



A Strategic Roadmap to
Market Development of Certified Heavy Duty Gaseous Fuel (methane/LPG)-Diesel
Engines¹

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Background

The Clean Fuels Consulting Critical Issues Workshop *Dual-fuel Gaseous/Diesel Engines: Challenges, Opportunities and Strategies to Build the Market* gathered 75 gaseous fuel stakeholders – system designers and suppliers, OEMs, the European Commission, national government representatives, emissions experts and others -- to evaluate the technical, economic, marketing and regulatory trends related to gaseous/diesel engines. The intention was to identify the opportunities and challenges in bringing these technologies to the market and to help foster the development of a regulatory framework that allows for the certification of dual-fuel gaseous engine systems be they for original equipment manufactured (OEM) or retrofit applications.

Methane & LPG/diesel engine technologies are improving

Contemporary gaseous dual-fuel-diesel (DF) engines have been under development in Europe and the U.S. since the early 1980s. These were designed to idle on diesel fuel, keeping the compression ignition (diesel) cycle, but use increasingly more natural gas (or liquefied petroleum gas [LPG]) as the vehicle moves toward full load performance – hence the name ‘dual-fuel’. The early technology was based on a mechanical ‘fumigation’ system where the gas would be introduced into the engine through the air intake manifold. But the performance and emissions results of these early engines were not optimal. As the fuel flowed into the engine different amounts of the gas/air mixture would enter the different cylinder chambers causing imprecise emissions control across the complete drive cycle and making the performance inconsistent.

Dual-fuel gas engines are designed to operate on natural gas (compressed – CNG or liquefied –LNG) or LPG with varying amounts of diesel fuel as a ‘pilot’ ignition source. Dual-fuel natural gas engines (including high pressure direct injection natural gas engines, also referred to as HPDI²) replace up to 85-95% diesel; dual-fuel LPG

¹ Based on results and conclusions at the Clean Fuels Consulting Critical Issues Workshop, *Dual-fuel (Gaseous/Diesel) Engines: Opportunities, Challenges & Strategies to Expand the Market*, 30-31 March 2010, Brussels.

² HPDI is a proprietary term to describe the Westport Innovation technology. For this paper it is considered as one of the technical options amongst the ‘dual-fuel’ technologies. Approximately 95% steady state replacement of diesel with natural gas/LNG is used and ‘diesel-only’ operation is not an option.

engines replace about 35-40% diesel. Most of these systems also can operate on 100% diesel if natural gas or LPG is not available or where operational vehicle range exceeds that of the vehicle gaseous fuel storage capability.

Many dual-fuel technologies include sophisticated, computer controlled retrofit systems developed as 'bolt on' technologies that can be removed if necessary, to resell the vehicle as a normal diesel engine. This flexibility makes these engines very useful for heavy duty applications, affording a good business case in many global markets. (The HPDI system differs in that it is integrated into the engine and is not removable.) A main advantage of all dual-fuel systems is that, because the compression ignition cycle is maintained, gaseous-diesel engines tend to achieve efficiency and power performance close to the original diesel engines.

More recently dual-fuel systems are being developed specifically for and in conjunction with major worldwide engine manufacturers and are delivered to customers as a factory-built engine or vehicle. In these cases the gaseous fuel system suppliers have direct access to the OEM's on-board computer system, allowing them to optimize the timing, engine settings and overall performance. Thus, adoption of dual-fuel technologies by vehicle manufacturers could make these systems more 'mainstream' as economical and environmental options to traditional diesel engines. Higher production volumes will drive down system costs which, in turn, will increase the economic attractiveness of the products, leading to greater demand and increasing market penetration.

As with other gaseous fuel engines, gas-diesel technologies can make an economical contribution to reducing air pollution and greenhouse gas emissions. They also are valuable where the gaseous fuel supply is considered important for energy security and fuel diversification reasons.

Dual-fuel engines are becoming more widespread for on-road and off-road applications

A 2010 inventory by Clean Fuels Consulting of companies engaged in dual-fuel gaseous/diesel engines and vehicles – natural gas and liquid petroleum gas (LPG) -- identified at least 34 different companies engaged in some form of development, production and sale of these emerging technologies. The companies, originating from 13 countries, represent a diverse range of technologies and there is growing interest in commercializing these economic and environmental alternatives to the straight diesel engine.

