7 HEAVY-DUTY ENGINES AND VEHICLES

7.1 General features

Substituting gasoline with natural gas in a light-duty vehicle engine is technically rather simple. As discussed in 3.1, the supply of high-displacement gasoline engines is rather limited, with the exception of North American markets. Therefore the gas engines for heavy-duty applications are mostly based on converted diesel engines.

It is rather difficult to build a gas engine that would have the same kind of power output, fuel economy and reliability as a modern diesel engine. Therefore, one has to make some compromises in order to achieve very low emissions (Figure 7.1).

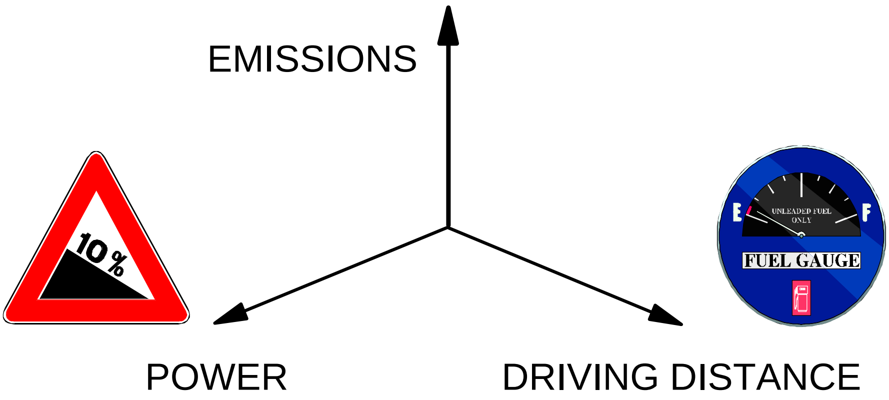

Figure 7.1. Balancing between emissions, power output and fuel economy.

The biggest problems with heavy-duty automotive gas engines based on converted diesel engines are related to the control the thermal loads of the engine and to the control of the NO_x emissions. As discussed in 3.2, the engine manufacturers use either stoichiometric or lean-burn combustion. From an engine durability point of view lean-burn combustion is generally the preferred alternative, whereas stoichiometric combustion in combination with a TWC catalyst gives lower emissions and better driveability.

As mentioned in 5., there are several OEM engine manufacturers offering heavy-duty engines. In addition, a number of smaller companies have made engine conversions, mostly for markets with less stringent emission regulations, i.e. Category 1 markets. For these markets the main drivers have been substitution of diesel fuel and the elimination of visible black smoke. A gas engine, which is not emission optimised can have a much higher NO_x emission than a conventional diesel engine.

The heavy-duty engines for the North American market have been emission certified over a transient duty cycle for a number of years. Europe is now introducing transient testing for gas engines beginning in the year 2000. Some European gas engines, which have performed very well in the steady-state European ECE R49 emission tests, have actually performed rather poorly in real-life running conditions. The new test requirements will certainly have a major impact on European gas engine technology.

The newest light-duty gasoline vehicles are approaching SULEV emission levels, as discussed in previous chapters. Therefore no major regulated emission reductions can be expected when substituting gasoline with natural gas.

In the case of heavy-duty engines, on the other hand, major emission reductions can be expected, at least with present technology, going from diesel to gaseous fuel. The combustion of a homogeneous lean mixture in a gas engine results in lower NO_x emissions than diesel combustion, and with stoichiometric combustion there is the option to use TWC technology for ultra low emissions. Regardless of the combustion system used, the fuel related particulate emissions from the burning of gaseous fuels are extremely low, the particulate emission originating almost solely from the lubricating oil.

Figure 7.2 shows the development of the European heavy-duty emission regulations (ECE R49 and ESC steady-state tests) in comparison with one of the best current European heavy-duty natural gas engines ("BAT CNG 99"). Tested using a steady-state cycle, this engine goes well below the oncoming 2005 Euro 5 requirements. This particular engine performs well also in transient operating conditions.

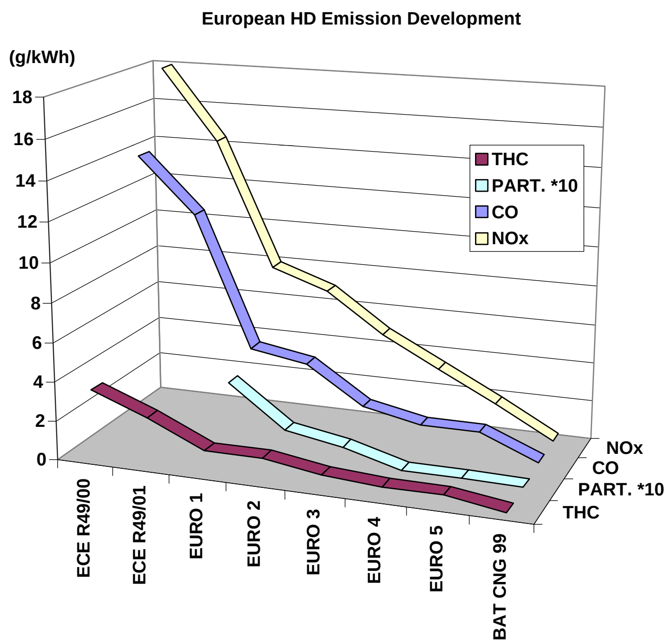

Figure 7.2. The development of the European HD emission limits in comparison with one of the best European CNG engines /86,87,92/.

Table 7.1 presents a comparison of natural gas and biogas versus diesel by Volvo Bus Corporation.

Table 7.1. A comparison of natural gas and biogas versus diesel /59/.

Vehicle	Natural gas	Biogas
• Exhaust gases		
NO_x, SO_x, PM	Lower	Lower
CO, HC excl. methane	Same	Same
CO_2, CH_4	Same/Lower	Negligible
• Noise and vibration	Lower	Lower
• Cost	Higher	Higher
• Payload/range	Lower	Lower
Fuel		
• Cost (excl. taxes)	Similar	Similar
• Availability	Good	Limited
• Demand	Increasing	Increasing
• Infrastructure	Expanding	Limited

7.2 OEM heavy-duty engines

The following examples highlight some OEM heavy-duty gas engines. Two advanced LPG engines are also included as reference. Only OEM engines are included in this overview, because conversions made without the back-up of an engine manufacturer would probably not meet the requirements for low emissions and adequate durability.

7.2.1 Caterpillar

Caterpillar is offering a wide range of industrial spark-ignition gas engines, power range from 34 to 3506 kW /126,127/. For on-road applications, however, Caterpillar is offering dual-fuel engines, i.e. engines, in which the combustion is initiated by a pilot injection of diesel fuel. By the year 2000, Caterpillar's program will cover dual-fuel engines based on the 3126B, C-10, C-12 and 3406E engines /20/. The power range will be from 190 to 500 hp.

Both diesel and natural gas injection are electronically controlled. Typical diesel fuel substitution is 85 %. The power in dual-fuel operation is the same as in diesel operation, and the engine provides full diesel backup if necessary. For the C-12 engine, the weight increase of the dual-fuel version over the diesel is only 10 kg.

