TRANSIT BUS EMISSION STUDY: COMPARISON OF EMISSIONS FROM DIESEL AND NATURAL GAS BUSES

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ABSTRACT

This study on the emission performance of both diesel and CNG buses was linked to a comprehensive national program on bus emissions carried out by VTT Processes in Finland. For emission testing of buses VTT is using a 2.5 meter dia. dynamic chassis dynamometer and a full flow constant volume sampler (CVS) system. VTT has been granted accreditation for its emission and fuel consumption measurements of heavy-duty vehicles.

For the CNG section of the study, seven European vehicles, three diesel buses and four natural gas buses were evaluated for dynamic emission performance. All vehicles were model year 2002...2004 vehicles in prime condition. The diesel buses represented Euro 3 technology with electronically controlled injection. The exhaust after-treatment options were without exhaust after-treatment, with oxidation catalyst, and with continuously regenerating trap (CRT) (particle filter) particulate filter installed by the original equipment manufacturer (OEM). The diesel fuel used was ultra-low sulphur diesel. All CNG vehicles were equipped with catalysts, and the emission certification ranged from Euro 3 to enhanced environmentally friendly vehicle (EEV).

For the evaluation of emissions, two dynamic duty cycles were used, the European Braunschweig and the US Orange County cycle. The list of emission components evaluated is comprehensive, including regulated emissions, unregulated gaseous components, chemical composition of particles, and even particle number and mass size distributions.

The results demonstrate that regarding particle mass and number emissions, the CNG vehicles, on average, are equivalent to CRT filter equipped diesel vehicles. The particle matter (PM) emissions of both CRT diesel and CNG vehicles were some two orders of magnitude lower compared with the baseline diesel engine. No abnormity could be found regarding the numbers of nanoparticles emitted from CNG vehicles. The formaldehyde emission of the catalyst equipped CNG vehicles was low, as well as the emission of polyaromatic hydrocarbons (PAH) components. The genotoxicity of CNG emissions was extremely low, determined by the Ames mutagenicity tests and calculated as a reference value per unit of driven distance. As for NO_x emissions, CNG vehicles provide similar or superior emission performance, depending on the emission certification class.

The results for the unregulated emissions from this study are in conflict with some US studies showing high toxicity for natural gas exhaust. One explanation is that US natural gas vehicles normally are not equipped with catalysts, whereas all European manufacturers use exhaust after-treatment and sophisticated fuel injection on heavy-duty natural gas vehicles.

PREFACE

A lot of confusing and contradictory data on the emission performance of different bus technologies has been published recently. Issues that have been discussed are, among others, the performance of clean diesel fuel, exhaust gas after-treatment devices for diesel engines and the true performance of various types of CNG buses.

It was recognised that there is a clear need for an objective emission study. VTT Processes (Finland) is running a comprehensive national program on bus emissions. The International Association for Natural Gas Vehicles (IANGV) provided additional funding to extend the scope of the work to cover comparison between newest diesel and CNG buses.

The additional funding made it possible to add three more CNG vehicles to the matrix, all of these certified for the most stringent European emission class, EEV. In addition, the additional funding made it possible to expand upon the diesel vehicle measurements. Three diesel reference vehicles were chosen, all of the same brand and model but with different options for exhaust after-treatment: without after-treatment, with OEM oxidation catalyst and with OEM CRT particle filter. As a result, altogether seven top-of-the line vehicles in prime condition (three diesel buses and four CNG buses) were subjected to comprehensive emission testing.

This is the final report of the of the in-depth transient bus emission evaluation. The main findings of the study will be presented at the NGV 2004 Conference in Buenos Aires in October 2004. The full report will be freely available through VTT.

The report was compiled by a team at VTT Processes consisting of Dr. Nils-Olof Nylund, Kimmo Erkkilä, Maija Lappi and Markku Ikonen.

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1 BACKGROUND

A lot of confusing and contradictory data on the emission performance of different bus technologies has been published recently. Issues that have been discussed are, among others, the performance of clean diesel fuel, exhaust gas after-treatment devices for diesel engines and the true performance of various types of CNG buses.

Among the claims that have been stated in various reports are:

- natural gas increases the number of nanoparticles in the exhaust
- natural gas increases formaldehyde emissions
- CRT- equipped diesel vehicles running on low-sulphur diesel will provide better emission performance than CNG vehicles

In many studies, vehicles of different age and representing various degrees of sophistication have been compared to each other. Some studies have compared new particulate filter equipped diesel vehicles with less sophisticated CNG vehicles without a catalyst, but also vice versa; old diesels against new CNG vehicles.

It is, however, beyond any doubt that old diesel vehicles in bad mechanical condition and running on poor quality fuels cause severe particle problems. Natural gas, being an inherently clean fuel with low or non-existent particle formation, has a potential for substantial emission reductions.

It was recognised that there is a clear need for an objective emission study. VTT Processes (Finland) is running a comprehensive national program on bus emissions. IANGV provided additional funding to extend the scope of the work to cover comparison between newest diesel and CNG buses.

The objective of the CNG bus emission study is:

- To provide unbiased emission data on current diesel and CNG vehicles
  - new vehicles in good condition (low mileage)
  - newest diesel technology with and without exhaust after-treatment (three combinations)
  - four representative CNG buses
  - comprehensive emission analyses, including detailed analysis of particles

2 NATURAL GAS AS A FUEL FOR BUSES

Natural gas is considered one of the most potential alternative fuels. The use of natural gas in transportation is growing very rapidly in countries like Argentina, Brazil, India, Iran and Pakistan. (IANGV 2004)

In Europe, in its Green Paper on Energy Security, the European Commission has set a preliminary target of a 20 % substitution of conventional fuel by alternative fuels in the year 2020. Natural gas is considered to have a potential for a 10 % substitution (Green Paper 2001). Recent EC communication affirms this view (Alternative Fuels Contact Group 2003). Within the European Union, Germany is the country with the fastest growth, both in refuelling stations and CNG vehicles (Kaiser 2004).

The EU White Paper on Transport calls for both a reduction in oil dependence and the need for clean and efficient public transport (White Paper 2001). In many countries, natural gas has first been introduced as a transportation fuel for urban bus fleets. Urban buses normally operate on fixed routes, and utilize depot-based refuelling. This makes refuelling natural gas buses easy. Converting diesel bus fleets to natural gas offers a huge potential for emission reductions, especially in the case of particulates from low-technology diesels. For these reasons urban buses have been the focal point of many natural gas developments.

Most natural gas buses have engines which are basically diesel engines converted to spark-ignition and gas operation. It is, in principle, relatively easy to convert a direct-injection diesel into a spark-ignited gas engine. The two main challenges are controlling the thermal loads of the engine and controlling the exhaust emissions. The oil consumption of the gas engine has also to be controlled.

An OEM (Original Equipment Manufacturer) naturally has a better chance than a conversion shop in making a good engine conversion. Operating the engine with a lean mixture makes it easier to control engine thermal load. This is why many engine manufacturers prefer lean-burn combustion over stoichiometric combustion. Diesel engines always operate on an excess of air, and if lean-burn operation is chosen for operation with gas, smaller changes in the cooling systems and materials are needed compared with stoichiometric combustion. (Nylund 1995)

If no special measures to reduce exhaust emissions are taken the emission of nitrogen oxides (NO_x) of gas engines can be quite high, higher than for the original diesel engine. NO_x emissions are at their highest with a slightly lean mixture. To reduce NO_x emissions, either real lean-burn operation (LB, relative air/fuel ratio λ around 1.5) or stoichiometric combustion (SM) in combination with a three-way catalyst (TWC) has to be applied. Both these technologies are represented among current European heavy-duty natural gas engines. The US manufacturers have been in favour of lean-burn combustion.

Independent of combustion technology, natural gas engines produce very little particles, as methane gives soot-free combustion. The source of possible particles is the lubricating oil of the engine, not the fuel itself. This means that natural gas engines, partly operating in throttled conditions, should have good oil control.

Methane is a relative stable molecule. When operating with lean mixtures, small amounts of unburned fuel may enter the exhaust system. An oxidation catalyst reduces the amount of both unburned methane and formaldehyde. However, to work properly, the temperature of the catalyst should be quite high, preferable some 500 ^{o}C, to ensure high conversion rates for methane. At low loads, the exhaust temperature of a lean-burn engine might be too low to ensure proper catalyst operation. A catalyst also reduces aldehyde emissions effectively.

A prerequisite for good dynamic emission control on a gas engine is a sophisticated engine control system, capable of exact fuel control even under transient load conditions. The best gas engines of today, independent of combustion system, are equipped with electronically controlled fuel injection systems with closed-loop fuel control. (Nylund & Lawson 2000)

3 SIGNIFICANCE OF THE DIFFERENT EMISSON COMPONENTS

Nitrogen oxides and particle matter are considered to be the most harmful regulated emission components in urban air. Carbon monoxide (CO) is of less importance, as is the methane emission from natural gas vehicles. The hydrocarbon concentrations in diesel exhaust are generally low, but diesel exhaust can contain toxic and smelly components.

3.1 Carbon monoxide CO

Normally, CO emissions from a diesel engine are low, because diesel operates on excess air. CO is mainly the problem of old gasoline cars without catalysts. In ambient air, CO is oxidised into carbon dioxide (CO_2). At high concentrations, CO can be dangerous, causing dizziness, unconsciousness and even death. High CO concentrations can be found in garages, tunnels, narrow street canyons and corresponding places. Catalyst-equipped natural gas engines, either stoichiometric or lean-burn, have CO emissions equivalent to diesel engines. The effects of CO on humans are instantaneous, but CO does not have a cumulative long-term effect.

3.2 Hydrocarbons, total hydrocarbons, non-methane hydrocarbons HC, THC, NMHC

In diesel engines, the exhaust contains hydrocarbons (HCs) derived from partly burned fuel. During the combustion process, some new types of hydrocarbons or components like aldehydes and ketones can also be formed.

Gasoline vehicles without catalysts are the main source of hydrocarbons in ambient air; two and three-wheelers equipped with two-stroke engines are especially troublesome.

The aggregate effect of hydrocarbons depends on quality and quantity; included in the group of hydrocarbons are many carcinogenic compounds. Some hydrocarbons are reactive, and contribute to the formation of ground-level ozone and even smog.

In US legislation a differentiation between methane and non-methane hydrocarbons (NMHC) has been in effect made already for many years (DieselNet.com 2004), basically regulating non-methane hydrocarbons. The rationale for this is that methane is neither toxic nor reactive; it is, however, a relatively strong greenhouse gas, with an effect approximately 20 times as strong as CO_2.

In a natural gas engine, typically more than 90 % of the total hydrocarbon value (THC) is methane, and only a small portion is NMHC. For the time being, the European legislation for heavy-duty vehicles regulates total hydrocarbons (THC) for conventional diesel engines and both methane and NMHC for natural gas engines. (1999/96/EC)

3.3 Nitrogen oxides, NOx

Emission legislation regulates NO_x, which is a sum of nitric oxide (NO) and nitrogen dioxide (NO_2). In ambient air, NO is oxidized into NO_2. It has a tangy smell, and is irritating to the respiratory organs. Therefore ambient air quality regulations set limits values on NO_2. Nitrogen oxides also contribute to acidification.

A conventional diesel engine emits mostly NO (NO being some 90 % of NO_x). Some diesel exhaust after-treatment devices, e.g. effective oxidation catalysts and catalysed particle filters, increase the share of NO_2 in the exhaust. This is undesirable, as this can lead to smelly exhaust and locally elevated NO_2 concentrations, for example in street canyons.

3.4 Particle emissions, PM, and associated PAH compounds

The human respiratory system is protected against coarse particles, such as dust from the ground. Combustion in general, and especially combustion in internal combustion engines, may produce huge numbers of very fine particles. The human body does not have a protective system against these ultra-fine particles, and it is suspected that they can penetrate into the blood and other body fluids. Figure 1 shows how particles of different size penetrate the human body.

The health effect of particles is probably dependent on both particle size and particle chemistry. Emission particles are divided into size classes, which have different origins and different properties. The particles that make up most of the particle mass and can be trapped by particle filters are called accumulation mode particles. They are larger than 30-50 nm in diameter and mostly made up of products of incomplete fuel combustion, soot. These particles carry the most suspected genotoxic constituents of the emission, higher molecular weight polyaromatic compounds.

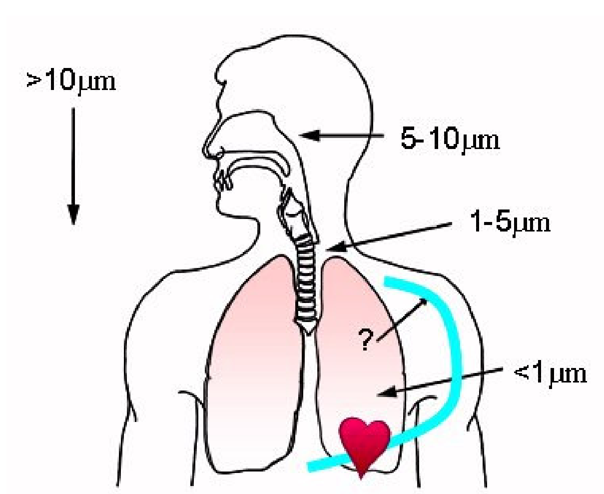

Figure 1. Particles entering the human body (Altshuler 2002).

Altogether seven individual up to 6 ringed polyaromatic hydrocarbons (PAH) are classified as possible human carcinogens by Environmental Protection Agency (US) (EPA) and International Agency for Research on Cancer (IARC) (EPA 2000, IARC 1989). The lower molecular weight PAHs, 2 – 3 ringed compounds mostly found in the semivolatile phase, are considered less noxious.

Nitro-PAHs (e.g. 1-nitropyrene) can be formed in combustion, but they are also found as secondary formation products in the atmosphere. According to IARC, several nitro-substituted PAHs are classified to group 2B as being possibly carcinogenic to humans (IARC 1989). Nitro-PAHs are direct acting mutagens and also react in *Salmonella typhimurium* cell test without metabolic activation (TA98-S9). With metabolic activation (+S9), some additional response is typically obtained by indirect acting un-substituted PAHs. (Maron & Ames 1983)

The smallest particles with a diameter less than 30...50 nm, are mostly condensed volatiles. These particles are called nucleation mode particles. For clean engine technologies, these small particles typically account for more than 90 % of total particle number. They are made up of sulphates originating from fuel and lube sulphur plus condensed organic material, added with minor portion of solid fuel and lube constituents like metals and ‘ash’. Most volatiles have gone through gas-to-solid conversion during exhaust cooling and dilution. The significance of these aerosols is not clear from a health point of view. However, these aerosol constituents cannot be overlooked as these smallest particles have the highest potential in penetrating into the lowest parts of the respiratory tract (alveoli region) and as they may, due to their mostly non-solid nature, dissolve into the body fluids and the blood circulation system,.

The tendency of natural gas to form PAH compounds in the combustion process is small. However, detectable amounts of PAH compounds originating from the engine lubricating oil can be found in the exhaust of natural gas engines.
Current CNG bus engines are throttled spark-ignited engines, working with vacuum in the inlet manifold under some load conditions. Thus, CNG engines are more prone to oil leakage through the inlet valve guides than their un-throttled diesel counterparts. Therefore, CNG engines should be designed for very good oil control. One option would be to use non-aromatic lubricant.

3.5 Other components

Sulphate and nitrate may have some adverse health effect, especially in combination with other emission compounds. However, the concentrations from modern vehicles with low sulphur fuels and lubricants are low compared with other emission and inhalation sources.

The incomplete combustion of any hydrocarbon, including methane, can generate aldehydes. For methane, the dominating aldehyde is formaldehyde, a substance included in the list of Mobile Source Air Toxics (MSAT, Table 1) of the US Environmental Protection Agency. Diesel particles per se are listed as priority mobile toxics. Table 1 also lists the 7 PAH compounds classified as carcinogens (see 2.4). A catalyst on a natural gas engine significantly helps to reduce formaldehyde emissions.

