5   GAS FUELLED VEHICLES - GENERAL

The world population of gas vehicles is estimated to be around 5.5 million units. The number of vehicles using CNG is estimated to be some 1 million units, and the rest of the fleet runs on LPG.

The vast majority of the gas vehicle population is retrofitted passenger cars with relatively simple gasoline/gas bi-fuel systems. Over the years the main motivation to use gas in transportation has been to reduce fuel costs; traditionally, gaseous fuels have been less heavily taxed than liquid fuels. However, over the last 10-15 years gaseous fuels have received attention also for environmental reasons.

Today gas fuelled vehicles have reached a certain technical maturity. Natural gas vehicles are supplied by OEMs (Original Equipment Manufacturers) both for light- and heavy-duty applications. In 1998 there were 43 OEMs around the world producing over-the-road natural gas vehicles, 11 heavy-duty engine manufacturers producing natural gas engines and also a number of manufacturers producing a variety of off-road natural gas vehicles /102/.

The prototype phase is long gone. However, one has to bear in mind that the auto manufacturers still invest only marginal sums on the development of gas fuelled vehicles compared to the investments in traditional gasoline and diesel technology. Thus one could expect that there still are possibilities for technology improvements in gas vehicles, especially in the heavy-duty sector.

In the near future, two major issues will have a major impact on gas engine technology:

- the introduction of OBD requirements for light-duty vehicles (USA and Europe)
- the introduction of a highly transient emission test cycle for emission certification for heavy-duty vehicles (Europe)

In addition, due to international treaties to reduce greenhouse gas emissions, more emphasis will be given on energy efficiency within the transportation system in general in the future. This means that high efficiency will be sought for also in the case of gas fuelled engines. This will be a great challenge especially in the case of heavy-duty gas engines, as the current HD gas engines are less fuel efficient than their diesel counterparts.

The automobile and engine manufacturers associations (AAMA in the US, ACEA in Europe, EMA in the US and JAMA in Japan) presented their "World-Wide Fuel Charter" in 1998 /103/. The document aims at world-wide harmonisation of gasoline and diesel fuel recommendations. The document also defines three different market categories with varying emission and vehicle performance concerns. The categories are:

Category 1:
Markets with no or minimal requirements for emission controls; based on fundamental vehicle/engine performance concerns.

Category 2:
Markets with stringent requirements for emission control or other market demands. *For example, markets requiring US Tier 0 or Tier 1, EU Stage 1 and 2 (1993/1996), or equivalent emission levels.*

Category 3:
Markets with advanced requirements for emission control or other market demands. *For example, markets requiring US California LEV, ULEV and EU Stage 3 and 4 (2000/2005), or equivalent emission levels.*

These three categories also correspond to the generations of gas fuelled vehicles. Category 1 is equivalent to the 1st generation gas engines equipped with mechanical fuel systems mentioned in 3.3. Category 2 may include 2nd and 3rd generation gas vehicles and Category 3 correspondingly 3rd and 4th generation vehicles.

6   LIGHT-DUTY VEHICLES

6.1   General

Several auto manufacturers have CNG vehicles available, either as regular products or demonstration/experimental vehicles. Included on the list of manufacturers supplying natural gas light-duty vehicles are, among others, BMW, Daimler-Chrysler, Fiat, Ford, Honda, Mitsubishi, Nissan, Toyota and Volvo /104,105,106,107,108,109,110,111,112/. Information about vehicles available is easily found on the US Department of Energy Web pages /105/. Many manufacturers can offer both dedicated natural gas vehicles and bi-fuel vehicles capable of running on both natural gas and gasoline.

Some of the gas equipment manufacturers have joined forces with the automotive OEMs. The GFI company, for example, works together with Ford /113/, and IMPCO together with GM /114/.

In light-duty vehicles, especially passenger cars, the fuel tanks often intrude on either the passenger or luggage compartments. Exceptions are the Fiat Multipla car and the Malaysian built Proton Wira, which package fuel storage cylinders under the floor, and the 1,000 Malaysian taxis (built by Matra) which have fuel cylinders under the floor and a passenger seat. In the future, we can expect more integrated fuel tank approaches to minimise waste of space. At 200 bar fast fill pressure, one litre of CNG tank volume holds the equivalent of roughly 0.2 litre of gasoline.

The following examples highlight some recent OEM natural gas vehicles. Included are European, Japanese and North American manufacturers.

6.2   Examples on OEM vehicles

6.2.1   BMW 523 g

BMW offers a range of sedan and station wagon type vehicles on CNG /104,115/. The BMW 523 g has a six-cylinder dedicated CNG engine, which delivers 135 kW. The vehicle is equipped with two CNG tanks with a total volume of 145 litres /104/. BMW claims that the emissions of this vehicle comply with the EZEV requirements. BMW also states that the overall efficiency of this car is better than that of a fuel cell vehicle. Figure 6.1 shows a MY 97 station wagon type vehicle.

Figure 6.1.   BMW 520 series CNG (biogas) vehicle (photo by VTT).

6.2.2 Chrysler Maxivan (Dodge Ram)

The CNG Dodge Ram was the first natural gas vehicle series-produced by an auto-maker. The first year of volume production was 1993. The production stopped after the 1996 model year, but the Ram was back again for the 1999 model year /116/. The full-size Ram was accompanied by mid-size van for a while.