Caterpillar lists the advantages of the dual-fuel system as follows:

- similar power to diesel
- same heat rejection as diesel
- allows use of cleaner, lower cost fuel (natural gas)
- longer engine life/lower maintenance
- retains full diesel back-up
- retains Jake-Brake capability
- resale value unaffected

The engines are US EPA LEV and California Low NO_x certified. In Australia, Caterpillar has calculated that for trucks running 200,000 km per year, the payback time of the dual-fuel system is only 2 years.

7.2.2 Cummins

Cummins is one of the engine manufacturers that have been active in developing and commercialising natural gas engines for heavy-duty vehicles. Like many other OEM engine manufacturers, Cummins has evaluated a number of different fuel options. Figure 7.3 shows the evaluation of Cummins alternate fuel product evolution. Cummins' choice for natural gas combustion system is spark-ignition and lean-burn combustion.

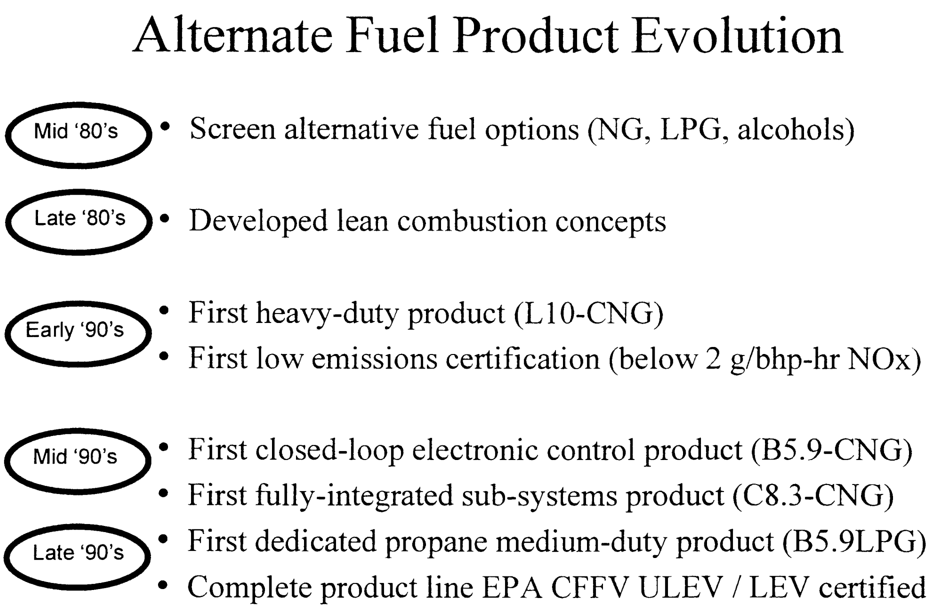

Figure 7.3. Evolution of Cummins alternate fuel products /128/.

By 1999, Cummins has put more than 3800 HD natural gas engines on the road /128/. This, however, has to be put in perspective, as Cummins produces some 250,000 diesel engines yearly.

The 10 litre Cummins L10 was Cummins' first product for the CNG market. This engine was launched in the early 1990s. Development work on this engine was initiated in Canada in 1985, and the first prototype engine was built by Ortech. A test fleet consisting of 50 Cummins L10 natural gas engine powered Orion V buses went into service in Canada in1989. Much development effort was put in to achieve diesel-like reliability.

The turbocharged, lean-burn L10 engine had a rather simple fuel system, an all-mechanical IMPCO system (Figure 7.4). Despite this the emission performance was good, and two engine versions, the L10-240 G and the L10-260 G, were emission certified by California Air Resources Board for a 290,000 mile service life.

The most recent natural gas engine from Cummins is the C8.3G engine, which Cummins calls its first fully-integrated sub-systems product. The engine management system of this engine is shown in Figure 3.9. The engine has a gas mixer with gas flow valve for air/fuel ratio control. The closed-loop control system incorporates an exhaust gas oxygen sensor.

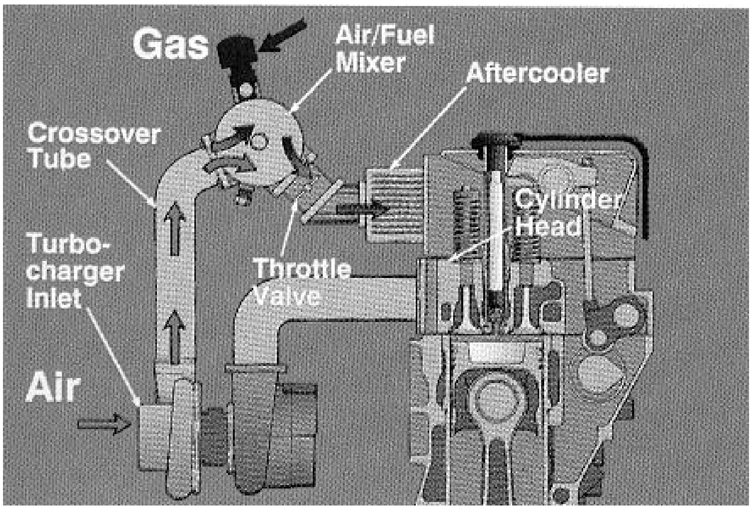

Figure 7.4. The schematics of the Cummins L10 natural gas engine /129/.

The L10 engine is not available any more. The Cummins gas engine range now covers the following products:

B5.9 engine:

- three natural gas versions (150, 195 and 230 hp)
- one LPG version (195 hp)

C8.3 engine:

- two natural gas versions (250 and 275 hp)

All current Cummins gas engines are EPA CFFV ULEV/LEV certified.

7.2.3 DAF

The Dutch company DAF has concentrated on LPG engines. In 1994 DAF introduced liquid LPG injection (Figure 3.7). This technology has the advantage of charge cooling through evaporation of the fuel. This increases volumetric efficiency and suppresses knock tendency. Since 1994, DAF has delivered more than 500 LPG engines for bus applications /130/.

The current LPG engine (no CNG version is available) has a displacement of 8.65 litres. The turbocharged engine runs on stoichiometric mixture, and is equipped with a TWC. DAF states that the NO_x emission of the engine is below the oncoming Euro 5 limit (2 g/kWh), and that the engine is up to 6 dB quieter than a diesel engine. Although LPG is heavier than air, the LPG tanks of the new LPG buses running in the city of Copenhagen are placed on the roof of the buses (Figure 7.5). This kind of installation needs special ventilation arrangements for the LPG tanks.