Table 1. EPA's list of Mobile Source Air Toxics. (EPA 2000)

List of Mobile Source Air Toxics (MSATs)

Acetaldehyde[4]	Ethylbenzene	Naphthalene
Acrolein[4]	Formaldehyde[4]	Nickel Compounds[1,4]
Arsenic Compounds[1,4]	n–Hexane	POM[3]
Benzene[4]	Lead Compounds[1,4]	Styrene
1,3-Butadiene[4]	Manganese Compounds[1,4]	Toluene
Chromium Compounds[1,4]	Mercury Compounds[4]	Xylene
Dioxin/Furans[2,4]		
Diesel Particulate Matter & Diesel Exhaust Organic Gases	MTBE	

[1] Although the different metal compounds differ in their toxicity, the on-road mobile source inventory contains emissions estimates for total metal compounds (i.e., the sum of all forms).
[2] This entry refers to two large groups of chlorinated compounds. In assessing their cancer risks, their quantitative potencies are usually derived from that of the most toxic, 2,3,7,8-tetrachlorodibenzodioxin.
[3] Polycyclic Organic Matter includes organic compounds with more than one benzene ring, and which have a boiling point greater than or equal to 100 degrees centigrade. A group of seven polynuclear aromatic hydrocarbons, which have been identified by EPA as probable human carcinogens (benz(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, chrysene, 7,12-dimethylbenz(a)anthracene, and indeno(1,2,3-cd)pyrene) are sometimes used as surrogates for the larger group of POM compounds.
[4] Although the different metal compounds differ in their toxicity, the on-road mobile source inventory contains emissions estimates for total metal compounds (i.e., the sum of all forms).

4 EMISSION REGULATIONS

Road transport is a major contributor to emissions. Its contribution to CO_2 is typically 20...30 % depending on country, whereas contribution to criteria pollutants can be in excess of 50 % for certain components. For road vehicles, there are emission regulations in place in most parts of the world. In developed markets (Europe, North-America, Japan) step-by-step technology improvements have reduced criteria pollutants dramatically, and new road vehicles are close to zero-emission levels. In Europe, sulphur-free fuels are entering the market.

Figure 2 shows the development of European on-road emission regulations.

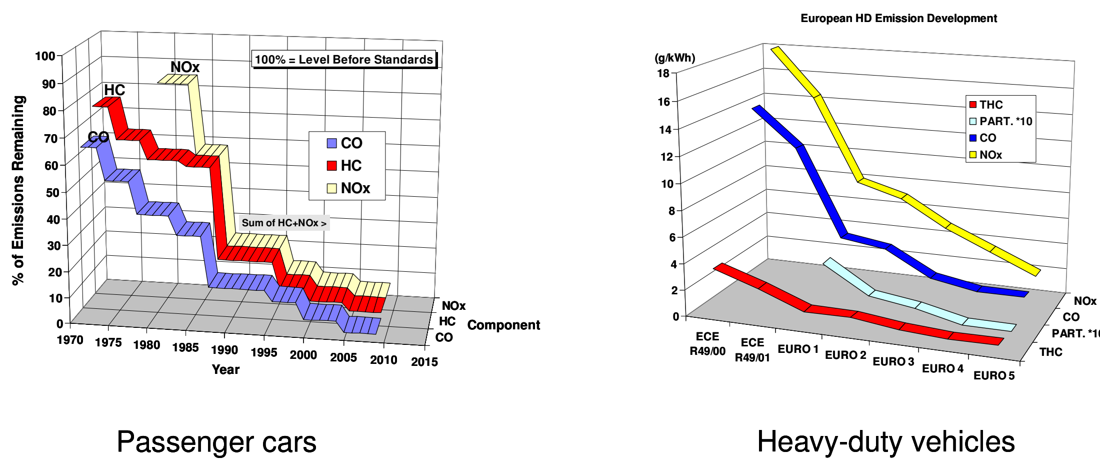

Figure 2. Development of European on-road emission regulations.

Table 2 summarizes current and oncoming emission regulations for heavy-duty on-road vehicles both for Europe and US. Emission certification is done running stand-alone engines on an engine dynamometer. The emission limits are expressed as aggregate specific emissions over the test cycle.

In the US, transient-type testing has been used already for a number of years; this better reflects real-life engine operation than steady-state testing. Starting with the Euro 3 regulations for the year 2000, transient-type testing was also introduced in Europe. Directive 1999/96/EC requires gas engines and diesel engines with advanced exhaust after-treatment to be tested over the dynamic European Transient Cycle (ETC). Starting 2005, dynamic testing will be required for all types of engines.

Directive 1999/96/EC also lists a special voluntary emission certification class, Enhanced Environmentally Friendly Vehicle (EEV). The best European natural gas engines have been certified for this class.

US will introduce even more stringent regulations than Europe. New emission regulations will be phased in between 2007 and 2010. In 2010, the limits will be 0.2 g NO_x and 0.01 g PM/hph (equivalent to 0.27 g NO_x and 0.014 g PM/kWh).

Table 2. On-road emission regulations (1999/96/EC, DieselNet.com)

	CO (g/kWh)	**THC (g/kWh)**	**NMHC (g/kWh)**	**NO_x (g/kWh)**	**Part. (g/kWh)**	**Smoke (m^{-1})**
ECE R49/ Euro 2	**4.0**	**1.1**	**-**	**7.0**	**0.15**	**-**
ESC/ELR						
A (2000)	**2.1**	**0.66**	**-**	**5.0**	**0.10**	**0.8**
B1 (2005)	**1.5**	**0.46**	**-**	**3.5**	**0.02**	**0.5**
B2 (2008)	**1.5**	**0.46**	**-**	**2.0**	**0.02**	**0.5**
C (EEV)	**1.5**	**0.25**	**-**	**2.0**	**0.02**	**0.15**
ETC						
A (2000)	**5.45**	**1.6 *)**	**0.78**	**5.0**	**0.16**	**-**
B1 (2005)	**4.0**	**1.1 *)**	**0.55**	**3.5**	**0.03**	**-**
B2 (2008)	**4.0**	**1.1 *)**	**0.55**	**2.0**	**0.03**	**-**
C (EEV)	**3.0**	**0.65 *)**	**0.40**	**2.0**	**0.02**	**-**
US 2007/10			**0.19**	**0.27**	**0.014**	

*) **CH_4 for natural gas engine only**

A= Euro 3, B1= Euro4, B2= Euro 5, the US 2007 requirement for NO_x is 1.6 g/kWh

The Euro 3 emission standard is attainable without using exhaust gas after-treatment and with a fuel containing 350 ppm sulphur. The Euro 4 regulation enters into force in 2005. Euro 4 is called the “first exhaust after-treatment enforcing regulation for heavy-duty vehicles”. Compared with Euro 3, NO_x is reduced by 30% and PM no less than by 80%, the latter most probably forcing the diesel vehicle manufacturers to go for after-treatment.

5 STUDIES ON BUS EMISSIONS

A number of studies with comparisons of diesel and natural gas bus emissions have been published previously. The basis for these comparisons, the choice of vehicles and even the outcome vary significantly.

In the following section, four different studies are summarized. In addition, a comment is made on NO_2 emissions from DPF equipped diesel engines.

5.1 The Air Resources Board study

In 2000 – 2001, the California Air Resources Board carried out a comprehensive study comparing emissions from diesel and natural gas buses. The objectives of the study were to assess driving cycle effects, to evaluate toxicity between new and "clean" heavy-duty engine technologies in use in California, and to investigate total PM and ultra-fine particle emissions. (ARB 2002)

The buses were run on a chassis dynamometer using five different duty cycles. In the first phase, two diesel buses, one equipped with an oxidation catalyst (DOC) and one equipped with a diesel particle filter (Continuously Regenerating Trap or CRT) were compared with a natural gas bus without catalyst. Obviously, this created some discussions, so the natural gas bus was re-tested equipped with an oxidation catalyst and a second, catalyst-equipped CNG bus was added to the test matrix.

In the complete setup, five vehicle configurations were investigated:

1. A CNG bus equipped with a 2000 DDC Series 50G engine certified for operation without an oxidation catalyst

2. The same CNG bus retrofitted with an OEM oxidation catalyst

3. A diesel bus equipped with a 1998 DDC Series 50 engine and a catalyzed muffler

4. The same diesel vehicle retrofitted with a Johnson Matthey CRT diesel particulate filter (DPF) in place of the muffler

5. A CNG bus equipped with a 2001 Cummins Westport C Gas Plus engine and OEM-equipped oxidation catalyst

Collection of PM over multiple cycles was performed to ensure sufficient sample mass for subsequent chemical analyses. Information on regulated (NO_x, HC's, PM, and CO) and non-regulated (CO_2, NO_2, gas-phase toxic HC's, carbonyl compounds, polycyclic aromatic hydrocarbons, and elemental and organic carbon) emissions was collected. Size-resolved PM mass and number emission measurements were conducted and extracts from diesel and CNG total PM samples were tested in the Ames mutagenicity bioassay analysis to determine mutagen emission factors. (ARB 2002)

Figures 3 (NO_x and PM), 4 (carbonyls) and 5 (mutagenicity) show examples of ARB findings.

CNG gives lower NO_x than diesel, whereas CNG and the CRT equipped diesel have roughly the same PM emission (close to ambient air values). Formaldehyde emission is very high with CNG without catalyst. With the oxidation catalyst formaldehyde emissions of CNG are reduced to the level of the DOC equipped diesel, the CRT equipped diesel being clearly lower.

Mutagenicity with CNG without a catalyst, is higher than for the DOC equipped diesel, with catalyst, CNG falls in between the DOC diesel and the CRT diesel.

As for particle number emissions, the ARB results show a reduction going from DOC diesel to CRT and CNG. Within the nanoparticle range (below 50 nm), however, CNG without catalyst produces more particles than the CRT diesel. An oxidation catalyst helps to bring down nanoparticle numbers close to the values of the CRT diesel.

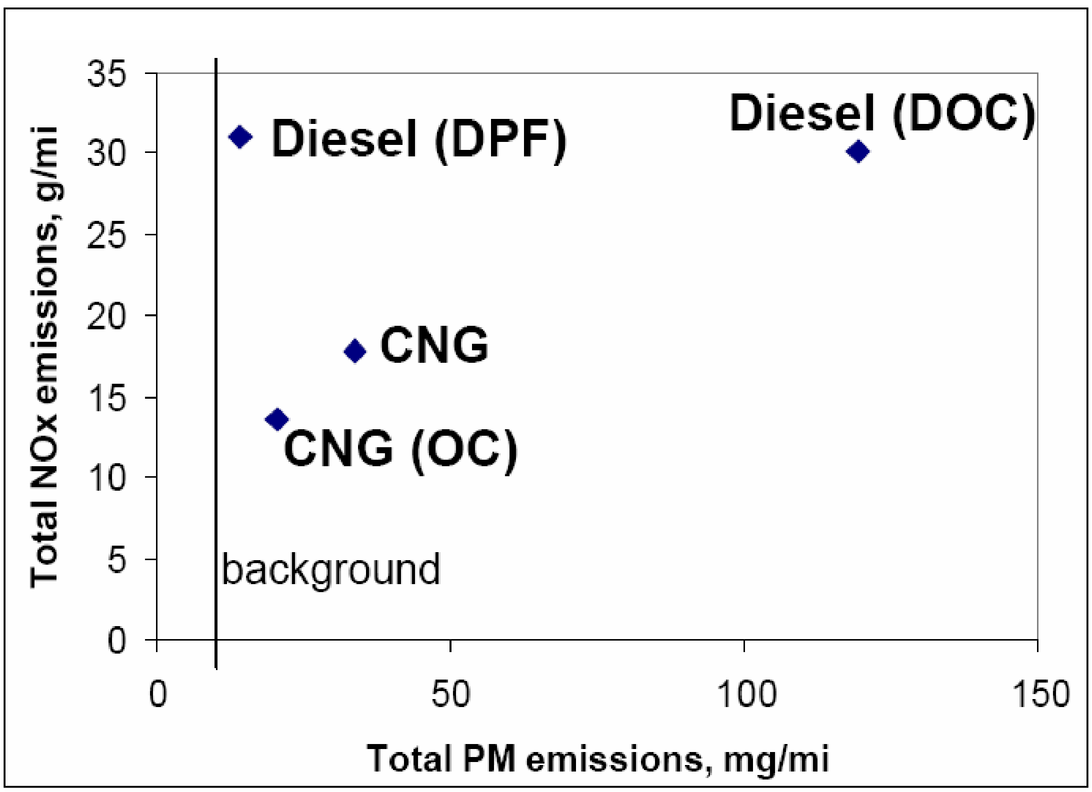

Figure 3. NO_x and PM emissions, CBD cycle. (ARB 2002)

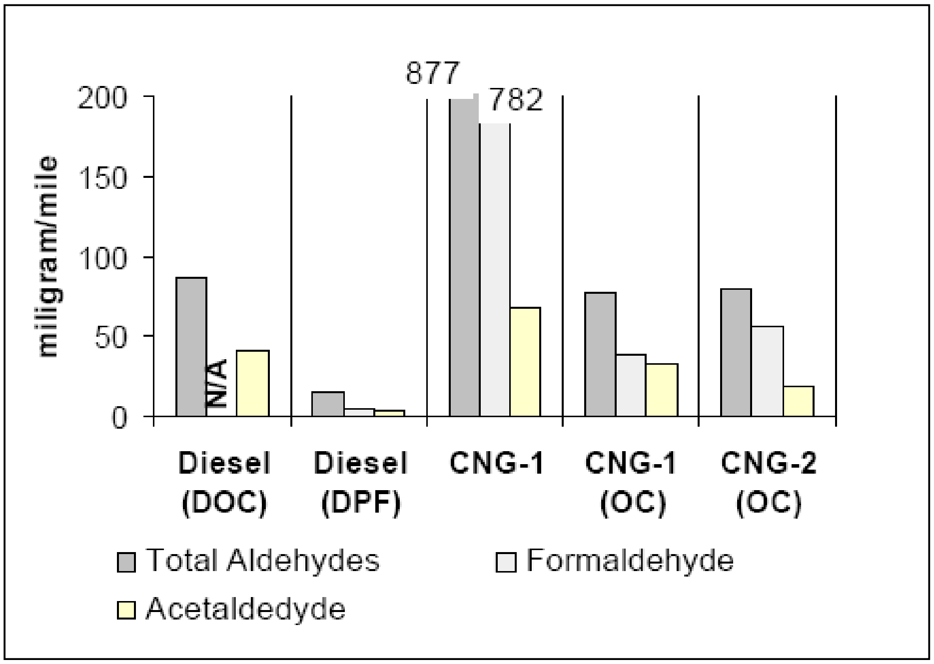

Figure 4. Carbonyl emissions. (ARB 2002)

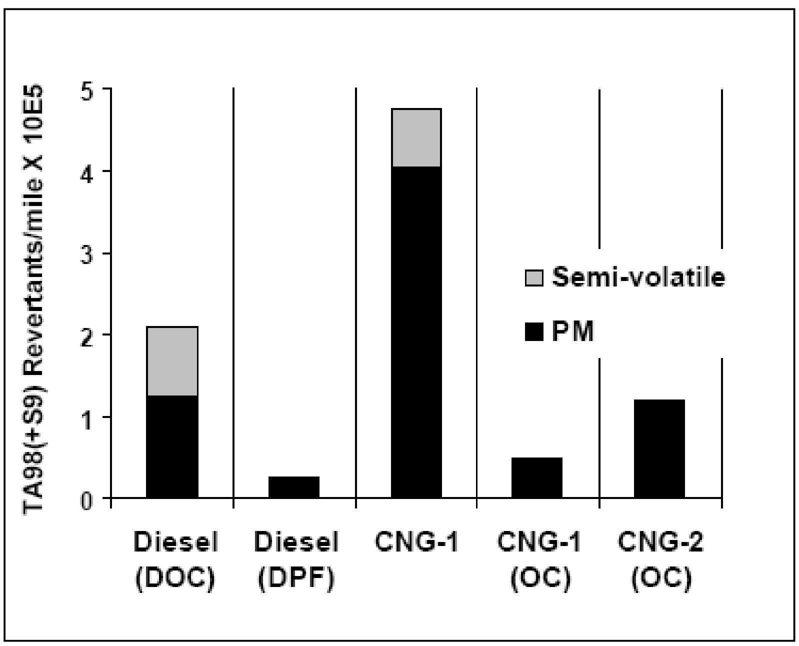

Figure 5. Exhaust mutagenicity. (ARB 2002)

ARB does not point out a clear winner or a loser. ARB is clearly in favour of exhaust after-treatment for all vehicle categories. ARB summarizes its results as follows:

- “Clean alternatives” can benefit from additional control and improvements
- Diesel trap changes PM composition, reduces toxic emissions but increases NO_2
- CNG emits lower NO_x but higher formaldehyde, catalyst reduces formaldehyde
- Lube oil plays a key role in PM toxicity
- Diesel PM defined as Toxic Air Contaminant (TAC), no such designation for CNG PM

5.2 International school bus study

International basically compared two buses, a model year (MY) 2001 diesel school bus equipped with a 8.7 litre International diesel engine and a MY 2000 CNG school bus equipped with a 8.1 litre John Deere natural gas engine. Two versions of the diesel engine were tested. The low-emission version (clean diesel) meant low NO_x engine calibration in combination with a diesel particle filter (DPF) from Engelhardt. For the conventional diesel configuration the DPF was removed and the low NO_x calibration was reset by modifications to the electronic engine control module (ECM). (International 2003)

Testing was performed on a chassis dynamometer using a transient-type duty cycle (City Suburban Heavy Vehicle Cycle).