The full-size van (Figure 6.2) is equipped with a 5.2 litre V8 engine with sequential multi-port fuel injection /106/. The vehicle is ULEV and SULEV certified. The composite fuel tanks are placed under the vehicle floor, so they do not compromise the cargo/passenger space. The claimed driving range with the standard fuel tanks is some 350-450 km (which is much more than the real-life driving range recorded at VTT).

Figure 6.2   Dedicated Dodge Ram CNG van /106/.

6.2.3 Fiat Multipla

The Fiat Multipla (Figure 6.3) is a recent model. The whole design is rather special, including three parallel seats in the front /107/. The chassis of the vehicle has been designed in such a way that 4 gas bottles of a total volume of 214 litres can be fitted under the floor without intrusions in the passenger compartment. This is a unique design for passenger cars.

For natural gas, the Multipla is offered both as a bi-fuel version (Bipower) and as a dedicated CNG version (Blupower). The 1.6 litre engine of the Bipower version delivers 76 kW on gasoline and 68 kW on natural gas. The dedicated Blupower CNG engine has a compression ratio of 12.5, and it delivers 70 kW.

The driving range on CNG is some 600 km for the Blupower version (214 litres tank capacity) and some 450 km on natural gas for the Bipower version (164 litres tank capacity).
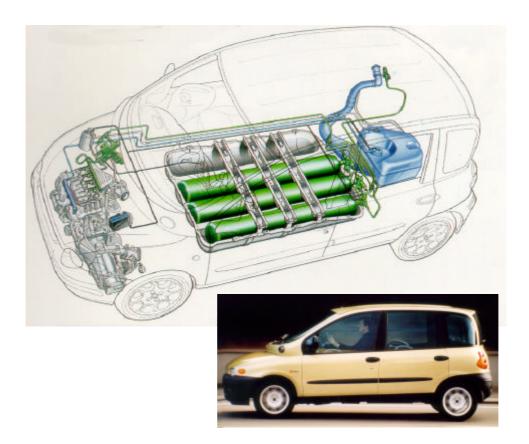
Figure 6.3.   Fiat Multipla /107/.

6.2.4 Ford Contour

Of all auto manufacturers, Ford has the broadest range of alternative fuel vehicles /108/. The bi-fuel Ford Contour (Mondeo) is an example of Ford's passenger cars for natural gas (Figure 6.4).

Figure 6.4.   The bi-fuel (gasoline/CNG) Ford Contour /108/.

The bi-fuel Contour comes with a 2.0 litre gaseous fuel prepared (GFP) Zetec-engine, which has been modified to include upgraded intake valve seat inserts to increase durability. This bi-fuel vehicle also operates with an EPA and California approved OBD II compatible engine management system. This is achieved through communication established between the GFI CNG computer and the Ford EEC-V computer. The steel natural gas tank has a fiberglass composite overwrap to increase cylinder strength and durability. For MY99 the bi-fuel Contour was certified for the TLEV class. The bigger Ford Crown Victoria, which is a dedicated CNG vehicle is ULEV certified /106/.

6.2.5 Ford F-150

The MY 2000 Ford F-150 pickup is another example of Ford's range of vehicles for natural gas (Figure 6.5). This light-duty truck is offered in six different models, regular and super cab, 4x2 and 4x4 configurations with single in bed tanks rated to 3600 psi (250 bar). They are equipped with a 5.4 litre GFP V8 Triton modular engine, developing 151 kW. Maximum driving range is some 320 km.

The bi-fuel vehicle is certified to a split-level standard of LEV on gasoline and ULEV on natural gas. Current EPA regulations do not allow certification of bi-fuel vehicles greater than one level below the gasoline certification level. This, however, is likely to change so that the advanced bi-fuel vehicles can achieve their full potential to be certified at the SULEV level on natural gas. Dedicated F150s are already SULEV certified /106/.

GFI is the manufacturer of record and cerificate holder for the Ford bi-fuel vehicles in North-America.

Figure 6.5.   Ford F-150 /106/.

6.2.6 Honda Civic

The dedicated Honda Civic 1.6 (Figure 6.6) is in mass production in the US /109/. In 1998 Honda claimed that this vehicle was able to reach emission levels equivalent to 1/10 of the ULEV-levels. The MY00 version is SULEV certified /106/.

The compression ratio of the 1.6 litre engine has been increased from 9.4 in the gasoline version to 12.5 in the dedicated CNG version. The gas engine also has a variable valve timing system (Variable Valve Timing and Lift Electronic Control, VTEC) to minimise loss of power and also to promote stable combustion of the gaseous fuel. The engine has four valves per cylinder. However, at low engine rpm one of the intake valves is almost closed to promote swirl and flame propagation. At high rpm both intake valves open. Fuel is metered using a sequential multi-point fuel injection system. The gasoline version has one close-coupled catalyst, the CNG version has a closed-coupled and an under-floor catalyst. Figure 6.7 shows the layout of the natural gas Civic engine.

As a result of the advanced engine technology the volumetric efficiency is higher than for normal gas engines, and the engine actually delivers a higher output on natural gas than on gasoline (84.6 kW versus 80.9 kW). One still has to bear in mind that the advanced valve train mechanism can also be used to optimise the power output of the gasoline version.