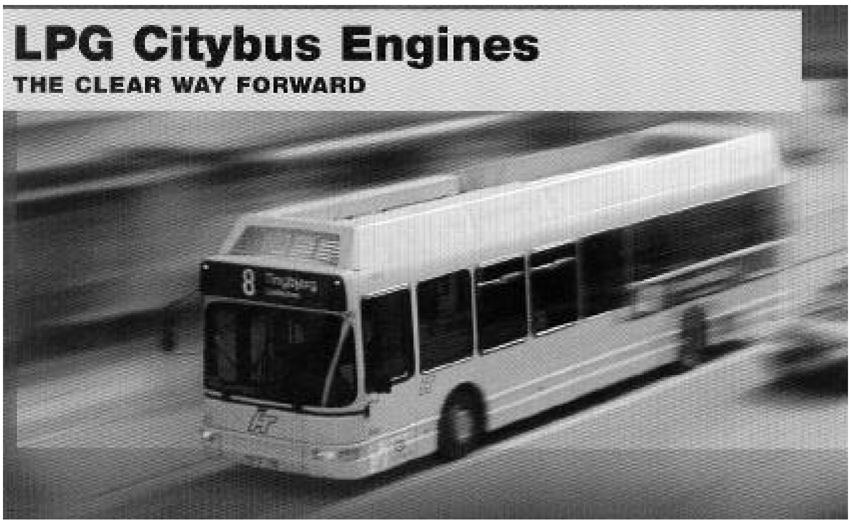

Figure 7.5. A Danish LPG citybus /130/.

7.2.4 Ford

In MY 2000, Ford has introduced a heavy-duty 6.8 litre V10 bi-fuel LPG/gasoline engine developing 228 kW power and 560 Nm torque. The engine is stoichiometric with a three-way catalyst, and has been certified to Californian ULEV standards.

When tested in an engine test bed the engine performs as follows:

- NO_x 0.7 g/kWh
- NMHC 0.15 g/kWh
- CO 3.8 g/kWh

The LPG engine is offered in a chassis cab configuration, which can be completed to form vans, trucks or buses. GFI is planning to offer also dedicated CNG and LPG versions of this engine. They will be certified to SULEV standards /122/.

7.2.5 Iveco

Iveco has chosen stoichiometric combustion for its natural gas engines. Iveco has two engines available, a four-cylinder 2.8 litre engine and a 6-cylinder 9.5 litre engine. The 2.8 litre engine is naturally aspirated, and the 9.5 litre engine is available in two versions, turbocharged (161 kW) and turbocharged plus intercooled (191 kW). The Iveco engines are equipped with sophisticated, closed-loop controlled multi-point fuel injection systems and three-way catalysts. The larger engines have one ignition coil per cylinder, the smaller one coil per two cylinders. Figure 7.6 is a schematic of fuel and ignition systems of the bigger engine. Iveco claims that the engine achieve NO_x levels of well below 1 g/kWh /131/.

7.2.6 Mercedes-Benz

Already in the 1980s, Mercedes-Benz had natural gas engines available for Category 1 markets, mainly South America. At that time the engines were optimised for low fuel consumption, not low emissions. In a technical paper from 1986 by Mercedes-Benz, no direct emission values are given. However, exhaust emissions were shown as concentration values as a function of engine load (Figure 7.7). At maximum load the NO_x concentration at λ=1.2 with natural gas was some 5000 ppm, for diesel at λ=1.4 some 1600 ppm. Converted to g/kWh these values mean approximately 30 g NO_x/kWh for the natural gas engine and 11 g NO_x/kWh for the diesel engine. The power output of the Series 407 gas engine was then 147 kW /132/.

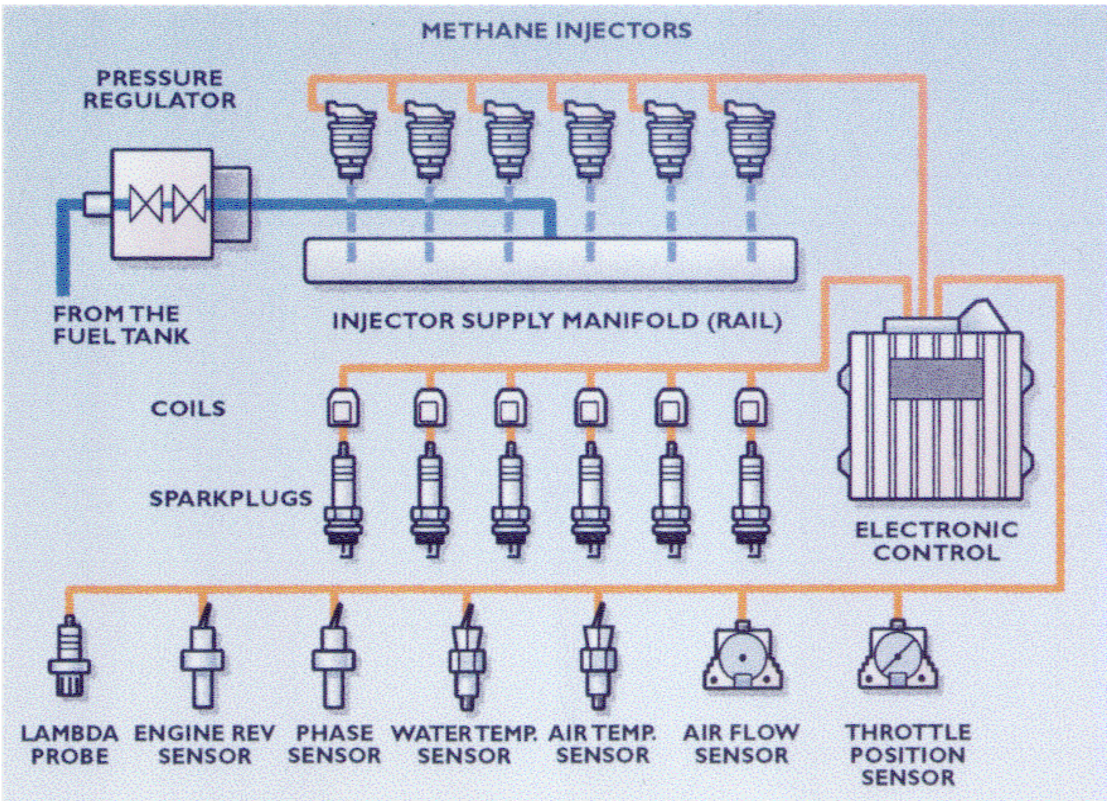

Figure 7.6. Fuel and ignition systems for the Iveco 8469 natural gas engines /131/.

The most important natural gas engine from Mercedes-Benz is the naturally aspirated stoichiometric M 447 hG engine (Figure 7.8). This vertical 12 litre engine, which is equipped with a mixer-type fuel system and a stepper motor valve for lambda control (see Figure 3.5) delivers 175 kW. Mercedes-Benz is rather conservative in stating the emission performance of the engine, CO and NO_x are said to be roughly 50 % of the Euro 2 level /133/. According to some recent information, Mercedes-Benz is going to discontinue this product for a new lean-burn engine /134/.

Mercedes-Benz also has a natural gas version of the Sprinter light-duty cargo vehicle. The vehicle, with a gross vehicle weight of some 3.500 kg, has a 2.3 litre engine delivering 92 kW on natural gas. The engine is equipped with a multi-point sequential fuel injection system /135/.