The 'inventory' (or survey) was complicated by internationally confused references between bi-fuel gaseous vehicles and dual-fuel diesel systems. Additionally, it is difficult to determine in many cases at what stage of development or sales these companies have achieved with their individual technological approaches. Furthermore, the relationship between various dual-fuel system developers, engine manufacturers and vehicle producers complicates the process of identifying the number of companies manufacturing and selling dual-fuel systems. Still other engine companies are 'known by reference' to be investigating the dual-fuel/HPDI options but have not emerged publically to announce their involvement.

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- Three principal gaseous/diesel system suppliers are engaged with eight engine and vehicle manufacturers who are either beginning or are actively marketing mostly heavy duty trucks and buses. At least two other large engine manufacturers make dual-fuel engines for marine applications. Some companies also sell dual-fuel engines as electricity generators but these stationary sources were not factored into this survey.
- There are 20 companies actively engaged in developing, producing and selling dual-fuel gaseous/diesel conversion systems. Most, if not all of these systems are not yet achieving Euro V emissions levels. Seven of these produce LPG dual-fuel systems; seven produce only compressed or liquefied natural gas dual-fuel systems; and six are developing or produce both natural gas and LPG dual-fuel conversion systems.
- An additional six companies are engaged in non-road applications including tractors, boats and trains.
- Two automotive research institutes, in India and China, are engaged in dual-fuel engine developments. They may have other associations with engine or vehicle manufacturers as well. A third, three-year LPG-diesel engine development project is underway at the University of Mississippi in the U.S.
- Of the road vehicle systems being developed, currently only two are for light duty cars.
- The equipment developers and suppliers come from thirteen different countries in Asia, Australia, Europe, North America and South America.

It seems from the initial contacts with dual-fuel developers and suppliers that many of the conversion systems are at Euro IV emissions levels and below. Those that are working with engines but without support of the engine manufacturers have greater challenges in producing high quality, reliable dual-fuel systems. But some of these may be successful in the market due to economic advantages of the dual-fuel systems, particularly in the emerging economy countries. Without national certification procedures or strict compliance enforcement many dual-fuel retrofit systems may appear in the market but the quality is likely to be inconsistent, at best.

Emissions performance is critical to making dual-fuel engines a market success

Gaseous –diesel systems seem to have varied emissions (and CO₂) results, often due to the wide range of operation characteristics related to the various drive cycles and the amount of diesel fuel substitution. When biomethane is used instead of fossil natural gas then claims of CO₂ reductions on a well-to-wheel basis are very large, but most gaseous-diesel vehicles will be operating on fossil methane or LPG, neither of which will compare with well-to-tank CO₂ reductions of renewable methane.

Despite these diverse factors, and the complication that different test cycles and test methods are used, a picture does emerge of the general potential emissions reductions that can be achieved over dedicated diesel engines.

- As more diesel is replaced, smoke and particulate emissions decrease significantly; to 90% by some claims.

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- CO₂ reductions vary widely, particularly considering part-or-full-load operation, however, consistent claims of 9-25% reductions can be verified in some engines; others are significantly lower but still are improved over normal diesel operation.
- Unburned hydrocarbons remains an issue for both LPG and methane-diesel engines. For methane-diesel engines methane catalysts, though expensive, can reduce emissions below regulated levels. Regulatory treatment of total hydrocarbons (THC) versus non-methane hydrocarbons (NMHC) will be a critical factor affecting the emissions performance and costs of gaseous-diesel engines.

Dual-fuel systems designed to be compatible with specific OEM diesel engines will tend to have better emissions performance than many retrofit dual-fuel systems.

Economics for truck operators is favorable but challenging³

The economics and cost-benefits of gaseous-diesel engines are based upon the cost of the fuel system modification (or the added cost to a dedicated diesel engine) and the amount of diesel fuel that is substituted across the full operational cycles of the vehicles (Fuelling station costs are excluded in these assumptions.) Steady, over-the-road driving might substitute 80% diesel in natural gas applications; 45% or less in urban traffic. For LPG systems the highest substitution rates tend to be about 45%, therefore, the economics will differ from methane-diesel vehicles. HPDI engines, due to their design, tend to substitute a more-or-less constant 95% natural gas for diesel across all drive cycles, so fuel replacement rates as well as emissions improvements will tend to be higher than for dual-fuel systems that vary the amount of diesel substitution. The gaseous-diesel systems developed in conjunction with OEMs tend to have higher first costs than retrofit systems due to their complexity and superior performance and emissions compliance. But with gaseous fuels (both LPG and methane) being 30-50% cheaper than diesel, savings for high fuel-consuming vehicles tends to provide attractive cost advantages over dedicated diesel vehicles despite the different diesel substitution factors. Additionally, LPG and natural gas tend to have less price volatility than diesel.