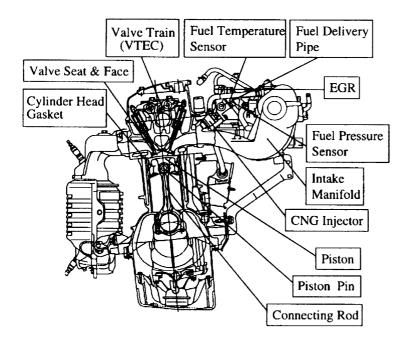*Figure 6.6.   Honda Civic /106/.*

Figure 6.7.   The Honda Civic VTEC CNG engine /109/.

Table 6.1 lists items which have an effect on the different emission components. It can be noted that exhaust gas recirculation, ignition retarding and enrichment after fuel-cut are used to suppress nitrogen oxide formation.

Although the maximum power output of the natural gas engine is higher than for the gasoline engine, the CNG vehicle is somewhat slower in acceleration, as 0-100 km/h takes 11.3 seconds with gasoline and 12.6 seconds with CNG. The energy consumption of the CNG version is some 6 % higher compared to the gasoline version (35.2 mpg equivalent for the CNG version and 37.5 mpg for the gasoline version).

Table 6.1.   Technical details needed to achieve very low emissions (arrows indicate reductions) /109/.

1/10th ULEV TECHNOLOGY	CO	NMOG	NOx
Sequential Manifold Injection	⬇	⬇	⬇
VTEC Engine	⬇	⬇	⬇
Full Electronic Exhaust Gas Recirculation			⬇
Ignition Retard			⬇
Enrichment after Fuel-cut			⬇
Dual Oxygen Sensor	⬇	⬇	⬇
Quick Warm-up Oxygen Sensor	⬇	⬇	⬇
Close-Coupled Catalyst	⬇	⬇	⬇
Optimised Catalyst Loading	⬇	⬇	⬇
Increased Catalyst Cells	⬇	⬇	⬇
Adaptive Fuel Control System	⬇	⬇	⬇

6.2.7 Volvo S/V70 & S80

Volvo offers bi-fuel versions both of the popular S/V70 series and the new luxury car S80 /111,112/. The Volvo S/V70 cars (Figure 6.8) have a 95 litre CNG tank, which Volvo claims gives a driving distance of some 250 km. The standard 70 litre gasoline tank is retained. Power output is 106 kW on gasoline and 95 kW on CNG, a difference of 10 %.
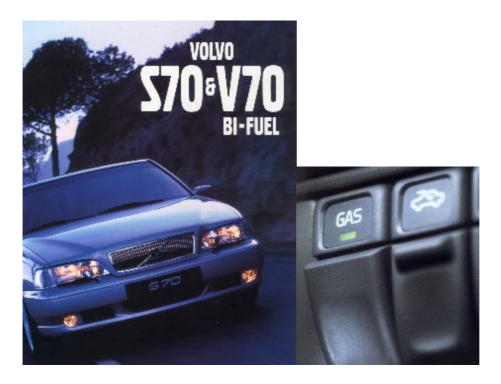

Figure 6.8.   The Volvo S/V70 /111/.

The Volvo S80 sedan has three CNG tanks, a large one in the trunk and two smaller ones under the rear seat (Figure 6.9). The total volume of the tanks is 100 litres. Volvo also has plans for a S80 version with all fuel tanks under the floor of the vehicle /117/. According to Volvo, the S80 Bi-Fuel is the cleanest Volvo ever built. On CNG, its emissions conform with the ULEV standards, and on gasoline it meets the LEV standards.
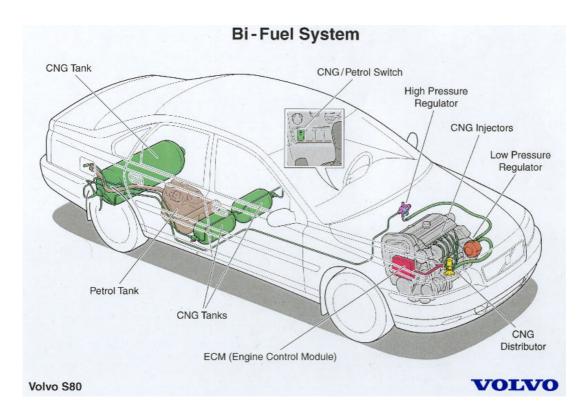
Figure 6.9.   A cut-through view of the Volvo S80 /112/.

6.3   Power output and fuel consumption

The performance of an engine running on natural gas very much depends on the sophistication of the engine, and whether the engine is dedicated for natural gas or not. Normally power loss due to reduced mixture energy density can be expected when switching from gasoline to natural gas (see 2.2).

If the engine is a bi-fuel engine, or originally a gasoline engine, which is converted to natural gas, the engine cannot fully utilise the high knock resistance of methane. If the engine is dedicated to natural gas, the compression ratio can be increased, valve timing and ignition settings can be optimised and thus the power loss, at least to some extent, can be reduced.

At a given compression ratio engine efficiency on natural gas should be equal compared to gasoline. Methane easily forms a homogeneous mixture, which is good for combustion. On the other hand, methane is hard to oxidise, and this again can cause flame quenching and leave unburned fuel in the crevices of the combustion chamber.

As can be seen in the previous section, the power output in general drops some 10 % in bi-fuel engines when switching to natural gas. The figure for dedicated engines is in general somewhat lower, and in extreme cases, like in the Honda Civic, a gas engine can give a higher output than a gasoline engine.