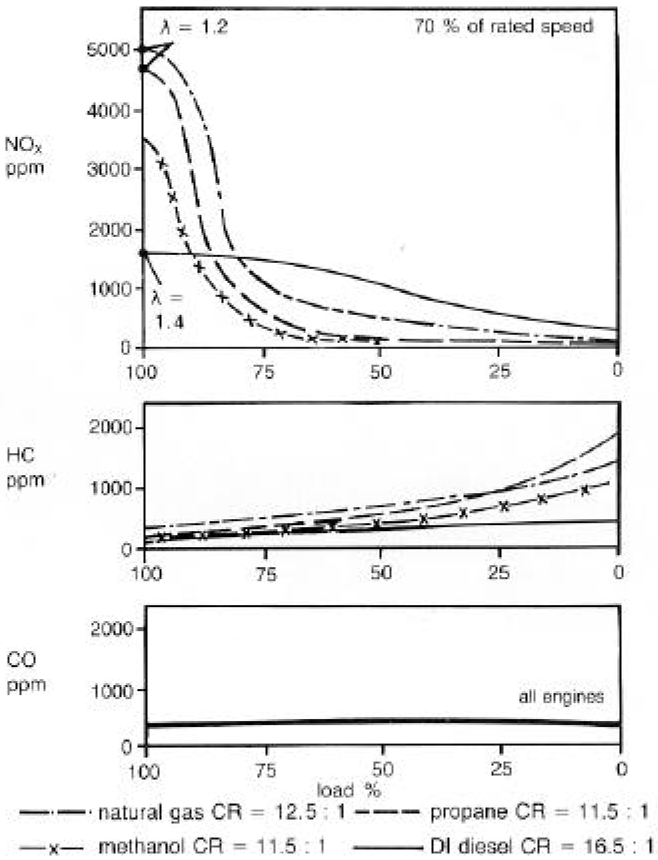

Figure 7.7. Exhaust component concentrations for different fuel alternatives /133/.

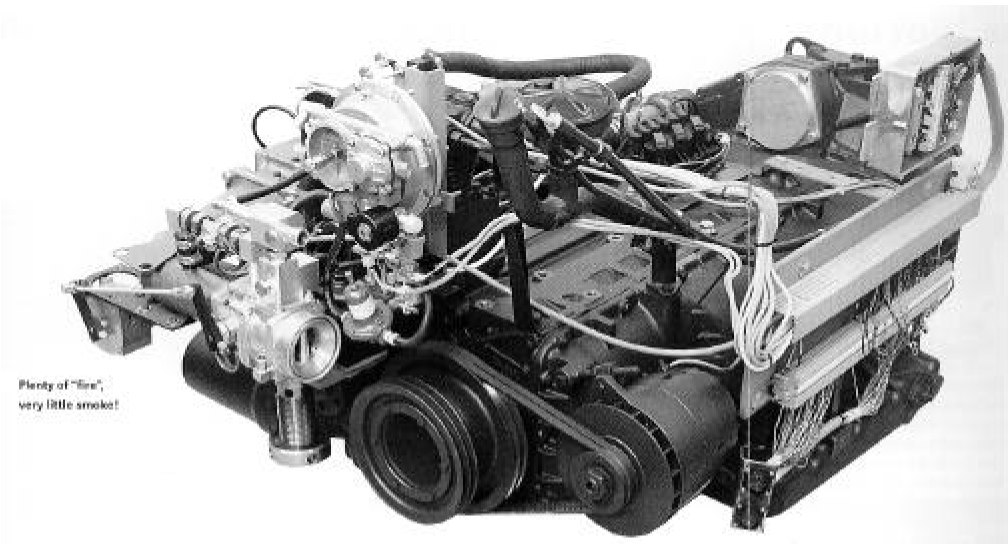

Figure 7.8. The stoichiometric Mercedes-Benz M 447 hG natural gas engine /134/.

7.2.7 Volvo

Volvo launched its natural gas bus engine in 1992. Since then, some 400 engines have been built, mainly for the Swedish market. Volvo has also delivered natural gas engines for truck applications.

The Volvo natural gas bus engine is based on the 9.6 litre vertical diesel engine. The turbocharged and intercooled GH10 gas engine utilises lean-burn combustion, and delivers a maximum power output of 180 kW /59/. The combustion system was originally developed together with the Norwegian Marintek research institute /49/. The fuel system is electronically controlled. The system has a centrally mounted fuel injection unit which contains four metering valves. The system, however, has no provisions for air/fuel ratio feedback control. Ignition is by a coil-on-plug-type ignition system (Figure 3.11).

Figure 7.9 shows the main components on the Volvo natural gas bus engine.

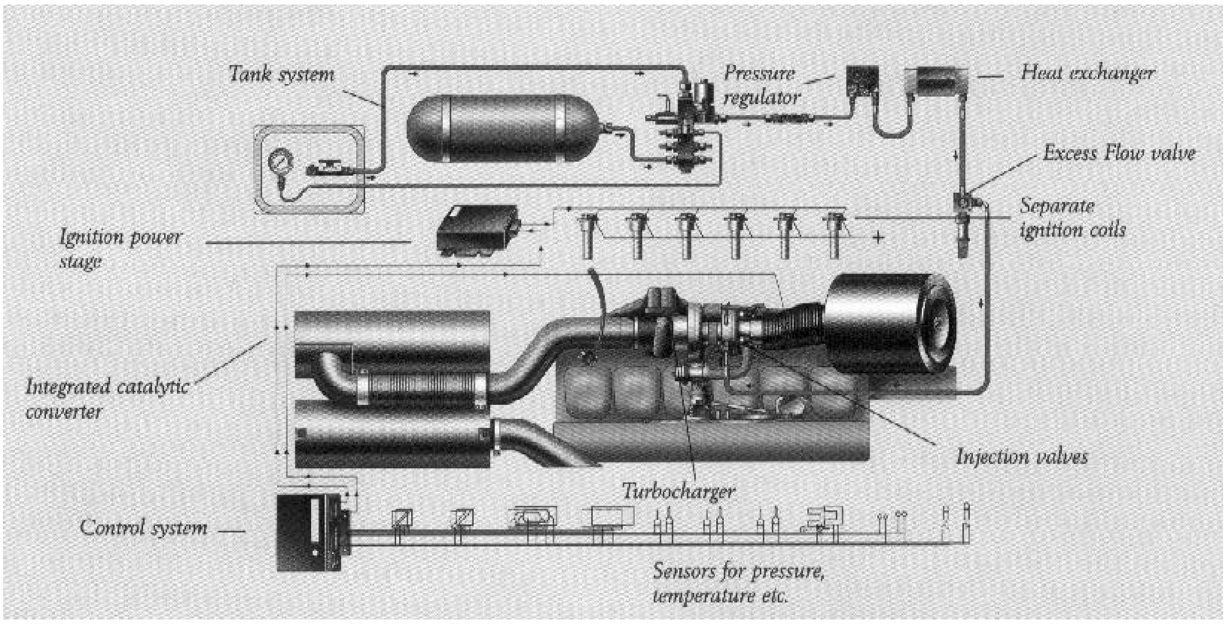

Figure 7.9. The main components of the Volvo GH10 natural gas bus engine /59/.