The CNG bus had no catalyst. According to International, the reason for choosing a non-catalyst CNG vehicle was that they were unable to find a CNG school bus of the required configuration equipped with after-treatment. The objective of the study was to determine the validity of California Air Resources Board’s claim that there are 41 TACs associated with current diesel exhaust, and to also determine the validity of the claim that natural gas school buses emit fewer toxics than low-emitting diesel buses.

Figure 6 shows results for regulated emissions and some other selected emission components. Clean diesel scored the best result with the exception on NO_2 and CO_2. In this study, CNG without after-treatment gave the highest emissions for 6 components out of 11, including highest CO, NMHC and NO_x values. The PM value for CNG was roughly five times higher compared to the DPF equipped diesel.

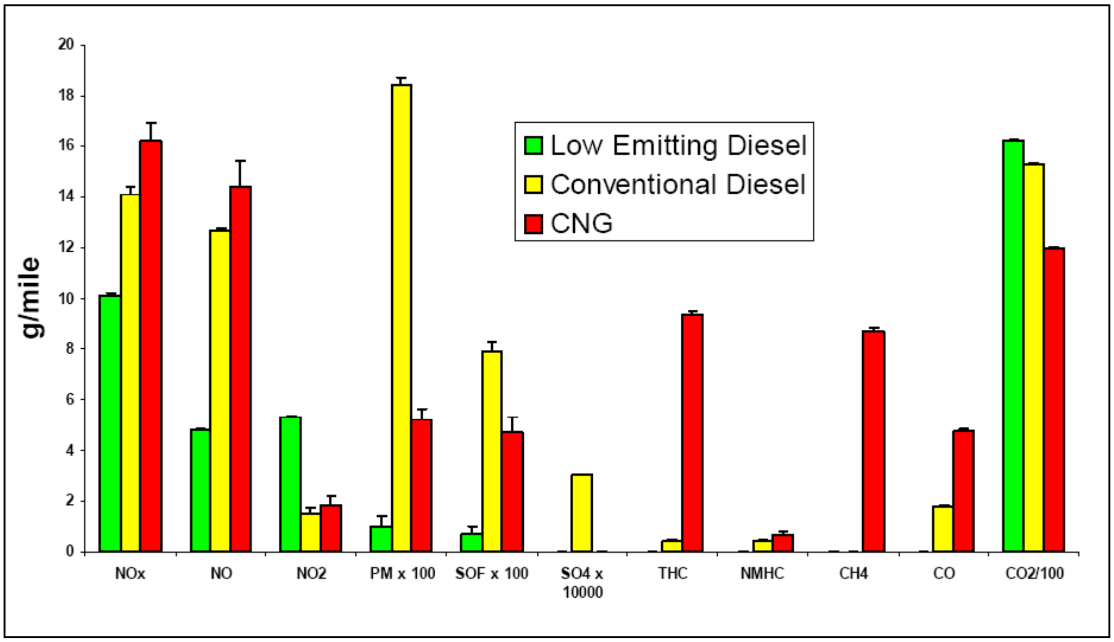

Figure 6. Air quality emissions for conventional diesel, low emitting diesel and CNG. (International 2003)

As for unregulated emissions and TAC components, the International study found no traces at all of 21 of the 41 TAC components listed by ARB. Five (5) TACs were statistically same for all three engine configurations, and nine TACs were statistically same between low emitting diesel and CNG. CNG was worse than low emitting diesel in the case of six TACs (acetaldehyde, acrolein, benzene, formaldehyde, methyl ethyl ketone and propionaldehyde). CNG was not better than low emitting diesel for any TAC (Figure 7).

As a summary, International presents an overall relative cancer potency for the three different technologies. Clean diesel is only slightly better than baseline diesel (-20 %). However, the result for CNG is quite astonishing, as International deems the cancer potency of CNG 12 times higher than for baseline diesel (Table 3). In this calculation formaldehyde and 1,3-butadiene are given high weighting, 95 % of the total score for CNG. As an oxidation catalyst effectively removes both formaldehyde and 1,3-butadiene, the outcome would probably have been different if the CNG bus had been equipped with a catalyst.

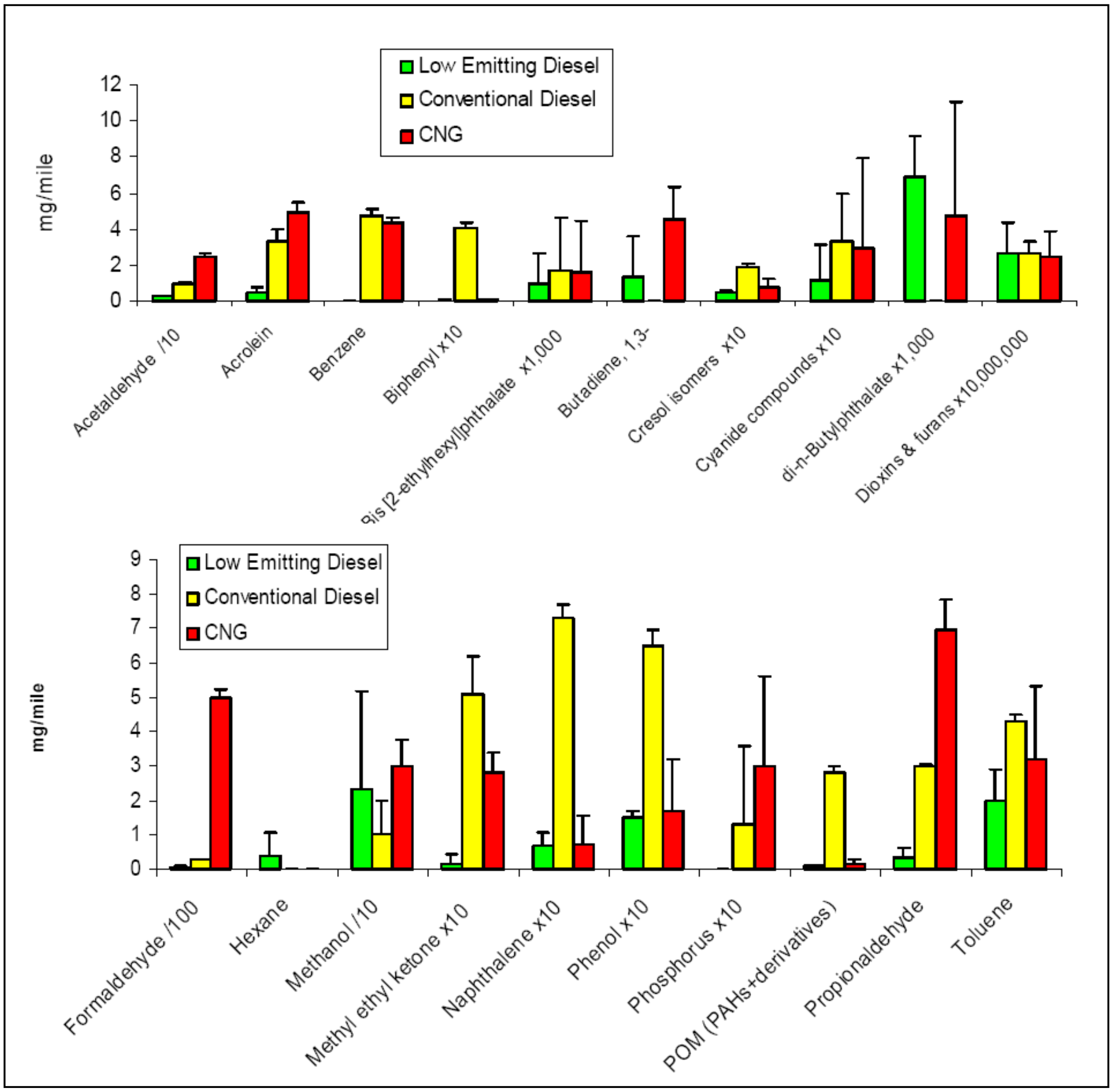

Figure 7. Toxic air contaminants. (International 2003)

Table 3. Relative cancer potency, weighted emission details. (International 2003)

	Low Emitting Diesel	Conventional Diesel	CNG
Formaldehyde	0.8	4.1	75.8
Butadiene, 1,3-	5.6	0	19.3
Benzene	0	3.4	3.2
Acetaldehyde	0.2	0.6	1.6
Dioxins	0.01	0.004	0.01
PAHs	0.0004	0.03	0.009
DHEP	0.00006	0.0001	0.00001
Total	6.6	8.2	100

5.3 TNO automotive study

On order by the Netherlands Agency for Energy and the Environment, TNO Automotive carried out transient-type engine dynamometer tests to evaluate the emissions of five different city bus engines. The technologies and fuels covered were LPG (stoichiometric/EEV), natural gas (stoichiometric/EEV and lean-burn/Euro 3) and diesel Euro 3 (without and with particle filter). The duty cycles used were the ETC certification cycle and the Dutch urban bus transient cycle (DBTC). In addition to regulated components, TNO also measured particle size distribution. (TNO 2003)

The results for regulated emissions and NO_2 are summarized in Table 4.

Table 4. Regulated emissions and NO_2. (TNO 2003)

Engine type	Test cycle	NMHC	CH_4	CO	NO_x	NO_2	PM
		g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
LPG λ= 1	ETC	0.0	0.0	1.8	0.1	0.0	0.009
	DBTC	0.0	0.0	0.1	0.6	0.0	0.007
CNG λ= 1	ETC	0.0	0.2	0.4	1.6	0.4	0.014
	DBTC	0.0	0.1	0.1	2.0	0.0	0.015
CNG lean burn	ETC	0.0	0.2	0.0	3.9	0.6	0.012
	DBTC	0.1	0.6	0.0	4.9	0.5	0.012
Diesel	ETC	0.3	0.0	2.5	5.6	0.5	0.109
	DBTC	0.3	0.0	2.2	6.4	0.4	0.114
Diesel + DPF	ETC	0.0	0.0	0.0	5.6	2.6	0.005
	DBTC	0.0	0.0	0.0	6.5	2.9	0.007

The engines with after-treatment systems (LPG, CNG, diesel with DPF) all have low or extremely low NMHC emissions. TNO states that due to the fact that methane is a stable molecule, the three-way catalyst or oxidation catalyst of a CNG engine has to be optimised with regard to methane conversion efficiency. The tested catalyst demonstrated good efficiency for methane conversion.

The CO emissions of all engines are below the EEV limit. TNO makes a note that CO is not a point of concern anymore.

The NO_x emissions show clearly the difference in emission performance of stoichiometric gas engines with a TWC and engines running with air excess (CNG lean-burn and diesel). The stoichiometric gas engines meet the EEV limit of 2 g NO_x/kWh. The emission of the lean-burn gas engine and the diesel engine (without and with DPF) is between 4 and 6.5 g/kWh. The Dutch bus cycle resulted in somewhat higher NO_x values than the ETC cycle.

The emissions of NO_2 of the gas engines and the diesel engine without DPF are relatively low. The DPF increases NO_2 emissions by a factor of five compared with diesel without DPF. TNO states that NO_2 is a direct toxic compound which causes breathing problems and lung damage.

The particulate emissions of the gas engines are very low, but the particulate emission level is even lower with DPF diesel. TNO states that for all these technologies PM emissions are close to detection limits.

TNO also performed measurements for particle size distribution using a Scanning Mobility Particle Sizer (SMPS) instrument. The measurements were made at selected steady-state load points of the European Steady Cycle (ESC). Figures 8 (diesel engines) and 9 (gas engines) present particle size distribution curves.

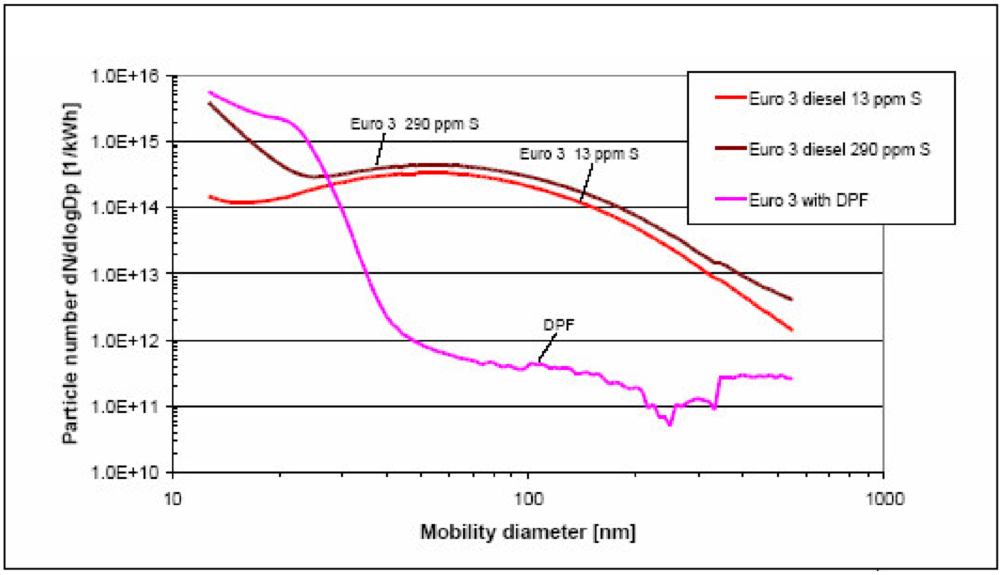

Figure 8. Particle size distribution (diesel engines). (TNO 2003)

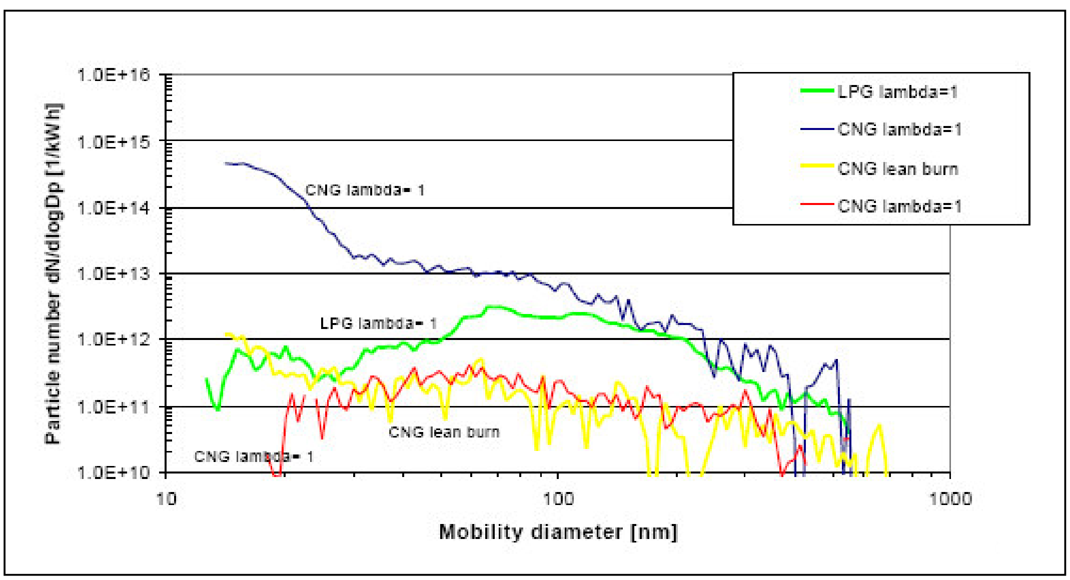

Figure 9. Particle size distribution (gas engines). (TNO 2003)

TNO found very little accumulation mode (>50 nm) particles with DPF, but in nucleation mode there was a sharp increase in particle numbers below 40 nm, even exceeding engine out numbers. TNO attributes this to formation of sulphate, even though the fuel sulphur content was only 13 ppm. The engine (without DPF) was also tested with a 290 ppm S fuel, producing almost equivalent numbers of nanoparticles to the DPF.