The maximum power drop when switching to natural gas is, however, so small that it in most cases will not affect the practicability of the vehicle. There will still be power enough even when driving on natural gas. This is especially true for big North American engines.

Natural gas is close to neutral compared to gasoline considering the energy consumption of the vehicle. A CNG vehicle, due to the gas cylinders, is slightly heavier than a gasoline vehicle, something that normally means increased energy consumption.

On the other hand, a dedicated natural gas engine might be a little more energy efficient than a gasoline engine, so these factors should more or less compensate each other. In the case of the dedicated Honda Civic CNG vehicle the reported additional energy consumption is 6 %. Depending on the vehicle, one could estimate that a CNG vehicle consumes 0-10 % more energy than a gasoline vehicle.

Taking into account the whole fuel chain, i.e. also the fuel production and distribution, the overall energy efficiency of CNG should equal that of gasoline (see Table 2.4). Due to fuel chemistry, the use of CNG instead of gasoline in light-duty vehicles will result in an overall CO_2 reduction of some 20 %.

6.4   Regulated exhaust emissions

As described in Chapter 2, the decisive factors for regulated emissions are the engine and exhaust gas aftertreatment technologies applied. In less sophisticated engines, a fuel switch can, however, lead to considerable reductions, both relatively and absolutely.

Category 1 vehicles

Figure 6.10 shows a summary of emission tests with 7 non-catalyst vehicles representing 1st generation or Category 1 vehicles. Switching from gasoline to gaseous fuels (LPG and CNG) results in a substantial reduction in the CO emission. CNG also reduced HC and NO_X emissions. The Figure is based on data from TNO /118/. Thus switching to gaseous fuels can contribute to the reduction of emissions from less sophisticated vehicles.
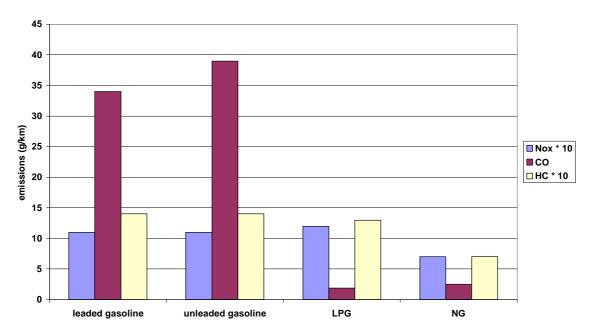
ECE 15 test results; 7 cars

Figure 6.10. *Emission test results with non-catalyst vehicles (ECE 15 test cycle, hydrocarbons measured with a NDIR instrument, TNO results) /118/.*

Category 2 vehicles

Figure 6.11 gives an emission comparison for 1993/1994 model year Category 2 vehicles running on different fuel alternatives (US FTP test). The work was done at VTT for the International Energy Agency (IEA). The Figure contains data from a total of 14 vehicles. Category 1 non-catalyst vehicles are included as a reference, all other Otto cycle vehicles use Category 2 TWC technology.

The vehicles on gaseous fuels have multi-point gas injection systems. Included in this group were two retrofitted vehicles and one dedicated vehicle. Actually, for testing purposes, one of the vehicles was equipped so that it could run on gasoline, LPG and also natural gas. Flexible fuel vehicles running on M85 methanol fuel were also tested. The diesel group is a mix of conventional and advanced passenger car diesels.

The emissions of the non-catalyst gasoline vehicles are approximately 10 g CO/km, 1.3 g HC/km and 2.5 g NO_x/km. The emissions of the TWC vehicles are roughly 1 g CO/km, 0.1 g HC/km (total hydrocarbons, THC) and 0.2 g NO_x/km. Thus one can say that the TWC technology reduces emissions by a factor of 10.
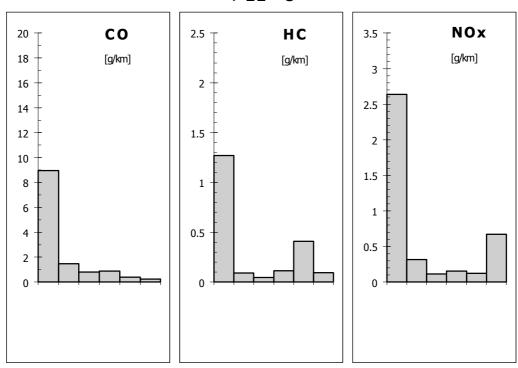
+ 22 °C

Figure 6.11.   Emission comparison of different fuel technologies using 1993/1994 vehicle technology (FTP test cycle, VTT results, number in parenthesis indicate the number of vehicles measured) /16/.

Within the group of TWC vehicles, natural gas gives the lowest CO emissions. Gasoline gives somewhat higher NO_x emissions than the alternative fuels. The total hydrocarbon emission of the natural gas vehicles is high, on an average 0.4 g/km. The spread is also high, from 0.2 to 0.6 g/km, the lower value coming from a dedicated CNG vehicle.

The dedicated MY 94 CNG vehicle (full size van) was subjected to a durability test at VTT. Figure 6.12 shows the FTP emission results over a time period of 5 years and a driving distance of 100,000 km. The vehicle has performed rather well, although the emissions have increased somewhat over time. This could be a result of the very harsh running conditions in Finland (severe winter conditions).