Cost and economic data from active dual-fuel and HPDI customers presented at the workshop showed favorable end results. Since the profit margins of line-haul trucking tend to be relatively low – 3-10% in the cases reported – savings benefits tended to outweigh the higher initial costs of the engines and vehicles.

- LPG customers using dual-fuel retrofit systems with up to 45% substitution of diesel found 8-13 months payback on investment in their DF systems. The longer payback was on urban waste trucks driving 50,000 km per year while the shorter paybacks came with vehicles driving 120,000-220,000 km/yr.
- 30% LPG substitution for a Dutch trucking company resulted in 15% savings on fuel costs per vehicle with an overall return on investment of 1.5 years.

³ Economic and cost information were obtained from Session III speakers: Tamme Leenstra, (H&S Group, Netherlands); Max Luhmann, (Luhmann GmbH, Germany) and Mark McKenzie, (Rare Consulting, Australia). Luhmann and McKenzie both presented economic cases for multiple customers. A total of nine different fleet vehicle case studies were included.

An added dimension to dual-fuel economics could be if governments provide financial incentives based upon their CO₂ or greenhouse gas (GHG) emissions reductions. Australian case studies showed that a natural gas dual-fuel line haul truck that cost €61,380 per truck, driving 300,000 km/year, at 80% diesel fuel substitution saved 8% on GHG emissions for a cost of €1,705 per ton. Trucks fitted with a €98,890 HPDI system substituting 95% diesel saved 24% (GHG) emissions for a cost of €915 per ton.⁴

Difficult regulatory challenges must be addressed to enhance market opportunities

Dual-fuel retrofit systems are available now and OEM systems will be available in the EU early 2011. Widespread adoption will be driven by OEM product, not retrofit systems, but good retrofit systems help seed the market and generate early market adoption. International regulations covering both types of systems need to be advocated and adopted.

Currently only national type approval of retrofit solutions are possible for methane-diesel and LPG-diesel engines. In the absence of clear regulatory guidelines, some countries allow dual-fuel vehicles, some provide 'exemptions' on a case-by-case basis, and other countries prohibit the systems altogether. But the *national approach* is not cost effective and is only sustainable when small volumes of engines are being converted. If OEMs are to produce engines and vehicles in volume then, in the interest of harmonization, new international certification regulations ought to be created, most likely at the United Nations level. These regulations then can be adopted by countries (UN 'Contracting Parties' and others) to ensure consistency of the technologies and their environmental and safety performance. Likewise, international standards or regulations for retrofit systems also are critical because they provide guidelines to help ensure that these systems are safe, reliable and in compliance with emissions regulations.

There are a variety of regulatory and technical questions and challenges brought up by the workshop participants that need to be addressed to avoid impeding the rapid market penetration of gaseous-diesel engines and vehicles:

- In most dual-fuel systems, the base diesel engine is unchanged. Should these engines be tested only as a diesel; as a diesel with multi-fuel capability; as a gaseous engine; or both, and under what conditions? Which emissions test cycles should be used, the European Stationary Cycle [ESC], the European Transient Cycle [ETC] or other)?
- In the case of gaseous-diesel engines, the heavy duty ETC is applicable only for positive ignition (PI)⁵ gas engines. It includes a non-methane hydrocarbon standard (NMHC) and for methane engines a specific CH₄ limit value. Would the

⁴ *High Pressure Direct Injection Systems for Heavy Vehicles (LNG & CNG) – The Australian Experience*, Mark McKenzie, Rare Consulting Pty Ltd, Australia.

⁵ Positive ignition = spark ignited, Otto cycle engine.

ESC with only a total hydrocarbon (THC) limit value be prohibitive for gaseous-diesel compression ignition engines as well as for positive ignition engines?

- Particulate matter is not applicable for gaseous fuelled engines but presumably would be for dual-fuel engines.
- Should gaseous-diesel engines comply with both the diesel and the gaseous fuel requirements (including on-board-diagnostics [OBD] and fuel quality standards) or only the gaseous fuel requirements if, for example, the diesel fuel consumption is less than a certain percentage?
- Because some systems continue to use diesel fuel as a dedicated fuel, complicated emissions after-treatment systems also may be necessary, which increases the cost and complexity of the vehicle system. Can regulations be designed that are favorable to using less after-treatment systems under certain conditions (i.e. 'limp-home mode').