Three out of four gas engines produced very low particle numbers over the complete nanometer size range. One stoichiometric gas engine showed an increase in nanoparticles in the size below 30 nm. This phenomenon was found at one load point only (1300 rpm, 25 % load). TNO speculates that the difference between particle numbers of the gas engines may be explained by different oil consumption behaviour in combination with different catalyst behaviour regarding the oxidation of particles. TNO states that some of the gas engines show particle numbers which are almost equal to the numbers determined in the dilution air of the constant volume sampling system with disconnected exhaust.

5.4 Study on particles, National Energy Technology Laboratory/West Virginia University

U.S. National Institute for Occupational Safety & Health (NIOSH) and U.S. Department of Energy co-sponsored a study on the mutagenic potential of particulate matter from diesel engines. The research work was carried out at the National Energy Technology Laboratory (NETL) and at West Virginia University (WWU). (Particles 2002)

One on the major findings was that large diesel particles exhibit a significantly greater mutagenic effect than their smaller counterparts. It was also found that ultra-low sulphur, ultra-low aromatics Fischer-Tropsch (FT) diesel tends to produce particles with less mutagenic potential than ordinary diesel fuel. Implications of the findings lend support for the current trend toward installation of DPFs and cleaner ultra-low sulphur diesel (ULSD) fuel, including FT diesel.

The DPF/ULSD combination tends to eliminate the larger (>100 nanometers) solid fraction of PM emission, although it doesn't make much impact on "volatile" ultra-fine PM, which includes water vapour, sulphuric acid and some hydrocarbon slip.

It is believed that lube oil is a strong contributor to the PM chemical toxicity. In diesel engines, the lube oil contribution to the particulate SOF is greater than the fuel contribution under almost all operating conditions, and can be as much as 95 % of the solubles. This is most likely the case in natural gas or CNG engines, as well.

Dr. McMillian and Prof. Mridul Gautam of West Virginia University (WVU) have showed research findings that tie nano-PM emissions differences to lube oil sulphur differences, or possible lube/fuel interactions during combustion.

In tests, WVU found that higher-sulphur lube oils, along with phosphorus and other additives, might have a profound influence on PM size distribution and concentration of

PM emissions. According to WVU, some of the findings also might help to explain the relatively high toxicity of PM from CNG engines found in some US studies.

According to Gautam, some current state-of-art oil control technology in CNG engines suffers from problems with valve stem seals and oil rings. This might explain higher oil contribution to CNG PM emissions, and why many studies show CNG engines produce higher toxic PM than DPF-equipped clean-diesels, Gautam explains.

Lube oils for "clean" technology such as CNG or DPF-equipped diesels can contain up to 4,500-ppm sulphur, or roughly the equivalent of 4...5 ppm fuel sulphur, depending upon engine lube oil consumption rate. The related studies by WVU at NETL found that a low-sulphur (280 ppm) lube oil could lower concentrations of nanoparticle emissions.

5.5 NO_2 emissions from DPF equipped diesel engines

As mentioned in 2.3 and also pointed out by TNO, NO_2 is a direct toxic compound which causes breathing problems and lung damage. In a catalysed DPF system (Continuously Regenerating Trap), NO is oxidised into NO_2 by a high loading of platinum in an oxidation catalyst upstream of the filter. Essentially, NO_2 is used as an agent to facilitate auto regeneration. NO_2 reacts with the carbon particles captured in the filter part to form CO_2, nitrogen and oxygen. Normally, more NO_2 is formed than necessary to convert the carbon, and NO_2 is leaving the exhaust unmodified (TNO 2003).

Although NO_2 is not regulated in automotive or non-road emission regulations, there are limits for ambient air NO_2 concentrations both in air quality and occupational safety standards.

In addition to on-road applications, DPFs have been promoted for diesel powered working machinery operating in underground conditions in mines. Now a controversy has arisen as high NO_2 concentrations have created occupational safety risks in mines (NSSGA 2004).

The US National Stone, Sand and Gravel Association states as follows: *“Acting on an MSHA (US Mine Safety and Health Administration) to implement platinum-based catalysts, mine operators learned that the catalysts could produce levels of NO_2 in excess of the MSHA standard. The Agency was forced to issue an alert to the mining community about the problem. Besides the fact fundamental questions still remain about DPF durability and reliability, DPFs coated with platinum-based catalysts are not ready for the underground diesel market. This is because, in helping alleviate one health problem, diesel particulate matter (DPM), they create another problem, elevated exposure to $NO_{2.}$”* (NSSGA 2004)

The situation in mines with confined air space is naturally different compared with outdoor conditions. However, the findings within the mining industry point out that controlling NO_2 emissions could be of general importance.

5.6 Summary

There is great variation in the outcome of different comparative studies on diesel and CNG emissions.

The PM mass emissions from CNG buses are low, independent of technology. Technology, on the other hand, is decisive for NO_x emission performance. Compared with current diesel engines, CNG buses can produce both higher and significantly lower NO_x emissions. The first case is true for badly tuned, lean-burn engines, which do not operate lean enough for NO_x suppression. Properly tuned lean-burn engines normally give somewhat reduced NO_x emissions compared with diesel. Very low NO_x emissions can be reached with stoichiometric combustion in combination with TWC technology.

DPFs effectively reduce PM mass emissions from diesel engines. DPFs are very effective in reducing accumulation mode particles, and some studies show even lower mass emissions for DPFs than for CNG. However, DPFs do not necessarily reduce the number of nanoparticles. Most gas engines emit low particle numbers in all particle size classes.

The biggest drawback of DPF technology is high emissions of NO_2, a direct toxic compound which causes breathing problems and lung damage. DPFs can increase the NO_2 emission by a factor of 5 or even more compared with diesel without after-treatment and natural gas engines.

Some studies attribute high toxicity to CNG exhaust. Methane as such is non-toxic, and has low reactivity. Combustion of any hydrocarbon fuel can result in aldehyde emissions, formaldehyde being the dominating aldehyde from methane. Formaldehyde is classified as a toxic air contaminant. However, a catalyst effectively reduces formaldehyde emissions.

It is believed that lube oil is a strong contributor to the PM chemical toxicity. In a gas engine, the sole source of PM is the lubricating oil. Some less advanced CNG engines may suffer from problems with oil control due to leakage through valve stem seals and oil rings. This might explain higher oil contribution to CNG PM emissions, and why certain studies show that CNG engines produce higher toxic PM than DPF-equipped diesels. Worn-out engines will naturally have high PM emissions.

It is worth noting that European heavy-duty gas engines always are catalyst equipped, whereas many US CNG vehicles lack catalysts. All engine technologies benefit from efficient exhaust after-treatment. When comparing diesel and CNG technology, comparisons should be made on a fair basis. Top-of-the line natural gas vehicles should not be compared with old diesel technology, nor should best diesel technology be compared with not-so-advanced CNG technology.

6 THE FINNISH NATIONAL BUS PROJECT

Within the Finnish national bus project, VTT Processes is generating specific emission factors for city buses. The partners are:

- The Helsinki Metropolitan Area Council
- Helsinki City Transport Planning Department
- Ministry of Transport and Communications Finland
- Gasum Oy (the Finnish natural gas company)
- The Swedish Road Administration
- VTT Processes

IANGV teamed up with the Finnish bus project in 2003, as did the Swedish Road Administration. The timeframe for the first stage of the project is 2002-2004. The experimental work for the first stage is now completed, and reporting is under way. VTT performed in total more than 200 emission measurements with 34 different buses. Some vehicles were subjected to a follow-up program to study emission stability and deterioration.

Variables in the study were, among others:

- vehicle certification class (Euro 1 to Euro 5/EEV)
- vehicle mileage
- fuel (diesel, natural gas)
- duty cycle (Braunschweig bus cycle, ECE, Orange Country)
- vehicle load

As the measurements are carried out on a chassis dynamometer, the results are calculated in specific emissions per driving distance (i.e., g/km). VTT has already accumulated so much data that it is possible to establish a correlation between vehicle emissions certification class (Euro1, Euro2, Euro3….) and anticipated g/km emission values.

As the emissions are calculated as specific emissions per driving distance, it is easy for the municipalities to estimate bus emissions just by multiplying specific emissions in g/km by driven distances. Figures 10 (NO_x) and 11 (PM emissions) summarise the emission trends found in the Finnish bus study (Braunschweig cycle). Both NO_x and PM emissions have a clear downward trend along with newer Euro emission standards, although certain bus models don't follow the general trend.

On average, a two-axle city bus requires approximately 1.8 kWh of work per km (on the crankshaft) over the Braunschweig cycle. The bars shown in the Figures are the certification limit values (in g/kWh) for the different emission classes converted to g/km by multiplying them by a factor of 1.8 to make the comparison with actual g/km values possible. One can note that for Euro 3 certified vehicles the average NO_x value (as g/km) matched very well with the scaled value (5 g/kWh * 1.8 kWh/km = 9 g/km). The solid part of the trend lines are based on measurements with diesel vehicles without exhaust after-treatment.

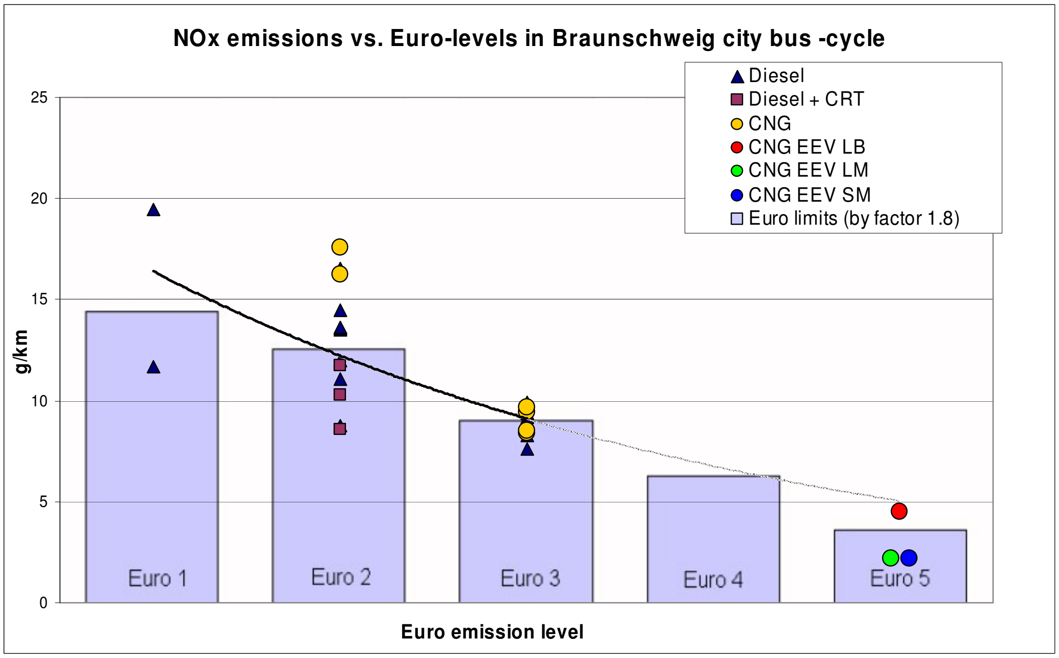

Figure 10. NO_x emission trends.

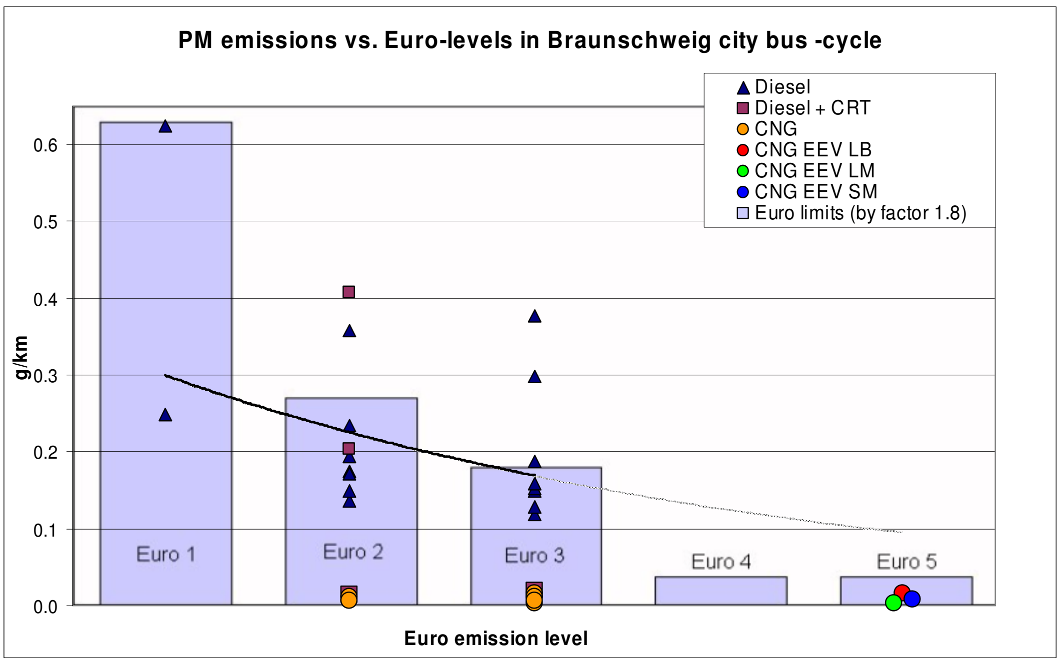

Figure 11. PM emission trends.

Results of older Euro 1 and Euro 2 buses spread significantly more than newer Euro 3 results as a consequence of higher mileage and inaccurate fuel metering in transient situations. CRTs reduce particles effectively even in older Euro 2 buses with high mileage. On the other hand, the CRTs seem to be vulnerable to poor maintenance or other failures. Both fully working and inactive individuals were measured (Figure 11).

CNG buses have, without exception, extremely low particulate emissions. NO_x for CNG vehicles generally follows the Euro certification class, hand in hand with corresponding diesels.

7 THE CNG BUS STUDY

7.1 General

The Finnish national bus project covers some CNG vehicles, from model year 1996 up to model year 2002. The additional IANGV funding made it possible to add three more CNG vehicles to the matrix, all of these certified for the most stringent European emission class, EEV. In addition, the IANGV involvement made it possible to expand upon the diesel vehicle measurements. Three diesel reference vehicles were chosen, all of the same brand and model but with different options for exhaust after-treatment: without after-treatment, with OEM oxidation catalyst and with OEM CRT particle filter.

Within the CNG bus study, altogether seven vehicles (three diesel buses and four CNG buses) were subjected to comprehensive emission testing.

The bulk of the measurements for the national bus project were carried out using the German Braunschweig bus cycle and the urban part of the ECE cycle used for passenger car emission certification. To give a more international dimension to the study, the testing was done using both the Braunschweig duty cycle and the US Orange Country duty cycle.

7.2 Test vehicles

Special effort was made to choose representative vehicles for the CNG part of the bus study. All seven vehicles (diesel and CNG) were commercially available, low-mileage vehicles representing model years 2002-2004. The vehicles were certified to Euro 3 or a more stringent emission class. Technical data of the vehicles is given in Table 5. For general reporting, the vehicles will not be identified by manufacturer or vehicle model. All vehicles tested were of European origin.

The Brand "B" EEV CNG vehicle was tested twice. When first tested, the NO_x emission was high. The reason was a combination of wrong gas quality setting and wrong transmission programming. The vehicle was later re-tested for regulated emissions at the expense of the vehicle manufacturer. The mileage of the vehicle when retested was 138,000 km, and the vehicle was still equipped with the original catalyst.

Table 5. *Technical data for CNG bus study vehicles.*

Identification	Brand	MY	Mileage (km)	Engine displ. (l)	Power (kW)	Comb. system	Exhaust after-treatment	Fuel system
Euro 3 diesel[1)]	C	2003	38 000	9.0	169	DI	w/o	electronic in-line pump
Euro 3 diesel+ OC[1)]	C	2003	27 600	9.0	169	DI	OC	electronic in-line pump
Euro 3 diesel+ CRT[2)]	C	2003	16 600	9.0	169	DI	CRT	electronic in-line pump
Euro 3 LB CNG+OC[3)]	A	2002	80 900	9.6	213	LB	OC	central injection
EEV LB CNG+OC[4)]	B	2002	31 000	12.0	185	LB	OC	central injection
EEV LM CNG+TWC[5)]	D	2003	42 000	12.8	228	LM	TWC	central injection
EEV SM CNG+TWC	E	2004	4 800	7.8	200	SM	TWC	multi-point injection

1) Same individual without and with oxicat. Exhaust components were aged to burn off storage grease and paint.
2) Vehicle equipped with OEM CRT (incl. insulated exhaust piping and modified engine calibration).
3) Because of high mileage, a new catalyst was installed (aged 2 weeks in normal service before the tests). A 184 kW engine version is also available.
4) For the first measurement, the vehicle was out of calibration (wrong gas quality setting, wrong transmission programming). The vehicle was retested later at 138,000 km (original catalyst).
5) This engine is primarily meant for 3-axle or articulated buses, measurements were made simulating the weight of a 2-axle vehicle.