Emissions durability tests of a MY 94 Ford F-Series bi-fuel pickup truck were also carried out by GFI Control Systems over 50,000 miles of mileage accumulation on a test track. Emissions deterioration factors were compared between gasoline and CNG operation, and the results in Table 6.2 show that the emissions deterioration on CNG was similar to that on gasoline.
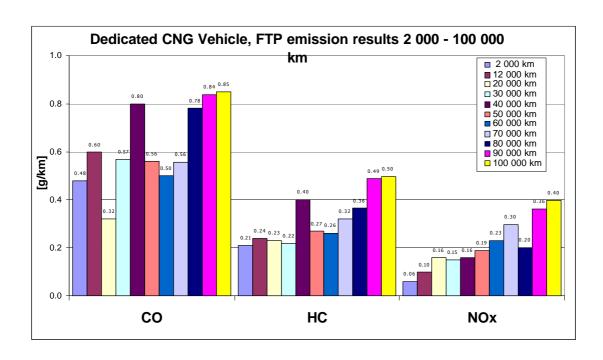
Figure 6.12. Emission results from a 100,000 km durability tests (dedicated CNG vehicle) /119/.

Table 6.2. Emissions durability tests of a MY 94 Ford S-series bi-fuel pickup truck /120/.

Vehicle/ Mileage miles	NMHC Indolene g/mile	NMHC CNG g/mile	CO Indolene g/mile	CO CNG g/mile	NOx Indolene g/mile	NOx CNG g/mile
4000	0.32	0.06	4.6	1.9	0.79	0.78
50,000	0.50	0.16	3.3	1.7	0.95	0.9
Emissions DF	1.56	1.78	1.0	1.0	1.20	1.15

TNO also carried out Category 2 vehicle tests similar to the ones at VTT. The vehicles running on gaseous fuels were converted vehicles using state-of-the-art conversion equipment. Part of these results are given in Table 6.3. TNO measured also total particulate emission. Hydrocarbon emissions are expressed as total hydrocarbons. TNO's results were quite similar to VTT's.

Table 6.3 Category 2 vehicle emission results (FTP tests cycle, TNO results) /43/.

	Gasoline	LPG	CNG	Diesel
CO (g/km)	1.12	0.91	0.45	0.67
HC (g/km)	0.15	0.12	0.36	0.14
NOx (g/km)	0.15	0.21	0.13	0.74
particulates (g/km)	0.015	0.005	0.025	0.094

The results demonstrate that for regulated emissions, there is no clear winning fuel alternative for Otto cycle engines using TWC catalyst technology. Much depends on the sophistication of the vehicle itself. As a corollary, emission comparisons between different vehicles and fuels should be made using only vehicles of comparable makes, model year and fuel and exhaust control systems of comparable sophistication.

The diesels, being lean-burn engines, perform very well regarding CO and HC, but the NO_x emission is high, on an average 0.7 g/km.

Category 3 vehicles

Table 6.4 lists the emission performance of some recent vehicles. Included in the table are also the ULEV and SULEV emission limits (passenger cars and medium-duty trucks) /87,95/. Please note that some values are actual certification data, some data is from experimental vehicles.

Table 6.4   ULEV and SULEV emission limits and emission values of MY 1997-MY 2000 vehicles /106,108,120,121,122,123/.

			CO (g/mile)	NMOG (g/mile)	NO_x (g/mile)	Ref.
ULEV (passenger cars, 100,000 miles)			2.1	0.055	0.3	
ULEV (MD trucks, 120,000 miles)			6.4	0.143	0.6	
SULEV (pass. cars, 120,000 miles, prop.)			1.0	0.010	0.02	
SULEV (MD trucks, 120.000 miles)			3.2	0.072	0.3	
Vehicle	**Fuel**	**MY**				
Buick LeSabre experim.	gasoline	97	0.25	0.013	0.048	/121/
Honda Accord	gasoline	00	<1.0	<0.010	<0.02	/95/
Nissan Centra	gasoline	00	<1.0	<0.010	<0.02	/122/
Honda Civic ded.	CNG	98	0.11	0.0015	0.0185	/108/
Toyota Camry ded.	CNG	99	0.69	0.007	0.015	/123/
Ford Crown V. ded.	CNG	99	0.87	0.0125	0.14	/120/
Ford F-150 truck bi-fuel	gasoline	99	2.94	0.16	0.19	/120/
Ford F-150 truck bi-fuel	CNG	99	1.3	0.057	0.2	/120/
Ford F-150 truck bi-fuel	gasoline	00	1.55	0.138	0.294	/120/
Ford F-150 truck bi-fuel	CNG	00	1.4	0.069	0.046	/120/
Ford F-150 truck ded.	CNG	00	<3.2	<0.072	<0.3	/106/

ded.= dedicated CNG, bi-fuel= bi-fuel gasoline/CNG

The ULEV limits are rather easily met using CNG both in the passenger car and light/medium-duty truck category. The SULEV limits are not so strict regarding CO, but the NMOG and NO_x limits, on the other hand, are very strict, especially for passenger cars. The 1998 Honda Civic CNG and the 1999 Toyota Camry CNG meet the proposed SULEV limits.

The experimental gasoline Buick was well below the ULEV limits. It was also below the SULEV CO limit and close to the NMOG limit, but the NO_x emission was roughly twice the SULEV limit. This indicates that it will be possible to reach SULEV emission levels also with gasoline. In December 1999 it was reported that the first gasoline vehicle to be SULEV certified was the Nissan Sentra /122/. Also the new gasoline Honda Accord is SULEV certified /95/.