7.3 Performance and regulated emissions

The performance and also the regulated exhaust emissions will vary considerably depending on the combustion and induction system of the engine and the exhaust gas aftertreatment technology applied. The gas engines targeted for well developed markets, i.e. Category 2 and 3 markets, often have a power output close to the corresponding diesel engines, but much lower emissions. The maximum brake mean effective pressure (BMEP), which describes the load level of the engine, is the range of 8-9 bar for naturally aspirated engines and 12-15 bar for turbocharged engines.

Independent of the engine technology, the maximum efficiency for automotive heavy-duty gas engines is in the range of 35-39 %. However, the maximum efficiency value has little correlation with real service life, as the part-load efficiency of gas engines is lower than that of diesel engines.

Table 7.2 summarises technical and key performance data for some heavy-duty gas engines. Comparing emission data one must bear in mind the differences between US and European test methods. There are also differences originating from the fact that some references contain "marketing type" data, some are real certification values and some data might have been generated during follow-up studies etc.

For comparison, the 11.4 litre Mercedes-Benz 407-engine mentioned in 7.2.6 had the following performance (exhaust emission values estimated from exhaust gas concentration values, no catalyst) /132/:

- power 147 kW
- BMEP 9.1 bar
- max. efficiency 39 %
- CO 2 g/kWh
- THC 1 g/kWh
- NO_x 25 g/kWh

Table 7.2. Technical and key performance data for selected gas engines.

Make	Cummins	Cummins	DAF	Iveco	Mercedes-Benz	Volvo
Code	L10-260G	C8.3-G	GG170 LPG	8469.41	M447hG	GH10
Fuel	NG	NG	LPG	NG	NG	NG
Cylinders	6	6	6	6	6	6
Type	horizontal	horizontal	horizontal	horizontal	vertical	vertical
Volume (l)	10.0	8.3	8.7	9.5	12.0	9.6
Comp.ratio (-)	10.5:1	10.5:1	9:1	10:1	12.5:1	12.7:1
Power (kW)	194	202	170	191	175	180
Torque (Nm)	1153	1017	940	1050	880	950
BMEP (bar)	14.5	15.4	13.6	13.9	9.2	12.4
Max. eff. (%)	38	38	?	36	?	38
Comb.system	LB	LB	SM	SM	SM	LB
Induction sys.	TC + IC	TC + IC	TC	TC + IC	NA	TC + IC
Fuel system	mixer	mixer	MPFI	MPFI	mixer	central FI
Control	open-loop	closed-loop	closed-loop	closed-loop	closed-loop	open-loop
Catalyst	OC	optional	TWC	TWC	TWC	OC
Emissions						
CO (g/kWh)	0.5	?	0.25	0.3	2.0	0.01
THC (g/kWh)	?	?	0.01	0.02	0.5	1.0
NMHC (g/kWh)	0.3	?	?	?		< 0.1
NMHC + NO_x	2.6	2.7	?	?		
NO_x (g/kWh)	2.3	?	0.4	0.7	3.5	2.0
Part (g/kWh)	0.03	0.014	0.015	0.03	0.05	< 0.01
Test cycle	US	US	ECE R49	ECE R49	ECE R49	ECE R49
Reference	23,136	47,128	52,137	131,137	133,137	59,137

LB= lean-burn, SM=stoichiometric, TC= turbocharged, IC= intercooled, MPFI= multi-point fuel injection, FI= fuel injection, OC= oxidation catalyst, TWC= three-way catalyst

7.4 Real-life exhaust emissions

In Europe, there has been much discussion on the real-life emission performance of gas fuelled buses. This discussion originates from the fact that some gas engines, although they give very good emissions in steady-state testing, do not perform so very well in real transient driving conditions. This problem should not be so severe for North American engines, as the heavy-duty engines for this market are certified using the US Heavy-Duty Transient cycle. The situation for Europe will change soon, as the new transient ETC test cycle will be required for gas engines starting with the new Euro 3 emission regulations.

The Belgian VITO research institute has performed on-the-road emission measurements on buses representing different engine and fuel technologies. Figure 7.10 shows a comparison of gaseous emission results from different buses on the bus line Number 59 in Brussels /18/. The CO analyser was out of order when the LPG bus was measured. For this study, VITO did not measure particulate emissions.

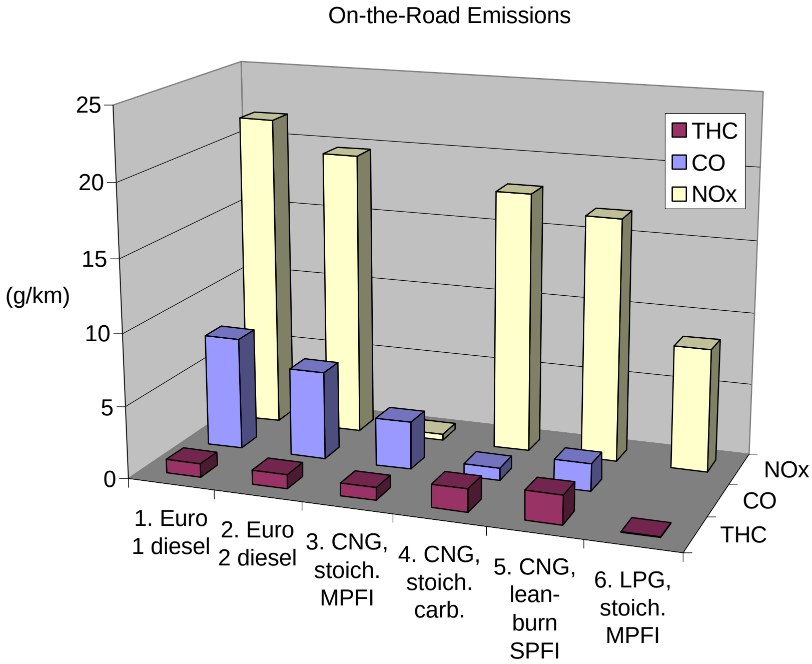

Figure 7.10. On-the-road emission results with different bus technologies on Line 59 in Brussels /18/.

The Generation 2 CNG buses (number 4. stoichiometric carburetted and number 5. lean-burn single-point injection) have a NO_x emission which is only some 15 % lower compared to the diesel buses. The multi-point fuel injected LPG bus gives a NO_x emission of some 40 % compared to the diesel buses.

The clear winner is the Category 3 multi-point fuel injected CNG bus, which has a NO_x emission of only some 0.5 g/km. Also the other emission components are well under control in this bus. The CO emission of the gas buses is lower than of the diesel buses. The LPG bus has the lowest THC emissions, which means that the catalyst works very well on hydrocarbons with stoichiometric mixture and LPG as the fuel. As can be expected, the lean-burn CNG bus has the highest THC emission.