One single diesel vehicle model was picked as the diesel reference. The vehicle is offered by the OEM in three versions: without exhaust after-treatment, with oxidation catalyst and with CRT particle filter. The same vehicle was tested both without and with oxidation catalyst. The idea of having a single diesel vehicle model as reference was that in this way the effect of the diesel exhaust after-treatment devices can clearly be demonstrated. It is important to notice that the CRT filter was installed by the manufacturer. The CRT equipped vehicle has an insulated exhaust pipe to keep the CRT temperature sufficiently high, and the calibration of the engine has been modified to enhance CRT performance.

All CNG engines were turbocharged. Two of the CNG vehicles were equipped with lean-burn (designation LB) engines and both had an oxidation catalyst. The third CNG vehicle was equipped with what the manufacturer calls a lean-mix combustion system (designation LM). On moderate load and speed, the turbocharged engine operates with stoichiometric mixture. In the high torque and/or high engine speed range the engine operates with lean mixture to reduce the thermal loads of the engine. The engine is equipped with a three-way catalyst. In lean conditions, the catalyst operates as an oxidation catalyst. Thus, in theory, NO_x emission of this engine is highly dependent on the engine load, as stoichiometric operation gives significantly lower NO_x emissions than lean operation. The fourth CNG engine was a stoichiometric engine with multi-point port fuel injection and TWC catalyst.

All vehicles were tested simulating the driving resistances of an ordinary two-axle city bus. The dynamometer settings are given in the part describing the test procedures.

7.3 Test fuels and lubricants

All diesel tests were carried out using the same batch of diesel fuel. Reformulated, low sulphur diesel fuel fulfilling the oncoming European 2005 specifications was used (Directive 2003/17/EC, Amending Directive 98/70/EC). The fuel batch was analysed for sulphur, and the sulphur content was 23 ppm.

The natural gas used in Finland originates from Siberia. The methane content is high, more than 98 %. The gas company Gasum Oy gives the following specifications for the gas:

- methane > 98 % (vol.)
- ethane < 1 %
- propane and other higher hydrocarbons < 0.5 %
- nitrogen < 1 %

No odorant is added to the gas, and the sulphur content of the gas is estimated to be less than 5 ppm (mass).

The vehicles were tested with the lubricants that were in the engines when received. All vehicles were subjected to normal service procedures specified by the manufacturer, but not especially serviced before the testing.

7.4 Test procedures and measurement equipment

All vehicle testing was carried out in the new heavy-duty test facility of VTT Processes, Finland. The new facility is equipped with a heavy-duty transient chassis dynamometer, a transient engine dynamometer, a full-flow CVS-emission system and versatile instrumentation for special emission analysis. Information on the facilities can be found at: http://www.vtt.fi/pro/pro3/pro31/indexe.htm

7.4.1 Chassis dynamometer measurements, general

VTT's new chassis dynamometer (manufactured by Froude Consine) has a roller diameter of 2.5 metres, and a power absorption capacity of 300 kW at the driving wheels (continuous). The dynamometer has a very fast control system and electric inertia simulation making dynamic (transient) testing possible. Inertia can be simulated in the range of 2 500 to 60 000 kg.

Emission certification for heavy-duty vehicles is performed by running stand-alone engines in engine dynamometers. Therefore, there are no official chassis dynamometer emission certification procedures. On the other hand, chassis dynamometer testing is used for light-duty vehicle emission certification.

At VTT, the need for an approved chassis dynamometer measurement procedure for heavy-duty vehicles was recognised. VTT developed its own in-house method based on existing elements (light-duty vehicles chassis dynamometer emission certification 70/220/EC, transient-type emission certification of heavy-duty engines 1999/96/EC, SAE J2711: Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles). In June 2003, the Finnish Centre for Metrology and Accreditation granted accreditation for VTT's method (T125, In-house method, VTT code MK02E). Figure 12 shows an emission test of a bus on the chassis dynamometer, including instrumentation for special emission analyses.

Figure 12. Emission testing of a bus on the chassis dynamometer.

7.4.2 Dynamometer calibration

The control system of the dynamometer makes it possible to freely simulate the driving resistance of any vehicle. All vehicles of CNG bus study were tested simulating the weight of the vehicle itself plus 50 % load. All vehicles were simulated as two-axle conventional city buses. As the CNG vehicles are slightly heavier than their diesel counterparts, this was taken into consideration. The same base coefficients and frontal area was used for all vehicles. Constant F0 coefficient and the inertia were adjusted regarding the mass of the vehicle.

The simulated inertias were:

- diesel vehicles 15 530 kg
- CNG vehicles 15 705 - 15 980 kg

Simulated total driving resistances are given in Table 6.

Table 6. Simulated total driving resistances.

Simulated driving resistances	F0	F1	F2	Inertia
	(N)	(N/(km/h))	$(N/(km/h)^2)$	(kg)
All diesels	963	15.071	0.0407	15 530
Euro 3 CNG+OC	991	15.071	0.0407	15 980
All EEV CNG	974	15.071	0.0407	15 705

In other projects, VTT has carried out coast-down measurements to establish representative driving resistance equations for various types of vehicles, and that data was now utilised to compile the resistance coefficients for the measurements.

7.4.3 Duty cycles

During the test, the driver follows a given speed vs. time profile. Two highly transient duty cycles were chosen, the European Braunschweig bus cycle and the US Orange County bus cycle. Table 7 presents data of the two cycles, and Figures 13 & 14 show the speed vs. time profiles. These two cycles were chosen so that the test results would be of relevance both for European and US parties.

However, the two cycles are quite similar, and the differences in emission results are rather small. The Orange County cycle has somewhat higher average load but somewhat milder accelerations than the Braunschweig cycle. As a consequence, the Orange County cycle gives slightly higher average fuel consumption (CO_2 emission). Further on, designations BSC (Braunschweig cycle) and OCC (Orange County cycle) will be used for the cycles.

Table 7. Data of the duty cycles.

	Length (km)	Duration (s)	Av. speed (km/h)	Max. speed (km/h)	Share of idle (%)
Braunschweig (BSC)	10.873	1740	22.5	58.2	25
Orange County (OCC)	10.526	1909	19.9	65.4	21

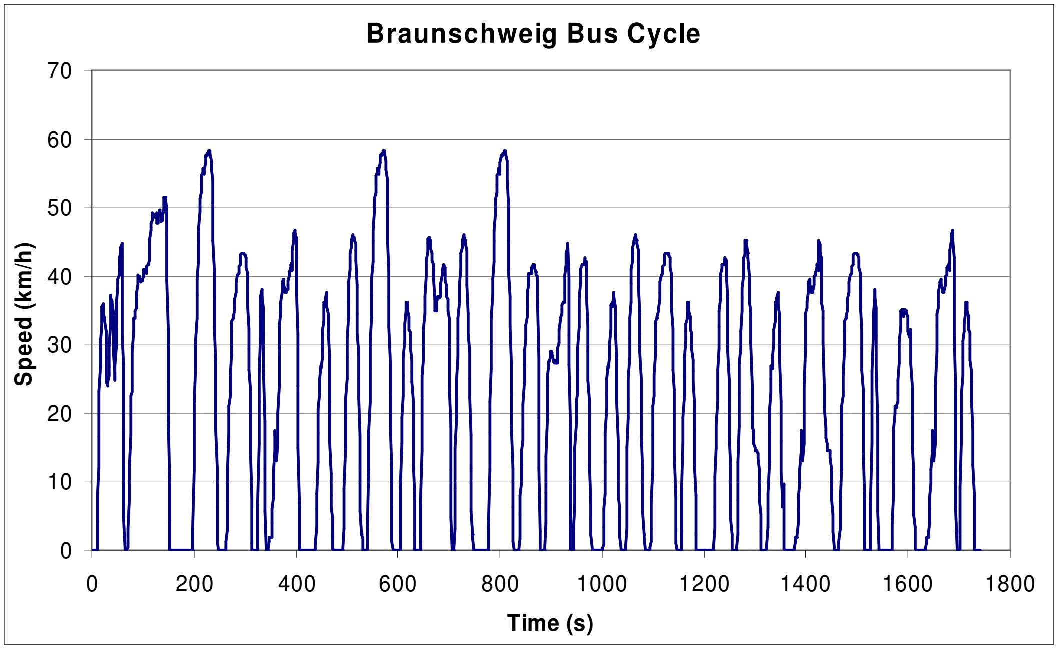

Figure 13. *Speed vs. time of the Braunschweig (BSC) bus cycle.*

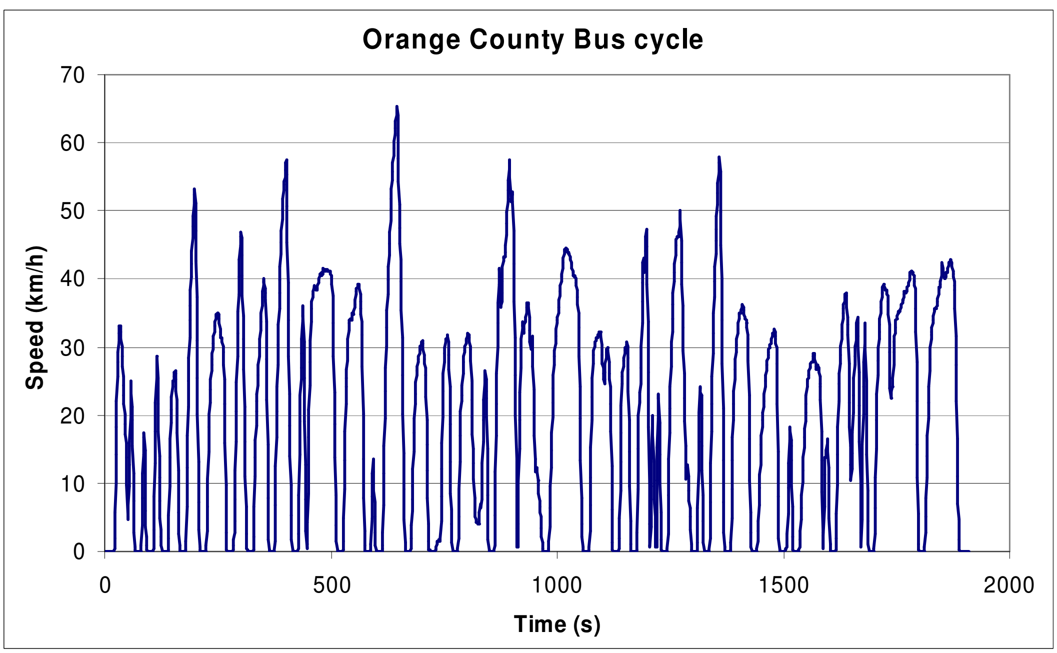

Figure 14. *Speed vs. time of the Orange County (OCC) bus cycle.*

7.4.4 Regulated emissions (CO, THC, NOx, PM)

The regulated emissions were measured using a full-flow CVS system (Pierburg CVS-120-WT) and an analyzer set (Pierburg AMA 4000) conforming to the requirements of Directive 1999/96/EC for the measurement of exhaust emissions of heavy-duty on-road engines. As the testing was made using transient driving cycles, the emission measurements were basically performed in the same way as for passenger car chassis dynamometer tests or transient ETC type engine tests.

For the measurements on the chassis dynamometer, the specific emissions were calculated per driving distance (g/km), whereas the results for an engine test are calculated per unit of work on the engine crankshaft (g/kWh).

Because the particulate emissions of natural gas-fuelled buses are extremely low, some measuring problems were encountered at the early stage of the project due to diesel soot carryover from the dilution tunnel. Therefore, a separate dilution tunnel, dedicated to gaseous fuel use only, was constructed and used for all gas-fuelled buses.

7.4.5 Particle size and number measurements

The sample for particle size and number measurements was taken from raw (undiluted) exhaust using a porous tube type partial flow diluter. The instantaneous dilution ratio was calculated using CO_2 tracing. Two different kinds of particle measuring instruments were used, an ELPI (Electric Low Pressure Impactor) instrument by Dekati Ltd and a CPC instrument by TSI Inc.

7.4.6 Unregulated components

A number of special emission analyses were also carried out. These measurements included:

Measurements of gaseous phase:

- hydrocarbon speciation up to C8-HCs (GC)
- aldehydes (DNPH sampling, HPLC)
- anions (capillary electrophoresis)
- nitrogen compounds (FTIR)

Measurements of semi-volatile phase:

- PAH compounds (collected in polyurethane foam, GC-MS (SIM))

Measurements of particle phase:

- PAH compounds (collected on filters, GC-MS (SIM))

- Ames mutagenicity of the particle matter (*Salmonella* strains TA98 –S9 and +S9)

The primary motivation for hydrocarbon speciation was to determine the methane part of the THC values, using gas chromatography. Individual TAC hydrocarbons were also analysed. For aldehydes, main attention was given to formaldehyde and acetaldehyde. The FTIR measurements were made to determine NO and NO_2 portions of the NO_x emissions.

Altogether some 30 PAH compounds were analysed (semi-volatile and particle phase). Seven of these compounds are considered to be especially harmful (priority PAHs). Nitro substituted PAHs were not analysed.

The Ames test is used as a bioassay for indicating a substance's short-term mutagenicity in the *Salmonella* bacteria cells. It has been an established and simple cell test for more than 20 years, but it is not a substitute for tests with animal or human cell lines or tests using living animals or epidemiological studies.

In the Ames test bacteria strains are subjected to extracts from the particle matter. The number of mutations in the bacteria is used as an indication of the mutagenicity of the particle matter. Different kinds of bacteria strains, responsive to different kinds of compounds can be used. The outcome of the Ames test is normally given in the form revertants/mass, typically krev/mg indicating specific mutagenicity of the material analysed. In this case, both specific mutagenicity and mutagenicity proportional to the driven distance (krev/km) are given. The latter takes into consideration both the specific mutagenicity of the particle matter and the amount of particle mass emitted.

8 RESULTS AND DISCUSSION

8.1 General

The results are presented in three main groups, regulated emissions, particle size and number measurements and unregulated components.

A comparison between diesel and CNG vehicles regarding regulated emissions is rather simple and straight forward. Based on the previous results from a relatively high number of different types of vehicles, it is also possible to make a judgement whether or not the emission performance of a new vehicle corresponds to what should be expected from its official emission certification class.

For the particle size and number measurements, and the measurements of unregulated components, comparisons are more complicated. For example, both PAH compounds and formaldehyde are known carcinogens. It is not, however, possible to create an unambiguous sum of harmful components. As the comparisons have to be made component by component, and all relevant components are not necessarily covered (e.g. nitro-PAH), it is not possible to give an all-embracing overall score for emission performance.

The Brand "B" lean-burn CNG vehicle was measured twice. The full spectrum of measurements was carried out for the first measurement, which resulted in high NO_x emissions. When recalibrated and tested for regulated emissions, the vehicle produced significantly lower NO_x emissions. For this vehicle, regulated emissions (CO, THC, NO_x, PM mass) and particle numbers for the second measurement and unregulated emissions for the first measurement are reported. The results of the special emission measurements were deemed valid, as they were in coherence with the results of the other lean-burn vehicle.

All results for regulated emission components are based on at least two parallel measurements.

The baseline diesel vehicle turned out to perform rather well compared with other Euro 3 diesel vehicles included in the National bus project. This is true for NO_x, PM and even fuel consumption.

8.2 REGULATED EMISSIONS AND CO_2 EMISSION

8.2.1 CO emissions

The results for CO are given in Figure 15. The CO emission of the diesel without after-treatment was some 1.3 g/km. Both the oxidation catalyst and the CRT particle filter effectively reduced the CO emission, by some 85 %.

