[10] www.hardstaffgroup.co.uk/ 2009-07

[11] www.ngvglobal.com/baf-technologies-joins-with-hardstaff-on-dual-fuel-0728#more-3563 2009-08-11

[12] http://www.baftechnologies.com/Home.html 2009-08

[13] http://www.ngvglobal.com/uk-logistics-provider-tenens-introduces-dual-fuel-technology-for-fleet-0725] 2009-08-11

[14] www.bosch.com 2009-08

[15] http://www.greencarcongress.com/2008/06/bosch-launches.html 2009-08

[16] SAE paper 2002-01-2737. An emission and performance comparison of the natural gas Cummins Westport Inc. C-Gas Plus versus Diesel in heavy- duty trucks -2002

[17] NREL/SR-540-33957. H.C Wong. Next Generation Natural Gas Vehicle Program Phase I: Clean Air Power 0.5 g/hp-h NOx Engine Concept. July 2003

[18] SAE paper 2003-01-3366. Chassis dynamometer emission measurements from refuse trucks using Dual-Fuel™ natural gas engines. 2003-11-10

[19] SAE paper 2002-01-1630. Direct injection of natural gas in a heavy-duty Diesel engine 2002-05-06

[20] SAE paper 2000-01-1386. Demonstration of Caterpillar C10 dual-fuel natural gas engines in commuter buses. 2000-03-06

[21] SAE paper 2002-01-2737. An emission and performance comparison of the natural gas Cummins Westport Inc. C-Gas Plus versus Diesel in heavy- duty trucks 2002-10-21

[22] An investigation of heavy-duty engines efficiency. Orbital Australia PTY Ltd, September 2007

[23] Emissions and fuel consumption of clean city bus concepts. Technical University of Graz. Forschungsgesellschaft für Verbrennungskraftmaschinen und Thermodynamik GmbH, November 2007.

[24] Austrian Advanced Automotive Technology - Heavy Duty Zero Emission (HDZ). FFG Proj.Nr. 810760. Wien 2007

[25] Natural Gas Vehicle Research Roadmap. CEC-500-2008-044-D. May, 2008

[26] The investment plan for the alternative and renewable fuel and vehicle technology program. The California Energy Commission, January 1, 2009

[27] Torben Kvist Jensen, Faster CHP gas engine start with less emission.
ISBN: 978-877795-306-4, 2007-09-30

[28] G Kadijk, R Verbeek - VDL Ambassador Diesel EEV bus: emission measurements and comparison with other buses. TNO report MON-RPT-033-DTS-2007-02723, 2007-11-12

[29] S.Bleuanus, Brandstoffen en Emissies: Brandstoffen / Olie, TNO | Science & Industry / MON-EST

[30] Emissions and Fuel Consumption of Clean City Bus Concepts, Report No. FVT-85/06/ Haus Em 29/04-6770, 2007-11-05

[31] Magazine “Diesel Progress International” May-June 2009

[32] Comparative Costs of 2010 Heavy-Duty Diesel and Natural Gas Technologies, Southern California Gas Company, TIAX Case No. D0286/D0288, July 15, 2005

[33] ENGVA position paper on Euro VI emission limits in relation to heavy-duty natural gas vehicles, European Natural Gas Vehicle Association, September 2007

[34] Michal Takats, Czech Technical University, Natural Gas Fuelled Spark Ignited $\lambda = 1$ / TWC Engine

[35] SAE paper 2000-01-1863, T Suga et al, Potential of a Natural Gas Vehicle as EEV, June 2000

[36] Gernot Graf, AVL, CNG Applications: Technology for HD Vehicles, Opportunities and Challenges

[37] H.S.Sohi, AVL Technical Centre Pvt. Ltd., Up Coming requirements in Calibration for "Alternative Fuels"

[38] GREEN – SPA1 "HD Gas Engine for Urban Area" TIP4-CT-2005-516195

[39] S Whelan, Clean Air Power, Summary of Current Performance & Emissions Status and Future Potential, March 2006

[40] Orbital project: GOV018, An Investigation of Heavy-Duty Engine Efficiencies, September 2007

[41] www.dft.gov.uk/pgr/freight/lowcarbontechnologies/ Published: 15 July 2009

[42] Freight Transportation Case Studies, #27 Transport Canada

[43] Greenhouse gas emissions from heavy-duty vehicles. Atmospheric Environment 42, 2008 4665 - 4681