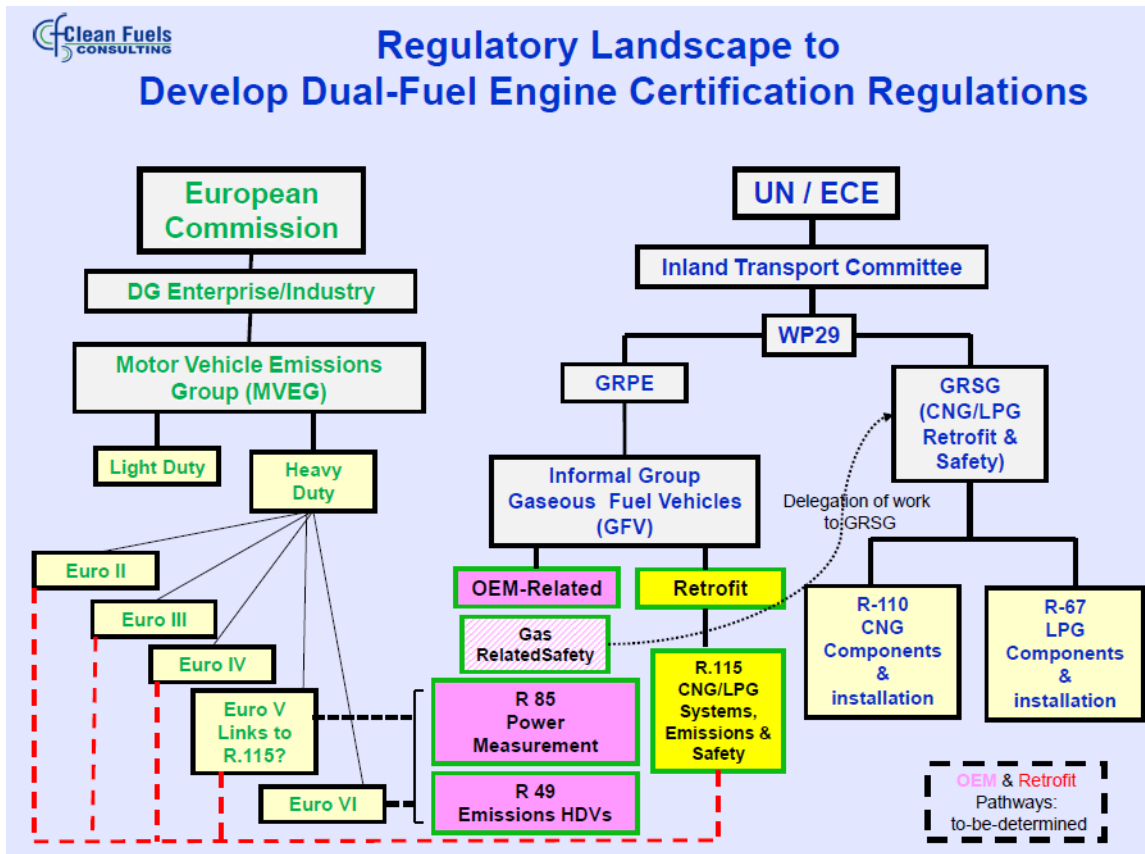
If governments and the industry move to create dual-fuel engine regulations for OEMs, this likely would apply to current Euro V and VI standards while older vehicles at Euro IV or below require retrofit certification under UN/ECE Regulation 115. The major issue requiring resolution in the development of regulations for either OEM, retrofit vehicles or both is whether the regulations can be developed simultaneously (to save time) or would they have to be done serially: OEM regulations first as the priority to bring in world class engine providers followed by retrofit regulations. If developing regulations for OEMs might take two-and-a-half- to-three years at a minimum, then can the NGV and LPG industries afford to wait that long until creating retrofit regulations thereafter? Clear regulation is urgently required to bring in world class engine providers but also to encourage retrofits of older, existing engines.

Conclusions

Reports on the use of dual-fuel and HPDI technologies for heavy duty trucks are very favorable despite high first costs to convert existing vehicles or purchasing new engines as well as steep learning curves dealing with new vehicle technologies, gaseous fuels, and new fuelling systems,

- **The best economics** of the current product offerings are the high annual kilometre HDV segment using large amounts of fuel.
- **Market potential** of dual-fuel technologies increases significantly when the capital cost of the vehicles is reduced, vehicle and engine offerings expand, and fuelling availability is facilitated.
- **Customer adoption** of dual-fuel engines is more challenging than using dedicated diesel engines and vehicles due to initial uncertainty regarding engine durability, maintenance costs, operational aspects of new engines, and unfamiliarity of using different fuelling technologies and practices.
- **Emissions reductions** vary but will be improved with the entry of OEMs versus some of the less certain retrofit systems. In either case, the emissions performance must be substantiated by the system suppliers.