As the US legislation regulates non-methane hydrocarbons or non-methane organic gases and not total hydrocarbons, chemically simple fuels like methane are helpful in achieving very low NMHC and NMOG values. With gasoline, the cold start enrichment makes a major contribution to the hydrocarbon emissions, and therefore it is more difficult (but not impossible) to meet the SULEV NMOG limits on gasoline.

The 1999 ULEV certified dedicated CNG Ford Crown Victoria shows much better emission values than its Tier 1 certified gasoline counterpart. In the bi-fuel Ford trucks, lower emissions are achieved when running on CNG than on gasoline. In fact, on CNG, the MY 2000 Ford F-150 bi-fuel truck also meets the SULEV limits. This demonstrates that also a bi-fuel vehicle can perform very well.

Some MY 2000 dedicated CNG vehicles are or will be SULEV certified. Included on this list are at least the Dodge Ram van, the Dodge Ram wagon, the Ford F-150 pick-up truck and the Honda Civic passenger car /95,106/.

Figure 6.13 shows typical emission data for Category 1 and 2 vehicles and projected Category 3 vehicle emission performance (gasoline vehicles). This figure clearly demonstrates the huge reductions in emissions that have taken place due to improved vehicle technology. It is easy to understand that no major absolute emission reductions can be expected in Category 3 vehicles just by switching fuels. Compared to vehicles without catalytic aftertreatment, the SULEV vehicles come very close to having "zero" emissions.

6.5   Unregulated emissions

As described in 2.3, the fuel effect on emissions is more qualitative than quantitative. Natural gas and LPG can reduce both exhaust gas reactivity and toxicity. In a vehicle burning natural gas, methane normally accounts for more than 90 % of the hydrocarbons in the exhaust stream. Therefore the reactivity of the exhaust is low. Also smaller amounts of heavier hydrocarbons are found in the exhaust, mainly due to the fact that every engine burns small amounts of lubricating oil.
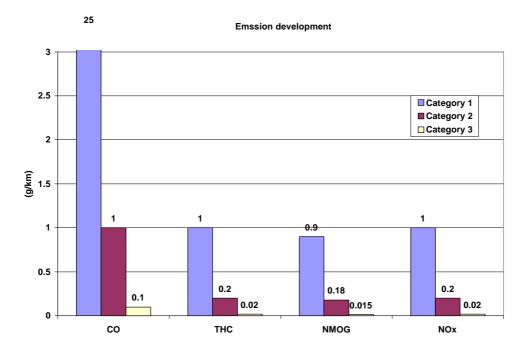
Figure 6.13.   Emission performance of different vehicle categories (CO 25 g/km for Category 1 vehicles).

Figure 6.14 shows hydrocarbon speciation for hydrocarbons up to 7 carbon atoms for gasoline, LPG and CNG exhausts. Gasoline exhaust contains also heavier hydrocarbons than this, up to 20 carbon atoms in certain heavy polyaromatic compounds.
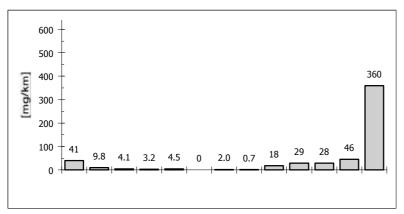
The tests were conducted with a special vehicle that had three separate fuel systems, and thus was able to run on all three fuels. The duty cycle was US FTP 75, and the vehicle was a Category 2 vehicle with fuel injection for all fuels. A standard gasoline catalyst was used, and this means that the hydrocarbon conversion running on natural gas was not necessarily at an optimum level.

With natural gas, the dominating hydrocarbon is methane, 92 % of the THC value. Also some ethane and propane can be detected. Benzene (C_6H_6), which is a known carcinogenic compound, is close to zero.
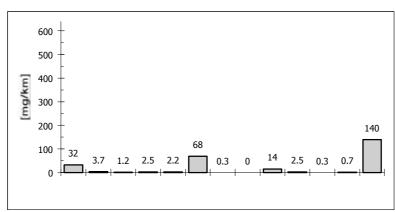
For LPG (in this case a propane/butane mix), the dominating hydrocarbons were propane, methane and butane (in decreasing order). These three hydrocarbons make up 81 % of the THC value, and methane alone covers 23 % of the THC value. Also with this fuel the benzene level was low. Alkanes like methane, ethane, propane and butane are not toxic nor reactive.

With gasoline, C_1 to C_7 hydrocarbons listed in the Figure make up some 50 % of the THC value, and some 10 % of the THC value is methane. The benzene emission was in the order of 100 times higher than for CNG and LPG.
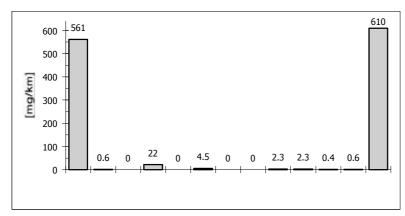
Figure 6.14.   Hydrocarbon speciation for gasoline, LPG and CNG /16/.

Table 6.5 lists some unregulated emission components for different fuel technologies. The vehicle categories are the same as in Figure 6.11.

Table 6.5.   Unregulated emission components (average values) for different fuel and vehicle technologies /16/.