The results indicate that the carburetted stoichiometric system does not provide adequate air-fuel ratio control for the catalyst to work properly. The lean-burn bus, which has an open-loop fuel system, probably suffers from large air-fuel ratio variations resulting in both high NO_x emissions and relatively high CO emissions.

Millbrook Proving Ground Ltd has performed dynamic bus measurements on a chassis dynamometer for London Transport, among others. Figure 7.11 shows an example of Millbrook results for different bus technologies. In this case the comparison is between low-sulphur diesel in a conventional diesel engine, ultra-low sulphur diesel in combination with a particulate trap (CRT), lean-burn CNG (open-loop, Generation 2) and stoichimetric LPG (MPFI, closed-loop, Generation 3). Millbrook also measured particulate emissions. The data was supplied through Shell International /138/.

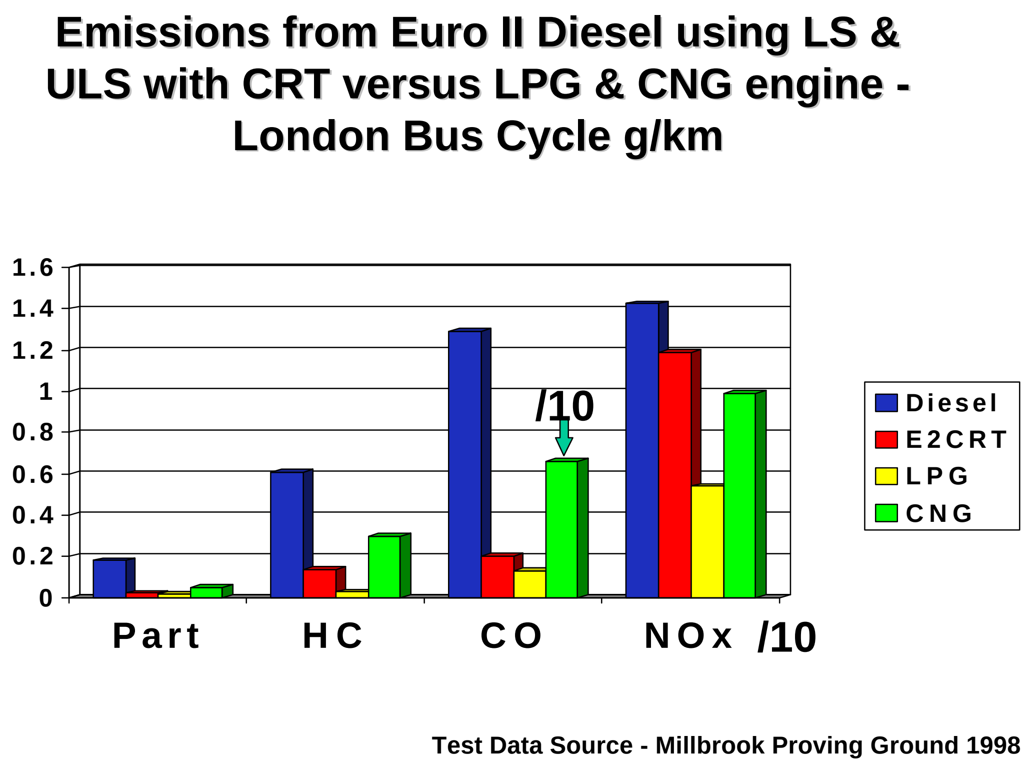

Figure 7.11. Dynamic Millbrook Proving Ground emission data /138/.

The Millbrook results have some similarities to the VITO data, especially for NO_x. The CNG vehicle should be equivalent to vehicle 5 in VITO's study, and the LPG vehicle equivalent to vehicle 6.

In the Millbrook study, the NO_x emission reduction compared to diesel is some 25 % with CNG and some 60 % with LPG. The CO emission on the CNG bus was quite high, roughly 5 times of that of the diesel without aftertreatment. The LPG bus performed rather well regarding all gaseous components.

Putting a particulate trap on the diesel and switching to a better fuel quality will effectively reduce particulate, CO and THC emissions, the reductions being in the range of 77 to 87 %. Even the NO_x emission is reduced some 15 %, probably both due to fuel chemistry and increased exhaust back pressure.

The particulate emission results are interesting. The diesel bus with the particulate filter and the LPG bus have a particulate emission of some 0.02 g/km (slightly lower value for the LPG bus), a level roughly 10 % of the level for a normal diesel bus. For the CNG bus a particulate emission more than twice as high as for the LPG bus and the diesel with particulate trap was reported. This difference should not be fuel related, and most probably originates from excessive oil consumption of the CNG bus. No detailed information on the condition of the test vehicles is available.

These results once again demonstrate that fuel comparisons should be carried out with vehicles of the same technical sophistication and same technical condition.

On many occasions, data like in the Millbrook study is used by advocates of diesel technology to state that by using gaseous fuels, only marginal reductions in NO_x emissions can be achieved, and that diesel particulate trap technology gives equivalent or even lower particulate emissions than gaseous fuels.

However, the VITO results clearly show that the best available gas engine technology can beat the diesel regarding NO_x emissions by a factor of more than 10. There is not so much good data on particulate emissions, especially since there are shortcomings in the standardised test methods when measuring very low levels of particulates. A qualified estimation is that gas engines in general and especially those engines applying stoichiometric combustion and three-way catalyst technology (high catalyst temperatures) should have particulate emissions comparable to particulate trap equipped diesel engines. As there always is room for technology improvements, one could also conclude that if there was a special reason, it might still be possible to further reduce the particulate emissions from gas engines either by engine modifications to control oil consumption or possibly through improved exhaust gas aftertreatment.

The US emission legislation contains definitions of useful service life for different vehicle categories. For heavy-duty engines the useful life is now defined as 290,000 miles or 8 years. In 2004 the useful life will be defined as 435,000 miles, 22,000 hours or 10 years, whichever occurs first. Minimum catalyst maintenance interval is 150,000 miles or 4,500 hours /87/.

In Europe, durability requirements have not been included in the heavy-duty emission legislation. In addition, the heavy-duty emission regulations will officially include spark-ignited natural gas and LPG engines starting only with the new Euro 3 regulations. This means that in Europe there has been no system in place to guarantee the emission durability of gas vehicles in service.

On several locations in Europe, follow-up studies to monitor the performance of alternative fuelled vehicles have been carried out. One example on such activities is the EU ZEUS project /15/.

In Finland, VTT has carried out follow-up studies on heavy-duty gas vehicles since the early 1990s. The emission measurements are done running a modified ECE R49 on a chassis dynamometer. No conclusions on dynamic emission performance can be drawn from these results.

Figure 7.12 shows emission results for a MY 1996 stoichiometric natural gas bus, Figure 7.13 for a MY 1991 stoichiometric LPG bus (both vehicles carburetted with closed-loop lambda control) and Figure 7.14 for a MY 1998 lean-burn natural gas bus /125/.

The stoichiometric natural gas bus has actually performed rather well. After a driving distance of 250,000 km with the original catalyst the NO_x emission was still below 4 g/kWh.