The LB CNG vehicles had the same or even lower CO emission than the diesels with exhaust after-treatment. With CNG, LM combustion resulted in higher CO emission than LB combustion. The level of CO for LM was well below but for SM roughly twice as high compared with the baseline diesel. Despite of this, the SM CNG vehicle was well below (appr. 50 %) the EEV limit value for CO. Anyhow, as stated in 3.1 and confirmed by TNO, CO is of little importance. The duty cycle had little effect on CO emissions.

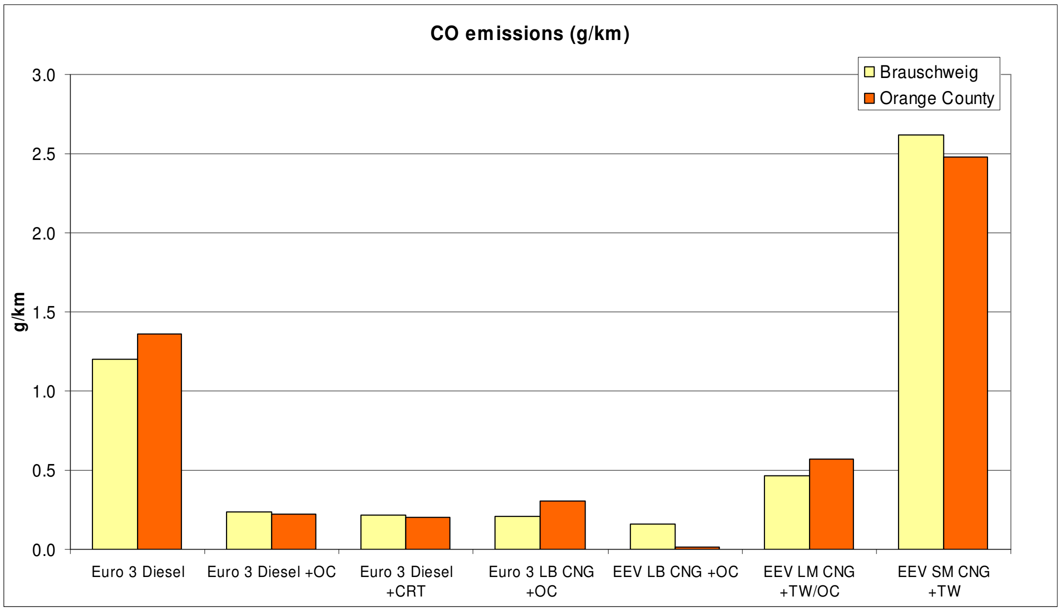

Figure 15. CO emission results.

8.2.2 THC and NMHC emissions

The results for THC and NMHC are given in Figures 16 and 17. In the case of diesel, the oxidation catalyst reduced THC by some 75 %. The CRT was even more effective, and the reduction was some 90 %. The THC values were within the range of 0.4 to 0.05 g/km. Among diesel buses, the NMHC part ranged from 85 % (without after-treatment) to some 30 % (with CRT) of the THC value. The CRT effectively reduced both THC and NMHC values.

As can be expected, the THC values with CNG were higher than with diesel. The THC values for CNG ranged from 0.25 to 2.0 g/km. The highest value was for the retested EEV LB vehicle. For this vehicle, THC had increased from some 1.2 to 2 g/km from 31.000 km to 138.000 km. The LM system performed quite well, and the THC value was around 0.2 g/km, i.e. roughly half of the value for the diesel without exhaust after-treatment. The THC emission of the SM CNG vehicle was higher than expected. One reason for this could be that the catalyst of this vehicle was placed on top of the roof, and the long distance from engine to catalysts cools off the exhaust preventing the catalyst from operating optimally.

Regarding driving cycles, OCC gave higher THC values than the BSC for all vehicles with the exception of the baseline diesel.

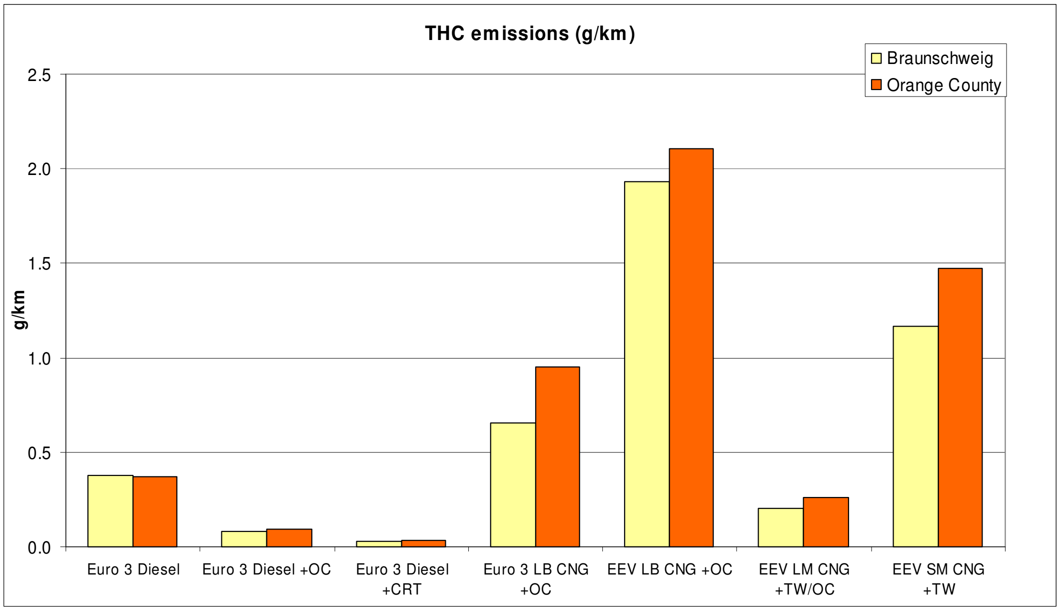

Figure 16. THC emission results.

The NMHC portion in the exhaust of the CNG vehicles was low, some 2 % of the THC value. This means that some 98 % of the hydrocarbon emission was methane (Figure 17). The level of NMHC for both diesel with CRT and CNG was below 0.01 g/km, with the exception of the retested EEV LB vehicle, which had a NMHC value of 0.03 g/km.

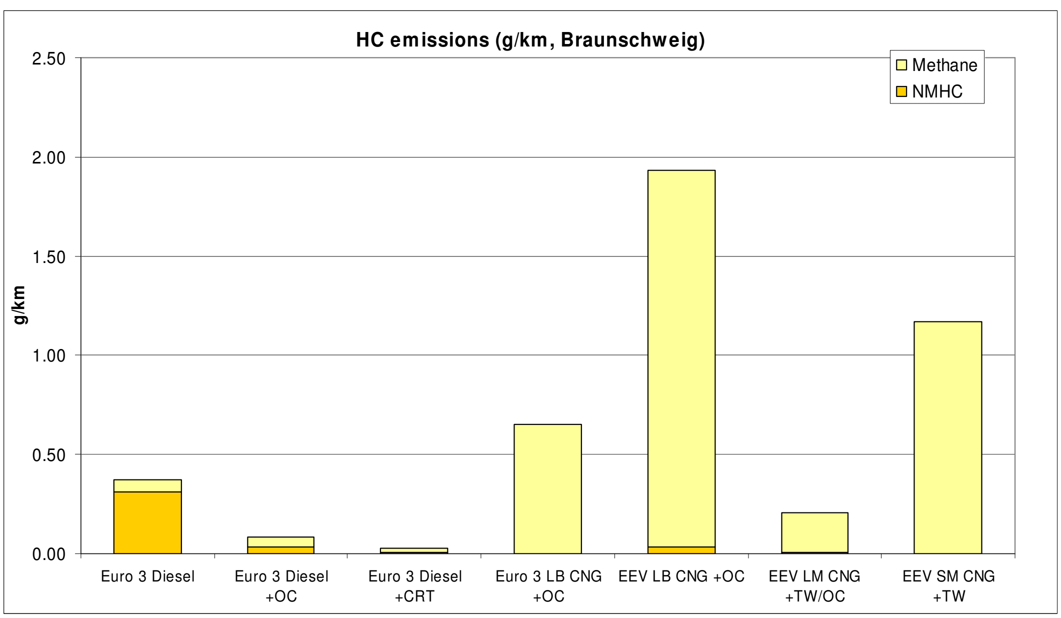

Figure 17. THC and NMHC emission results (BSC).

8.2.3 NOx emissions

Figure 18 presents NO_x emissions. For the diesel vehicles NO_x emission was around 8...9 g/km, with slightly higher values for the OCC than for the BSC, and even slightly higher values with than without exhaust after-treatment. The NO_x value for the Euro 3 certified LB CNG vehicle was around 9 g/km.

Figure 18 shows the NO_x value for the EEV certified LB CNG vehicle when retested. The value is roughly 50 % compared with the diesel vehicles. The LM and SM CNG vehicles gave superior NO_x performance, the value being some 2 g/km. Simulated as a three-axle vehicle, the NO_x value for the LM engine was around 3 g/km.

Exhaust after-treatment affects the ratio of NO_2 to NO_x (Figure 19). The CRT equipped diesel had the highest absolute and relative NO_2 values, 0.8 g/km and 10 %, respectively. The corresponding values for the baseline diesel were 0.14 g/km and 2 %. For oxidation catalyst equipped vehicles (diesel and CNG) the share of NO_2 was 4...5 %. For the LM and SM CNG vehicles the NO_2 emission was practically non-existent. (Effects on NO_2 see 3.3. and 5.5).

Although the CRT equipped diesel gave the highest NO_2 emissions in both absolute and relative terms, the result for this particular vehicle was significantly better than some other reported results, with NO_2 shares of up to 50 % of total NO_x.

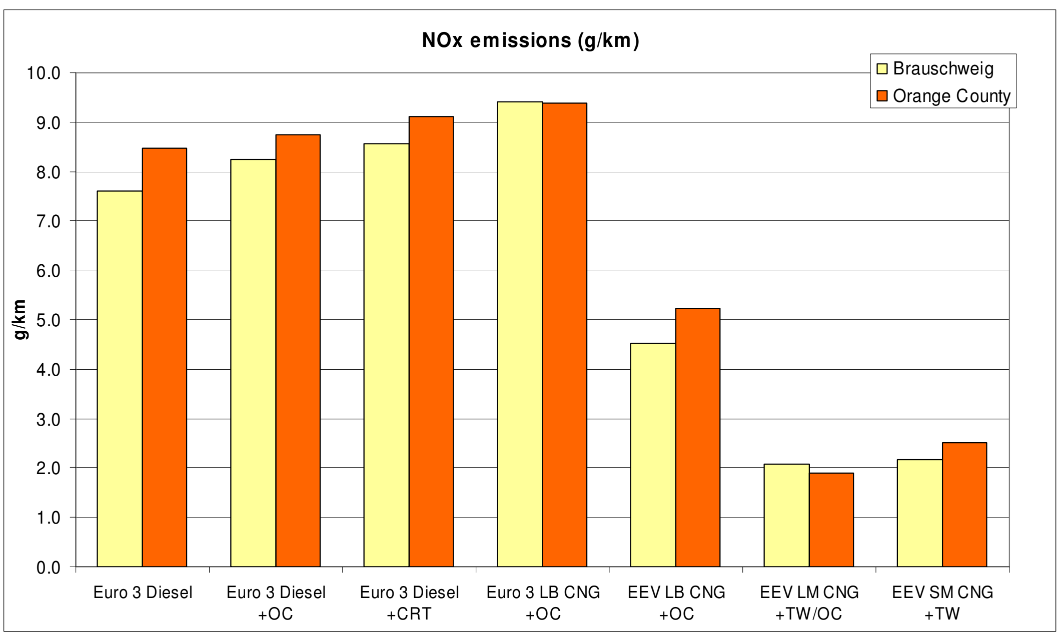

Figure 18. NO_x emission results.

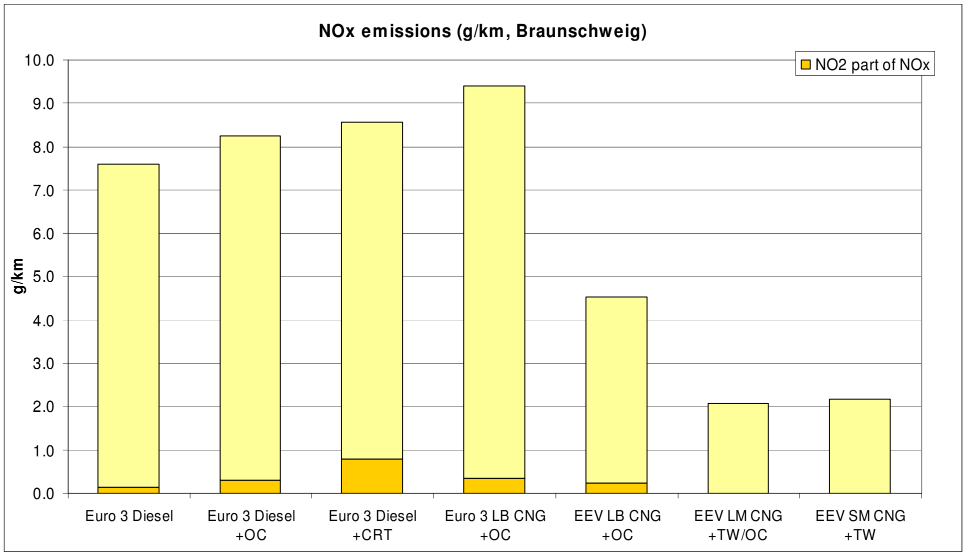

Figure 19. NO_x and NO_2 emissions (BSC).

8.2.4 PM emissions

Figure 20 presents PM emissions. This is the emission category for which the biggest differences can be found. The values were within the range of 0.2 (diesel without after-treatment) to 0.002 (LM CNG). The oxidation catalyst on the diesel reduced PM by some 20...30 % and the CRT filter by some 90 %. In general, the CRT diesel and all CNG vehicles provide excellent performance regarding PM mass. Three of four CNGs gave lower PM mass emissions compared to the CRT equipped diesel. In the CNG category, the retested LB EEV vehicle had the highest PM mass emission, equivalent to the CRT diesel.

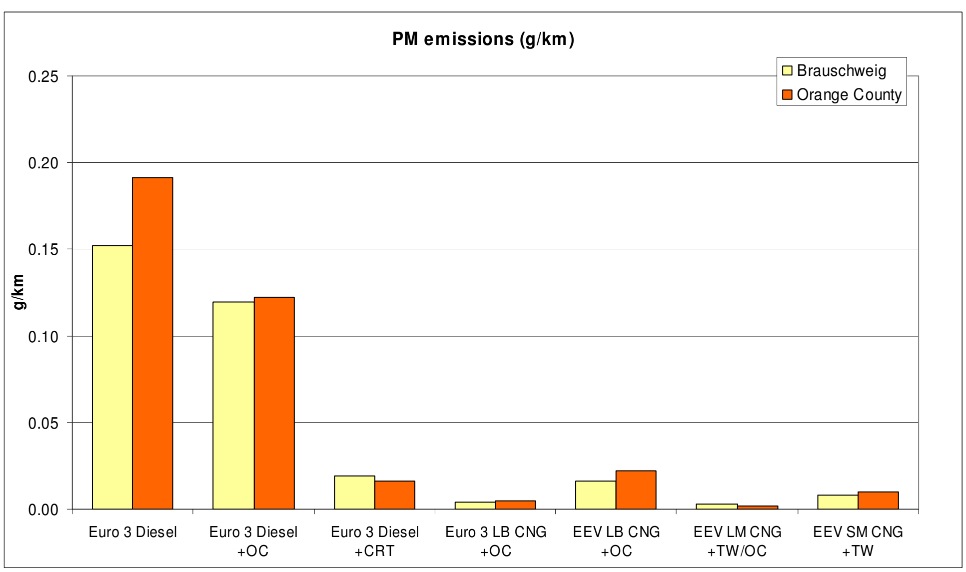

Figure 20. PM emission results.

8.2.5 CO2 emissions

Figure 21 presents tailpipe CO_2 emissions. The average CO_2 emission was 1224 g/km for the diesel vehicles and 1308 g/km for the CNG vehicles. The lowest and highest values were found within the CNG category, 1077 g/km for the EEV certified SM CNG vehicle and 1512 g/km for the EEV certified LB vehicle. Recalibration reduced NO_x but increased CO_2 emissions for the EEV LB vehicle. It is often claimed that lean-burn combustion is more fuel efficient than stoichiometric combustion. This study demonstrated the opposite. However, it should be noted that the SM engine was a new design, with rather small displacement (7.8 litre), benefiting from engine downsizing.