US FTP composite (mg/km)	1,3-butadiene	benzene	formaldehyde	methanol
gasoline w/o cat.	11.8	55	43	0
Gasoline	0.6	4.7	2.5	0
M85	<0.5	1.5	5.8	79
LPG	<0.5	<0.5	<2	0
CNG	<0.5	0.6	<2	0
Diesel	1	1.5	12	0

Three-way catalyst technology is efficient in removing not only regulated emission components but also harmful unregulated components. On gasoline, the TWC reduces 1,3-butadiene, benzene and formaldehyde emissions by a factor of more than 10. For these three components, LPG and CNG give lower emissions than gasoline and M85. M85 exhaust contains unburned methanol.

TNO has performed measurements of unregulated emissions both from Category 1 and 2 vehicles. Table 6.6 contains a summary of the TNO measurements on Category 2 vehicles.

Table 6.6.   Summary of TNO's measurements of unregulated emissions on Category 2 vehicles /43/.

	Gasoline	LPG	CNG	Diesel
Particulate emission (mg/km)	9	6	11	84
Lower aldehydes (mg/km)	3.5	2.5	0.5	29
PAH (mg/km)	9.0	5.5	4.0	62
BTX*) (mg/km)	42	3	2	4

*) benzene + toluene + xylene

Also in TNO's study the gaseous fuels stand out as winners over the conventional fuels. Diesel is worse than gasoline except for BTX. The relatively high particulate emission on CNG was explained by the high oil consumption of one of the tested CNG vehicles.

Figure 6.15 shows TNO data on PAH and aldehyde emissions from non-catalyst vehicles /118/. Switching from gasoline to gaseous fuels reduces PAH emissions by a factor of 10. The drawback is that the aldehyde emissions will increase, going from unleaded gasoline to CNG roughly by a factor of 1.5. However, one could estimate that the total toxic effects going from gasoline to natural gas in non-catalyst vehicles will be reduced substantially.
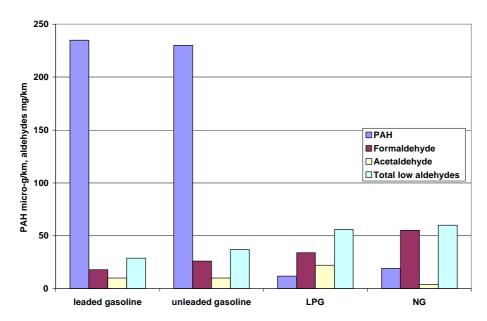
Figure 6.15.   Unregulated emissions from non-catalyst vehicles /118/.

A subject that has been much discussed for some time now is ultra fine particles. In the current legislation, there are no regulations whatsoever for particulate emissions from Otto cycle engines. The particulate emission from diesel vehicles is regulated by mass only.

Ambient air quality standards are often based on PM_{10}, i.e. particles with an aerodynamic diameter smaller than 10 microns. $PM_{2.5}$ limits are also under discussion. The rationale for setting limits on small particles is, that the smaller the particle is, the greater is the risk for the particle to penetrate far down into the human lungs.

Every type of combustion produces very small particles. The exhaust of an engine typically contains a lot of particles in the size range of 0.1 micron. Figure 6.16 shows an example of particle size distribution curves for a diesel engine.

Work is under way to improve the measurement technologies for particle size distribution and to establish the relation between particle size distribution and health effects.

There are, however, some indications that improved diesel technology, i.e. increased injection pressures might increase the number of very fine particles and that gasoline engines might produce more ultra fine particles than diesel engines. It could also be reasoned that natural gas might cause more ultra fine particles than gasoline.

At this moment, there is not enough data on ultra fine particles from different engine and fuel technologies nor data on correlation between ultra fine particles and health effects to make it possible to rank the different technology alternatives in this respect.

Although the size of the particle is one factor that might have implications on the health effects, the chemical composition of the particle must also be of importance. More research work has to be carried out to establish the importance and consequences of ultra fine particles.
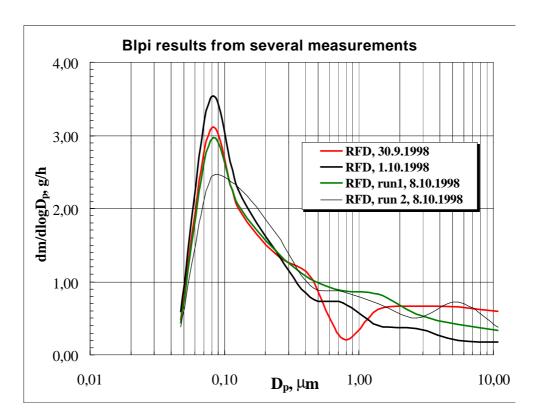

Figure 6.16.   Examples of particle size distribution curves (diesel fuel) /101/.

6.6   Low-temperature performance

During a normal emission test with a catalyst equipped vehicle, some 80-90 % of the total emissions of the test cycle are generated during the first couple of minutes of test. The exhaust clean-up system starts to work only when the engine is running on stoichiometric mixture ($\lambda=1$) and the catalyst is hot enough. The auto manufacturers work hard to improve the gasoline engines so that they can be started up with minimum enrichment and go to $\lambda=1$ operation as soon as possible. Today the best gasoline cars go stoichiometric some 20 seconds after start at normal ambient temperature.