In the case of the LPG bus (Figure 7.13), the catalyst was replaced at some 125,000 km. The original catalyst had limited durability, and the NO_x emission had risen to nearly 10 g/kWh. With the new catalyst, emissions have been rather stable over a driving distance of 250,000 km, and at the total driving distance of 380,000 km the NO_x emission is still only around 1 g/kWh. The THC emission is very low, due to the fact that the catalyst works efficiently with propane.

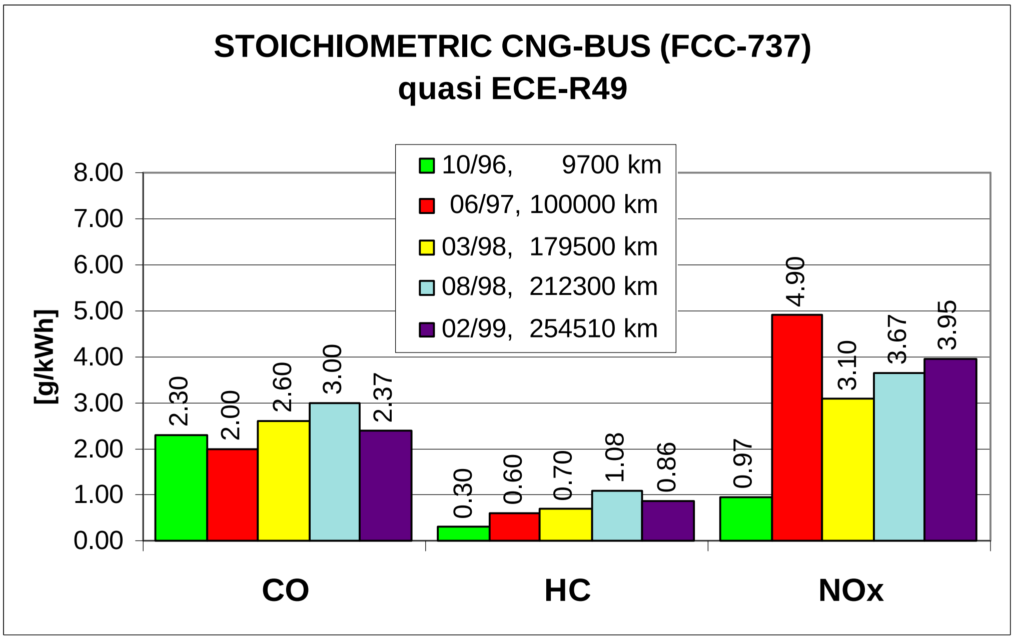

Figure 7.12. Chassis dynamometer emission results, stoichiometric CNG bus, measured by VTT /125/.

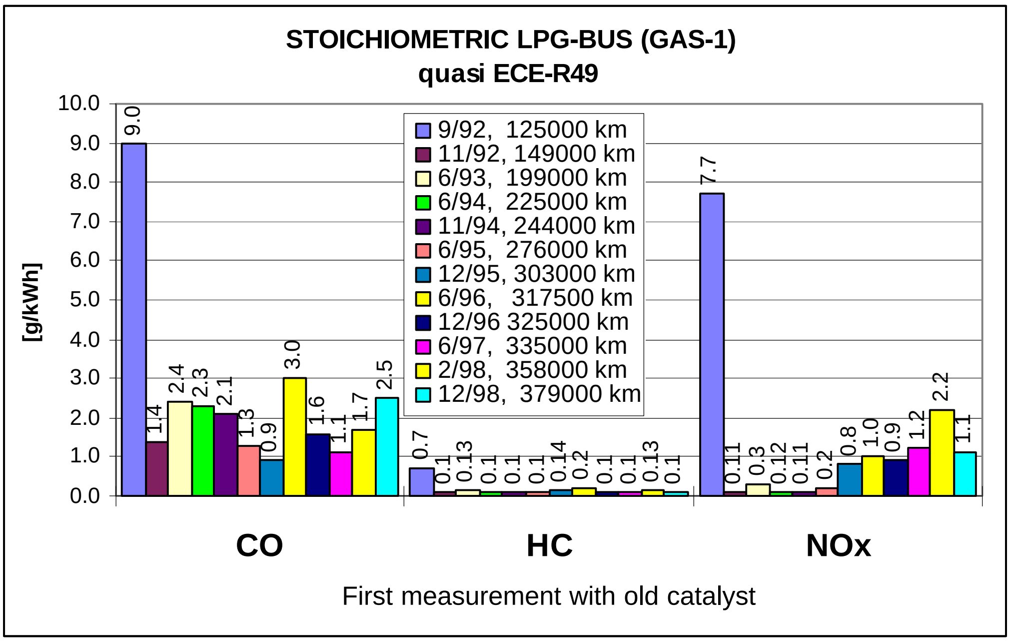

Figure 7.13. Chassis dynamometer emission results, stoichiometric LPG bus, measured by VTT /125/.

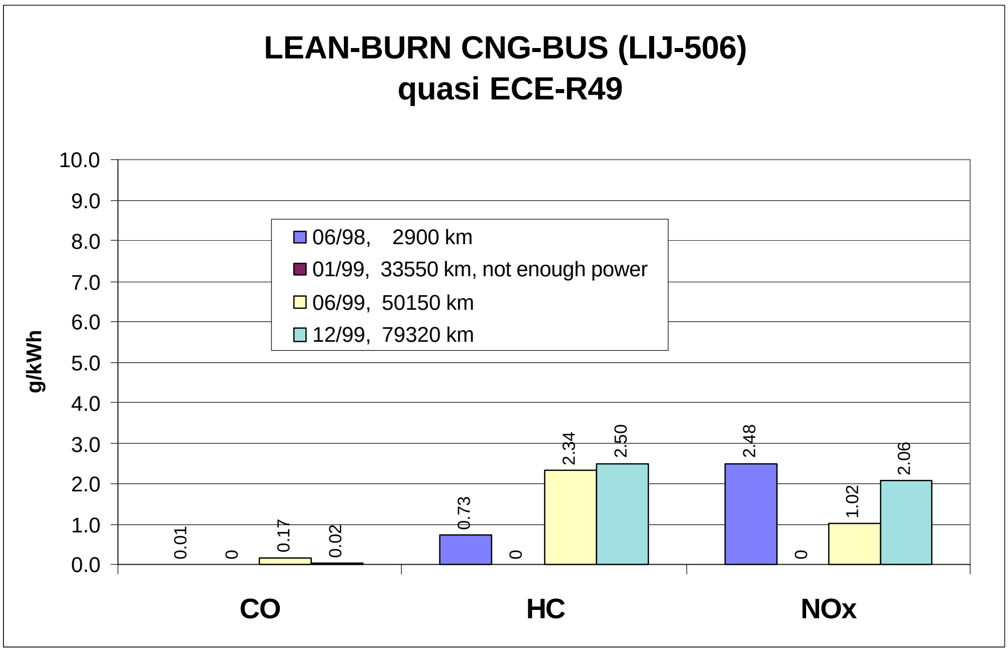

Figure 7.14. Chassis dynamometer emission results, lean-burn CNG bus, measured by VTT /125/.