The diesel vehicle with CRT filter consumed some 10 % more fuel than the vehicle without exhaust after-treatment. Low particle emissions do not come without cost. Compared with the CRT equipped diesel, the CNG vehicles produced, on average, some 3 % more CO_2.

All vehicles consumed more fuel and therefore produced more CO_2 emissions in the OCC than in the BSC. The average difference was some 5 %, and the results were consistent for all measurements.

The methane emission of all CNG vehicles was low. Even if the methane emission was multiplied by a factor of 20 and added to the CO_2 emission value to describe total greenhouse gas effects, this would not have changed the outcome of the comparison.

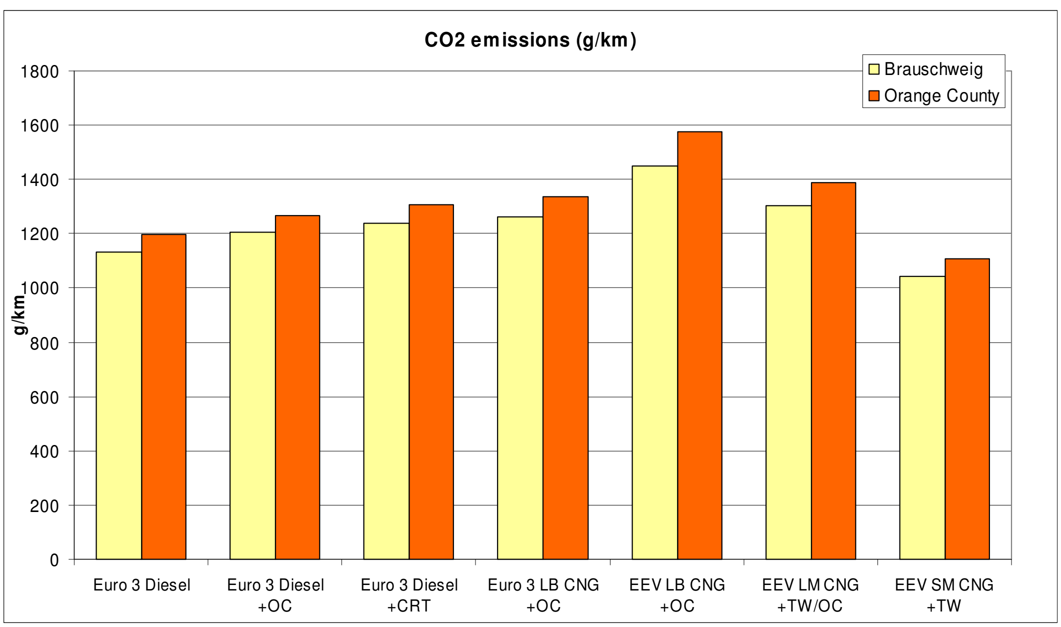

Figure 21. CO_2 emission results.

8.2.6 Retest of the LB EEV vehicle

Figure 22 presents a comparison of the regulated emissions of the LB EEV CNG vehicle for the first measurement and for the retest.

Recalibration and an additional 100,000 km in mileage reduced NO_x emissions some 60%, but at the expense of increased fuel consumption (+ 35%). The increase in other emissions (CO, THC, PM) can best be explained by somewhat reduced catalyst efficiency, the increase in THC also by a leaner mixture leading to higher engine-out THC emissions.

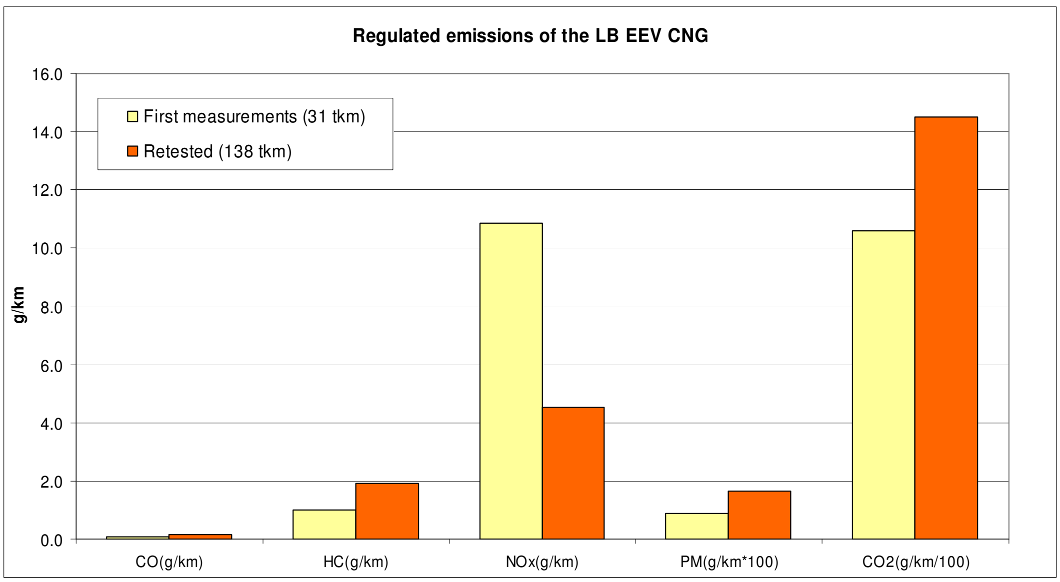

Figure 22. Test results for the LB EEV vehicle (BSC).

8.2.7 Summary

Regarding regulated emissions, no abnormalities were found. All vehicles performed as could be expected. All vehicles measured for the Finnish national bus project, including the CNG bus study vehicles, are plotted in Figures 10 (NO_x) and 11 (PM). Independent of age and mileage, all CNG vehicles tested give very low PM emissions. The Euro 3 certified CNG vehicle included in the test matrix gives equivalent NO_x performance compared with Euro 3 diesel vehicles. For NO_x, two of the three EEV CNG vehicles tested clearly fulfilled Euro 5 or EEV criteria. The EEV LB vehicle was not as good as the vehicles using stoichiometric combustion (fully or partly), but came very close to real EEV performance when tested dynamically on the chassis dynamometer.

The group of CNG vehicles showed both the lowest and highest CO_2 values. Somewhat surprisingly, the lowest CO_2 emission was recorded for the stoichiometric EEV CNG vehicle. On average, CRT diesel and CNG gave roughly equivalent CO_2 emissions. Figure 23 shows a comparison of NO_x and CO_2 values for all CNG bus study test vehicles. As the Figure presents two data points for each vehicle (two parallel measurements, three in the case of the CRT diesel), it also gives an indication of the repeatability of the tests.

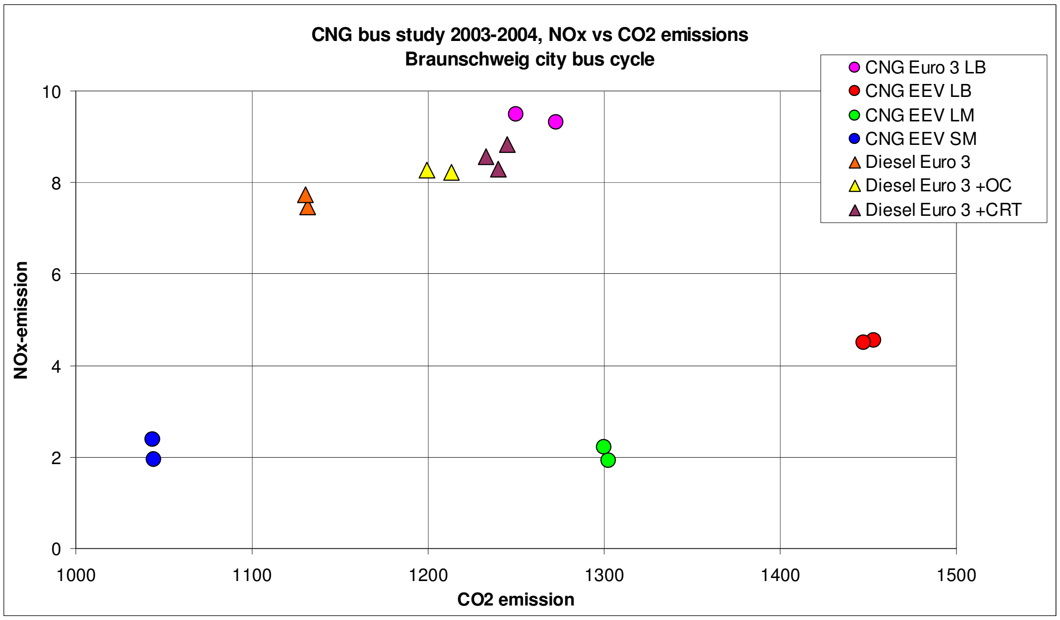

Figure 23. NO_x and CO_2 emissions (BSC).

8.3 Special emission measurements

8.3.1 Particle size and number

The results shown here are based on measurements with the ELPI (electrical low-pressure impactor) instrument. Please note that some of the Figures have a logarithmic scale.

Figure 24 presents particle number size distribution over the BSC and OCC duty cycles. Compared with the baseline diesel, the number of particles was reduced by two orders of magnitude both with CRT and three of the four CNG vehicles (lower group of traces in Figure 24). Particle numbers for the best vehicles are rather close to the particle numbers found in ambient air.

The fourth CNG vehicle, EEV SM, had particle numbers roughly one order of magnitude lower than the baseline diesel, but one order of magnitude higher than the other CNG vehicles. For this particular brand, Brand "E", TNO found a similar phenomenon in their test (see Figure 9). There are three possible explanations, oil consumption behaviour of the engine, catalyst performance, or both together. For the measurements at VTT, catalyst performance is the most probable one. As mentioned in 8.2.2, the catalyst was mounted on the roof. Low temperature might hinder the reduction of small oil droplets.

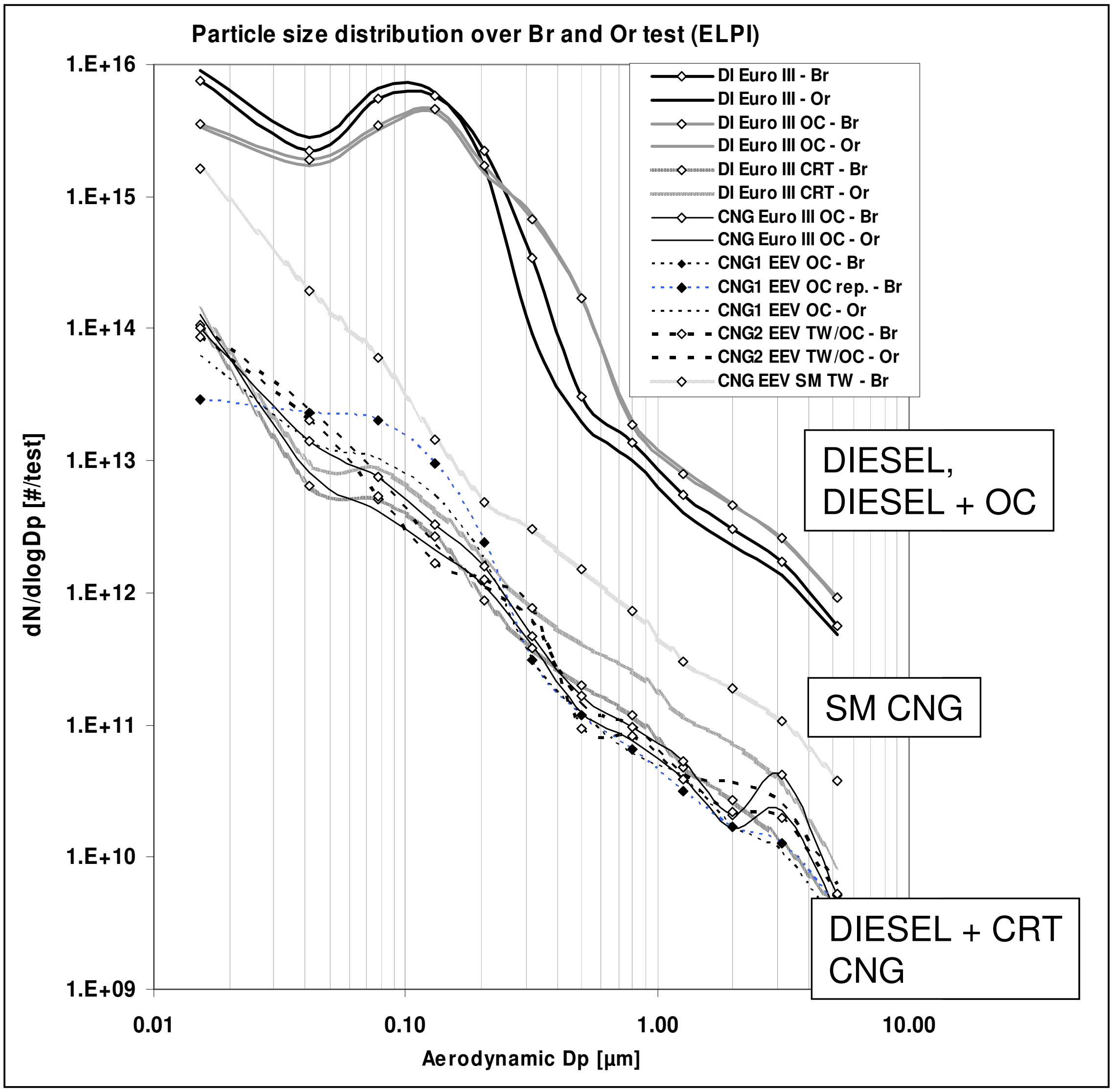

Figure 24. Particle number size distribution.

For the baseline diesel and diesel with catalyst, a clear particle accumulation mode peak was found around 100 nm. The catalyst was able to reduce particle numbers somewhat in the smallest categories. The re-test of the LB EEV CNG vehicle also shows a slight tendency to accumulation mode particle formation.

It is worth noticing that the particle size distribution curves are, on the log-log scale, rather linear for both CRT diesel and CNG. This means, for example, that the CRT filter effectively removes particles of all size classes and that no abnormalities regarding nanoparticles can be found either for CRT diesel or CNG. Regarding particle numbers, the SM EEV vehicle would most probably benefit from a hotter catalyst.

Figure 25 shows total numbers of particles in size classes below 60 nm (nanoparticles, aerodynamic size < 60 nm) and particles above 60 nm. The reduction in nanoparticles going from diesel without after-treatment to diesel with CRT or CNG is two orders of magnitude, with the exception of the SM EEV CNG vehicle. On average, CNG produced almost equivalent numbers of nanoparticles compared with CRT diesel.

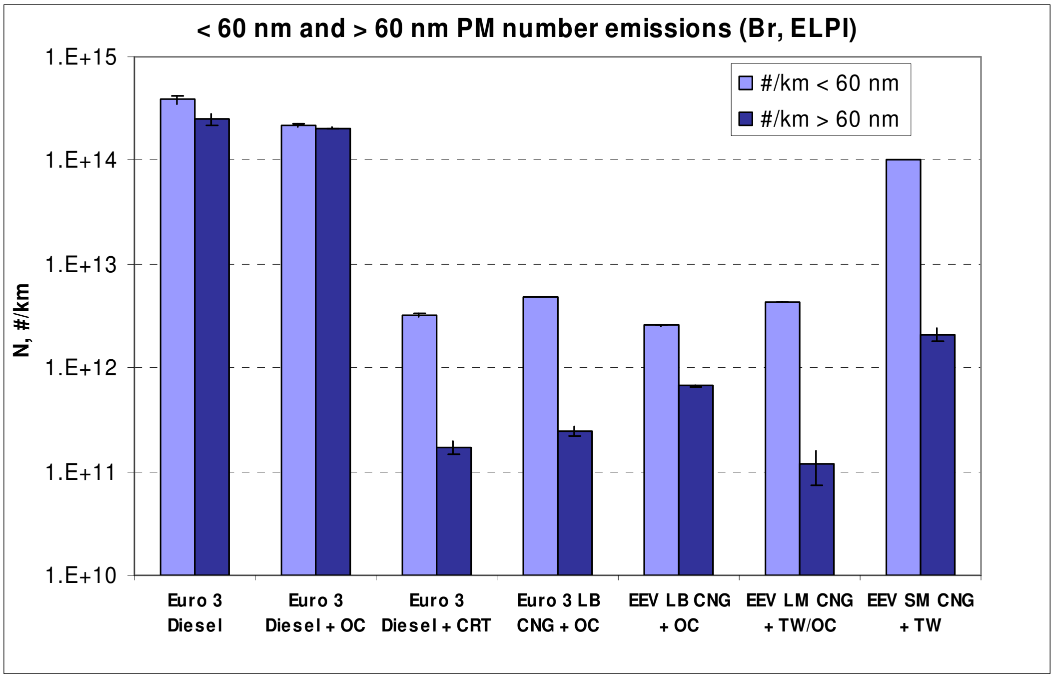

Figure 25. Particle number emissions (D_a < 60 nm, D_a > 60 nm, BSC).