In the US, there is a low temperature (20 ^{o}F/-7 ^{o}C) CO test. A similar test will be introduced in Europe in 2002. However, in Europe both CO and THC will be regulated. Over the years VTT has conducted a number of low-temperature emission tests both on conventional and alternative fuel vehicles.

VTT's experience is that lowering ambient temperature from around +20 ^{o}C to -7 ^{o}C will increase the emissions of catalyst vehicles by a factor of 3-5. With MY 99 vehicles certified for Europe, the catalyst systems start to work on an average after some 2-3 minutes and 0.7 km driving after a cold start at -7 ^{o}C /124/. Also, the emissions from non-catalyst vehicles increase with falling temperature, but relatively not as much as for catalyst vehicles.

Independent of vehicle technology, the ambient temperature has only a minor effect on NO_x emissions.

As described in 2.1, gaseous fuels are advantageous over gasoline regarding cold starts. Most of the dedicated engines perform very well at moderately low temperatures. Some bi-fuel vehicles, however, are designed in such a way that they always start up on gasoline independent of temperature. Such vehicles do not give an advantage over gasoline vehicles, as they run on gasoline whilst running in open-loop mode right after start-up.

In North America, all bi-fuel vehicle start on CNG. As a result, cold CO emissions are not required to be measured when the vehicle is operated on CNG, since EPA recognises the emissions contribution to be so much lower than on gasoline. Even with LPG, bi-fuel vehicles starting on LPG at 20 deg. F (-7 ^{o}C) show cold CO emissions to be one tenth that of gasoline.

Figure 6.17 shows low temperature CO performance of the vehicles presented in Figure 6.11. The CO emission with diesel, LPG and CNG is more or less independent of temperature. The curves for diesel and CNG fall together. With gasoline and M85 the CO emission will increase substantially with falling temperature. Figure 6.18 shows the corresponding situation regarding THC. The THC emission of the diesel does not change with falling temperature, and THC emissions with LPG and CNG increase only slightly. The emission performance of non-catalyst gas fuelled vehicles with simple mechanical fuel systems is also unaffected by temperature.

Figure 6.19 shows the emission performance of an European OEM bi-fuel vehicle on gasoline and CNG. The engine always starts on gasoline, and therefore the emissions are quite similar on both fuels. At normal ambient temperature choosing CNG-mode will decrease NO_x emissions slightly, at -7 ^{o}C this mode will increase THC emissions.

Figure 6.20 shows hydrocarbon speciation for the bi-fuel vehicle at -7 ^{o}C. The Figures with gasoline and CNG are almost identical, i.e. the gasoline used for cold start dominates the emission performance although "CNG" mode is selected.

As explained earlier, better emission performance, both in normal ambient temperature and low-temperature operation, can be expected with bi-fuel vehicles, which have a more sophisticated fuel system.
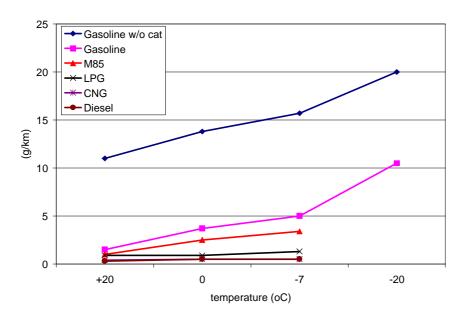
CO EMISSION VERSUS TEMPERATURE

Figure 6.17.   Low temperature CO emissions /16/.
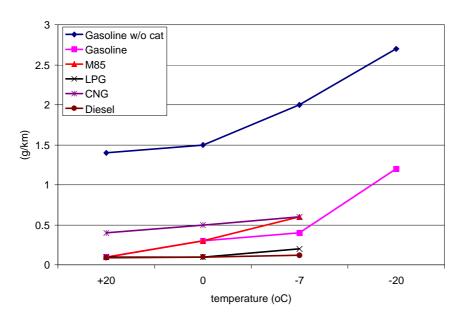
THC EMISSION VERSUS TEMPERATURE

Figure 6.18.   Low temperature THC emissions /16/.

BI-FUEL VEHICLE EMISSIONS

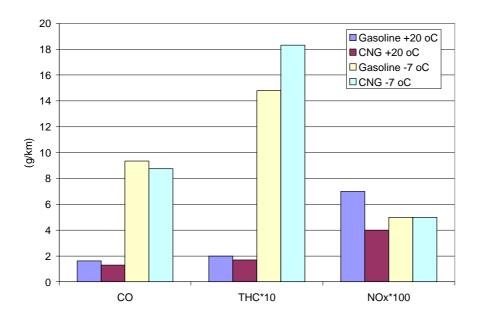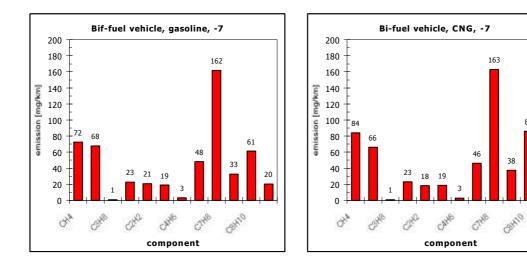*Figure 6.19.   Emission performance of an OEM bi-fuel vehicle /125/.*

Figure 6.20.   Hydrocarbon speciation for an OEM bi-fuel vehicle at -7 °C /125/.