- **Worldwide certification regulations** at the UN for OEM and retrofit technologies provide a mandate or model for national certification and will significantly enhance availability of high quality dual-fuel systems.
- **Support for certification regulations** from UN Contracting Parties (member states) and dual-fuel engine and vehicle manufacturers for both natural gas and LPG will be required to mainstream the technology.
- **Future dual-fuel markets** will depend upon a regulatory approach suited toward both dual-fuel OEM technologies and retrofit systems.



*Notes on nomenclature: WP29= Working Party 29: World Forum for the Harmonization of Vehicle Regulations; GRPE= Group of Experts on Pollution & Energy; GRSG= Group of Experts on General Safety.

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The Dual-fuel Workshop proceedings are available at:

<http://www.iangv.org/shop/143-dual-fuel-strategies-workshop-proceedings.html>

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ANNEX

Draft Certification Framework for Dual-fuel Gaseous-Diesel Engines (LPG & natural gas) & High Pressure Direct Injection Engines (Natural gas-diesel)

Topics may be suitable (interchangeable?) for OEM or retrofit vehicles but details of topic areas could differ significantly depending upon if the requirements are for R.115 (LPG/NGV conversion systems) or R.49 (heavy duty OEM vehicles).⁶

Preamble

Description of rationale to develop regulations, with the aim to have the most energy efficient and clean vehicles on the roads in respect of both climate change and air quality

1. Definitions.

There is no universally accepted definition of a dual-fuel engine and this would be necessary as a precursor to dealing with the other (below) substantive issues. Some concepts or definitions have been deliberated by different organizations that might be used as a starting point.

- *“Natural Gas/Dual-fuel Diesel Vehicle: A vehicle that has two independent fuel systems (one of them for natural gas) and can run on both fuels simultaneously. It also may run on Diesel fuel alone.”⁷*
- Compression ignition engines and positive ignition engines fuelled with NG or LPG

2. Engine

- Diesel engine of a certain type to be used as parent engine(?)

3. Vehicle type specified (?) (possible for light duty/light commercial)

- Family definition applied (?)

4. Test cycle

- Transient or steady state(?)
- Applicable measurement cycles are those applied during the type approval of the original Diesel engine(s)(?)
- Option: test modes and emission limit values are the ones applicable during type approval of the parent Diesel engine + the measured values of the parent engine

5. Test procedures

- Separate tests as gaseous engine and as diesel engine?
- Need to be developed to cover the “mixed operation” with diesel and gaseous fuels
- For vehicles that can operate in a pure diesel mode a flex fuel concept could be considered

⁶ Framework combined from presentations by: Petter Åsman (European Commission, DG Enterprise); Stefan Behring (TÜV Rheinland); and Per Öhlund (Swedish Transport Agency); André Rijnders (RDW, Vehicle Type Approval Authority] Netherlands).

⁷ Definition of the International Association for Natural Gas Vehicles (IANGV) and the International Standards Organization (ISO), 2009.

6. Test fuels (Ref. Diesel, Ref.LPGA, Ref.LPGB, Ref.G20, Ref.G25, others?)
7. Emissions
 - Procedures valid for one fuel at a time (petrol, diesel, LPG, NG/biomethane)?
 - Emission limits for CO, NMHC, NOx and PM (For NG engines also a limit value for CH4 might apply, within total hydrocarbon or as non-methane hydrocarbon (NMHC)
 - Current procedures for exhaust emissions are only valid for one fuel at a time (diesel, LPG, NG/biomethane, ethanol)
 - Noise
 - Other requirements might also need to be reconsidered
8. Exhaust aftertreatment
9. On-Board Diagnostics
10. New components for Dual-Fuel applications
11. New requirement, diesel substitution
12. Registration inspection

Specific OEM Aspects

13. Conformity of Production (COP)
14. Active Safety (OEM)
15. Passive Safety (OEM)
16. In-service conformity
17. Durability
18. Roadworthiness
19. Net Power (Reg.85)

Specific Retrofit Aspects

20. Components (retrofit only?)
21. Installation (retrofit only)
22. Vehicle registry updated (retrofit only)

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