The 22 lean-burn natural gas buses running in Helsinki have experienced some problems with fuel injector clogging. As the buses have an open-loop fuel system, the clogging leads to a lean-out of the mixture and therefore driveability problems. However, when the fuel system works properly, the emission values for CO and NO_x are rather good (Figure 7.14). The THC value, however, is high, around 2.5 g/kWh.

One can conclude that the emission performance of gas vehicles very much depends on the functioning of the fuel system and the catalyst. The conventional diesel engine is very stable regarding emissions. If the fleet operators of natural gas vehicles want to be sure that their vehicles perform satisfactorily, some kind of monitoring system has to be put in place.

What earlier was said about fuel effects on exhaust emission composition and unregulated components (gaseous fuels producing less toxic components) applies also to heavy-duty engines (see Figure 2.5). For heavy-duty engines the benefits are even larger, as the basis for comparison is diesel and not gasoline as is the case in most light-duty applications.

7.5 Energy consumption

The maximum efficiency of a spark-ignited gas engine is some 10-15 % lower (relative) than that of a good diesel engine (see Table 7.2). In real service, the energy consumption difference is higher, both due to reduced efficiency at partial loads, as mentioned earlier, and to increased vehicle weight.

Figures 7.15 (well-to-wheel CO_2 emissions and harmful tailpipe gaseous emissions), 7.16 (additional weight) and 7.17 (energy consumption of the vehicle) show Iveco's estimation of the impact of different vehicle technologies. Iveco estimates that a CNG bus, which weights some 700 kg more than its Euro 3 diesel counterpart, consumes 25 % more energy and produces 85 % less gaseous emissions compared to the diesel. Life-cycle CO_2 emissions are 5 % lower compared to the diesel /139/.

In Iveco's view, hybrid systems and fuel cells would render lower CO_2 emission and better overall efficiency than both diesel and CNG. The hybrid system in this case is a diesel hybrid system. Regarding gaseous emissions, the performance of CNG would fall in between the diesel hybrid and the fuel cell (estimated to have zero emissions).

TNO has made similar estimations. TNO's estimates are presented in Table 7.3. TNO states that the estimates are based partly on experience and partly on expert opinion.

The assumption that a $DeNO_x$ catalyst will lower fuel consumption is based on the fact that if nitrogen oxides are controlled by aftertreatment, the engine itself can be tuned for a higher engine-out NO_x emission and thus lower fuel consumption. A particulate trap on a diesel will increase fuel consumption by some 5 %.

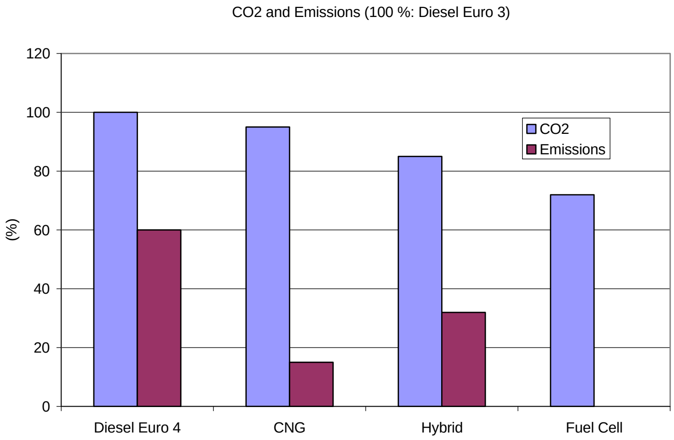

Figure 7.15. Relative CO_2 and harmful emissions with different bus technologies /139/.

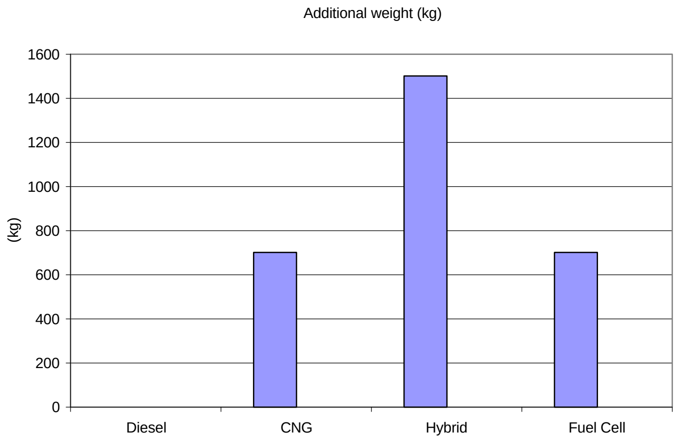

Figure 7.16. Weight increase with different bus technologies /139/.

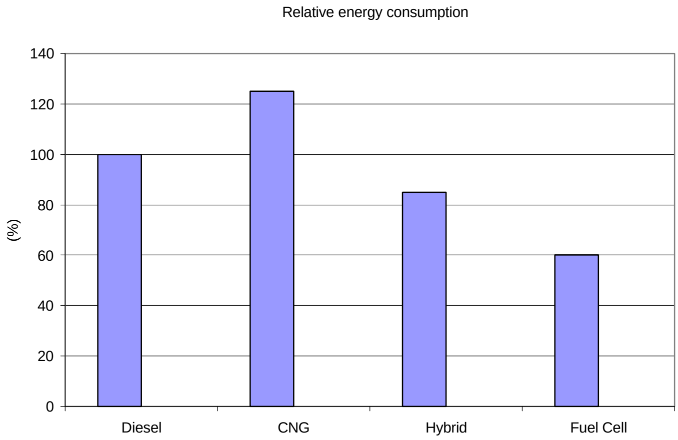

Figure 7.17. Relative energy consumption with different bus technologies /139/.

Table 7.3. TNO's estimation on energy efficiency of different bus technologies /140/.

Engine concept	Energy consumption (baseline = 100)
Diesel with EGR	102
Diesel with $DeNO_x$ catalyst	95
Stoichiometric LPG	128
Lean-burn LPG	117
Stoichiometric CNG	125
Lean-burn CNG	114
DME	103

When making comparisons on emissions and energy efficiency between engines for gaseous fuels and diesel engines, one should realise that the target is moving, i.e. that new technologies for diesels will reduce emissions, and that the effects of these new technologies on energy consumption can be either positive or negative.

TNO's figure for energy consumption using stoichiometric CNG is the same as Iveco's, +25 %.

There is a lot of variation in fuel consumption/energy efficiency figures among different operations and fleet tests. In a fleet test in Berlin, Germany, the energy consumption of gas buses was 8-30 % higher compared to diesel buses /141/. In VITO's on-the-road bus measurements the energy consumption was 6-34 % higher with gaseous fuels /18/. Canadian experience shows an additional energy consumption of some 20 % running on CNG /136/. In Helsinki, on some occasions, additional energy consumption figures of up to 50 % have been recorded /125/.

A qualified estimate is that the energy consumption of a heavy-duty vehicle will, in most applications, increase 20-35 % when switching from diesel to natural gas.