Figure 26 shows the driving speed trace (at the bottom of the graph) and the instantaneous particle flux. The technologies presented in this Figure are diesel without after-treatment, diesel with oxidation catalyst, diesel with CRT filter and LB CNG. As in the case of Figure 24, the traces fell into two distinct groups, diesel and diesel with oxidation catalyst in the high region and CRT together with CNG in the low region.

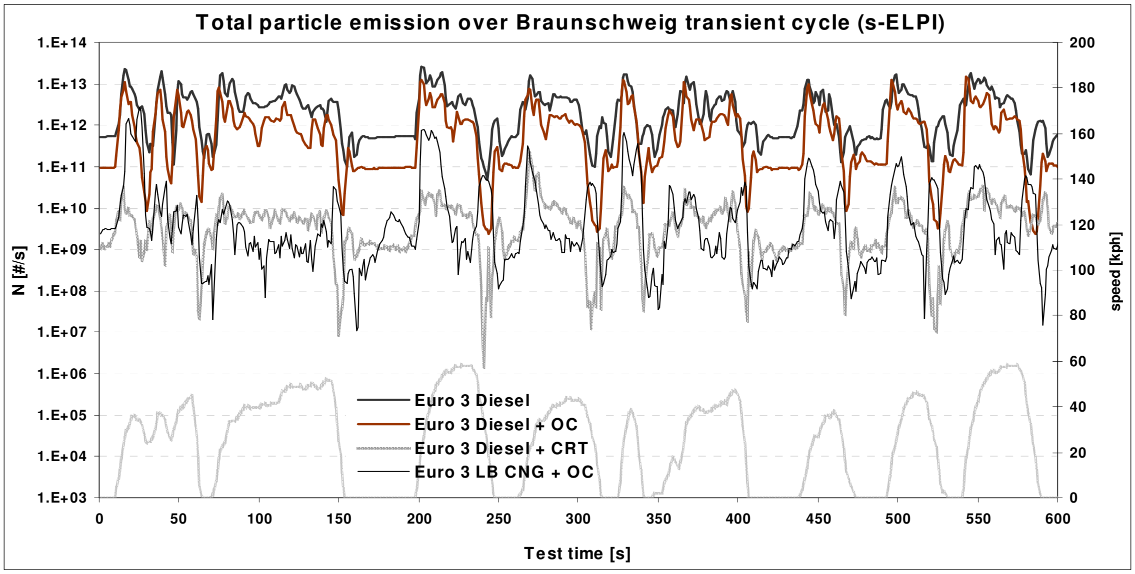

Figure 26. Instantaneous particle flux for diesel without after-treatment, diesel with oxidation catalyst, diesel with CRT and LB CNG (BSC).

8.3.2 Hydrocarbon speciation

Table 8 presents 12 hydrocarbons speciated by gas chromatography. In the case of the EEV LB CNG vehicle, the analysis was made for the first measurement. This explains why the methane emission is significantly lower than in Figure 17.

Table 8. Speciated hydrocarbons (BSC).

	Methane mg/km	Ethane mg/km	Ethene mg/km	Propane mg/km	Propene mg/km	Acetylene mg/km	Isobutene mg/km	1,3-Butadiene mg/km	Benzene mg/km	Toluene mg/km	Ethylbenzene mg/km	Xylenes mg/km
Euro 3 diesel	16	0	35	0	19	4	7	8	3	1	0	0
Euro 3 diesel +OC	5	0	0	0	2	0	2	0	1	0	0	0
Euro 3 diesel +CRT	18	0	0	0	0	0	2	0	1	7	0	0
Euro 3 LB CNG +OC	526	0	0	0	0	0	0	0	0	0	0	0
EEV LB CNG +OC	731	0	0	0	0	0	3	0	0	10	0	0
EEV LM CNG +TW/C	167	0	0	0	0	0	2	0	0	0	0	1
EEV SM CNG +TWC	1397	0	0	0	0	0	0	0	0	0	0	0

Of these components, 1,3-butadiene, benzene, ethylbenzene, toluene and xylene are listed on EPA's MSAT list. 1,3-butadiene can only be found in the exhaust of the baseline diesel without exhaust after-treatment. The exhaust of the baseline diesel also contains some benzene, traces of which can also be found in the exhaust of the diesels with after-treatment. For some reasons the CRT diesel and one of the CNG vehicles produced measurable amounts of toluene. For the other CNG vehicles all values for 1,3-butadiene, benzene, and toluene are nil. The emissions of ethylbenzene and xylenes are nil for all vehicles (with the exception of traces of xylenes in the exhaust of one of the CNG vehicles).

8.3.3 Aldehydes

Figure 27 presents form- and acetaldehyde emissions for all tested vehicles. The values were at maximum with diesel without after-treatment, 37 and 14 mg/km respectively. The oxidation catalyst reduced the values by some 50 %, the CRT filter by some 85 %. The LB CNG vehicles gave on an average the same formaldehyde emission as CRT, some 5 mg/km. For the LM and SM CNG vehicles aldehyde emissions were practically nil.

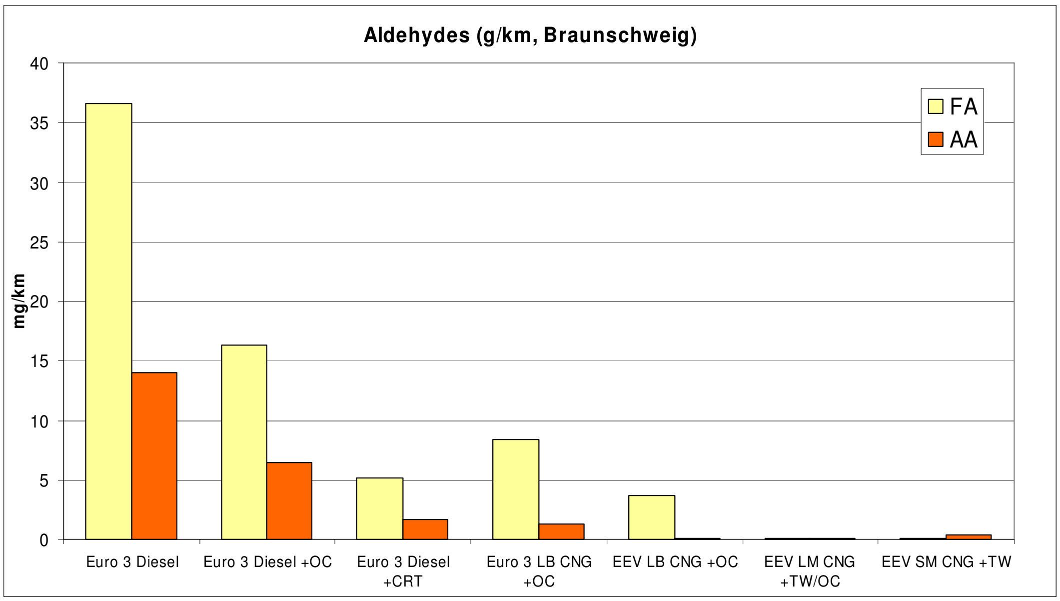

Figure 27. Form (FA)- and acetaldehyde(AA) emissions (BSC).

8.3.4 PAH emissions

Figure 28 shows the emission of individual PAH components (both semi-volatile and particle phase), from naphthalene to coronene, over the BSC for all seven vehicles. The scale in this Figure is logarithmic. In this case, three emission levels were formed, especially for the lighter, fuel derived PAH compounds: at the highest level were diesel and diesel with oxidation catalyst, at the lowest level CNG, whereas diesel with CRT was found in between. The CRT filter effectively reduced light-end PAHs.

Unlike diesel fuel, natural gas (methane) does not produce PAHs, neither light-end nor heavier PAHs. The PAH compounds found in CNG exhaust are engine oil derived heavier components. Figure 28 shows that the concentrations of the heavy-end PAHs were more or less the same with CRT and CNG. The EEV SM CNG vehicle stands out with low overall PAH emissions, and close-to-zero emission of 2-3 ringed PAHs.

Figure 29 presents the sums of different groups of PAH compounds (linear scale). Included are 7 known or suspected mobile source carcinogenic (priority) PAH compounds listed by EPA and IARC:

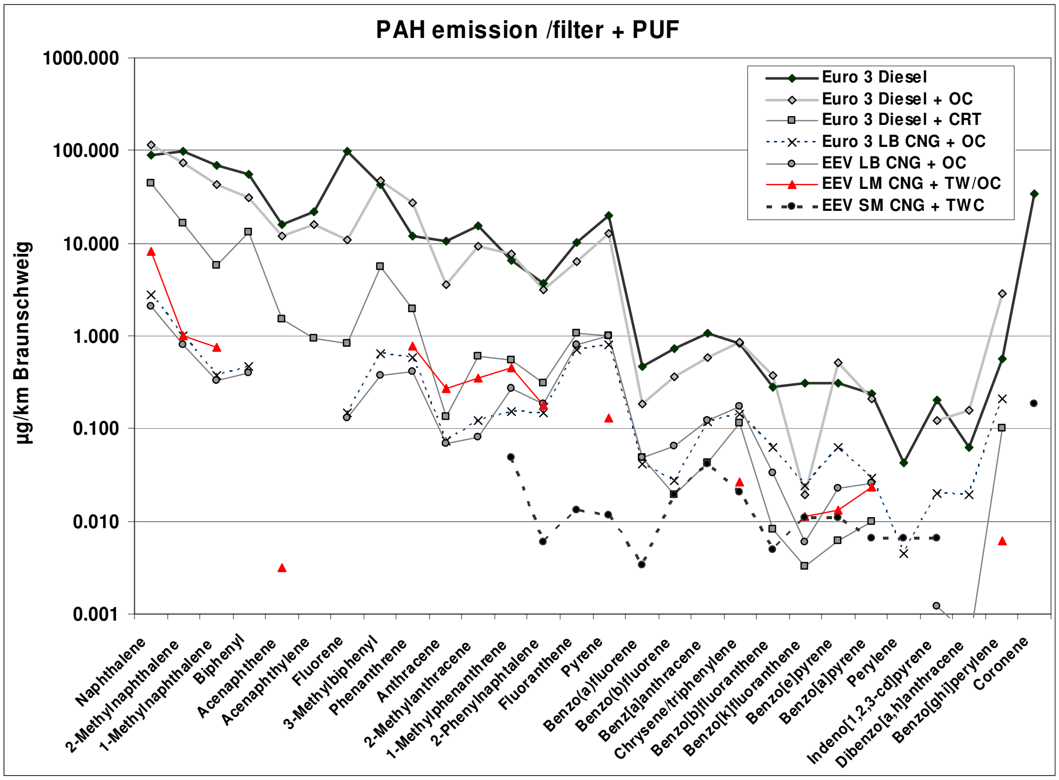

Figure 28. The emission of individual PAH compounds (BSC).

- Benz[a]anthracene
- Chrysene
- Benzo[b]fluoranthene
- Benzo[k]fluoranthene
- Benzo[a]pyrene
- Indeno[1,2,3-cd]pyrene
- Dibenzo[a,h]anthracene

The CRT effectively reduced PAH compounds in all categories. The reduction in priority PAHs was even 94 %. Compared with CRT, the LB CNGs gave slightly higher priority PAHs, equivalent +4 ringed PAHs and significantly lower 2-3 ringed PAHs.

Both the LM and the SM CNG vehicle showed outstanding performance regarding PAH emissions.

Compared with the CRT diesel the emission of both 2-3 ringed and +4 ringed PAHs is one order of magnitude smaller. The emission of priority PAHs is 50...70 % lower.

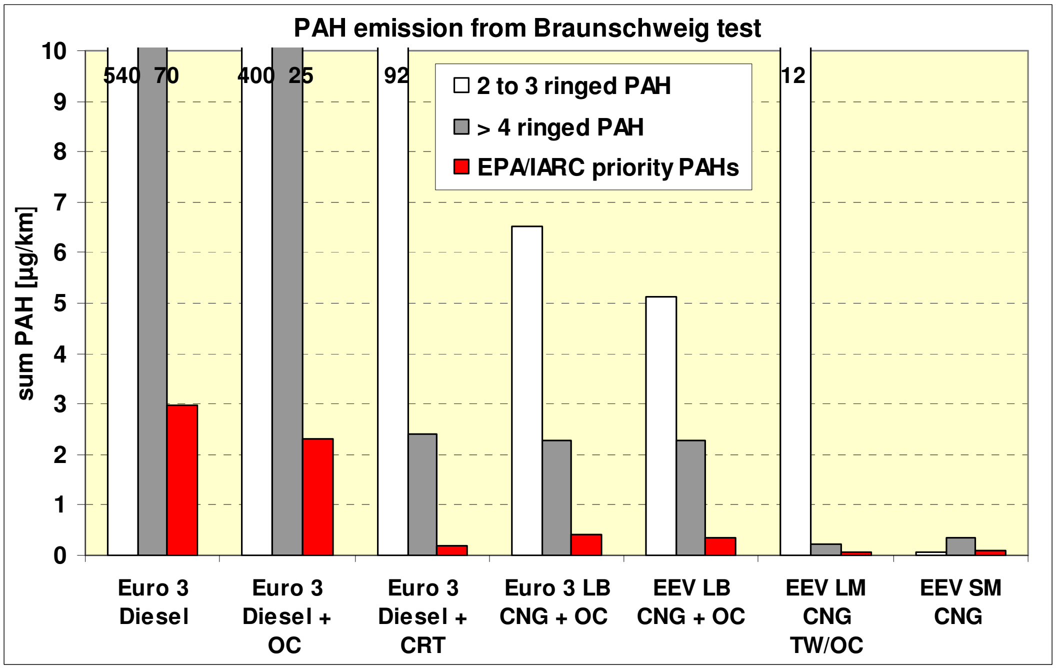

Figure 29. Sum of PAH compounds (BSC).

8.3.5 Exhaust mutagenicity

The results of the Ames tests are shown in Table 9. The Ames testing was made from solid particle matter collected on filters. With the baseline and OC diesels sufficient particle mass could be collected for testing with two bacteria strains, T98-S9 and T98+S9. Testing of the low-emission vehicles had to be limited to one strain only (T98-S9). Semivolatile components were not taken into account, since semivolatile components normally are less toxic than solid particle matter. The results of two parallel analyses are given for diesel without after-treatment and three parallel analyses for diesel with CRT. The results are given both calculated as rev/mg and krev/km.

Looking at the rev/mg values it can be concluded that the particle matter from CRT has the highest mutagenicity, on average some 1 100 rev/mg. This might be related to formation of nitro-PAH in the CRT filter, as the CRT filter contains a very effective oxidation catalyst to promote soot oxidation (the NO_2 emissions were also at maximum with CRT). The value for diesel without after-treatment is some 400 rev/mg, and the average value for CNG some 300 rev/mg. The diesel results were in line with the results of McGill et al. (2003).

Calculating the values to krev/km values means taking into account both specific mutagenicity and particle mass emission. The average value for CNG was less than 2 krev/km. The corresponding value for CRT was 25 and for diesel without after-treatment 60 krev/km. The DOC even increased mutagenicity, as the value was 85 krev/km. Both bacteria strains react in the same way on diesel exhaust. Figure 30 presents a graphic representation of the Ames mutagenicity results.

Table 9. The results of the Ames tests.

Bus type	PM g/km	Ames			
		rev/mg		krev/km	
		TA98-S9	TA98+S9	TA98-S9	TA98+S9
Euro 3 Diesel	0.151	382	363	58	55
Euro 3 Diesel	0.153	402	339	62	52
Euro 3 Diesel + OC	0.120	708	714	85	86
Euro 3 Diesel + CRT	0.0225	1344	-	30	-
Euro 3 Diesel + CRT	0.0185	1240	-	23	-
Euro 3 Diesel + CRT	0.0185	847	-	16	-
Euro 3 LB CNG + OC	0.0045	240	-	1	-
EEV LB CNG + OC	0.0070	693	-	5	-
EEV LM CNG TW/OC	0.0028	154		< 1	-
EEV SM CNG TWC	0.0088	146		1	-

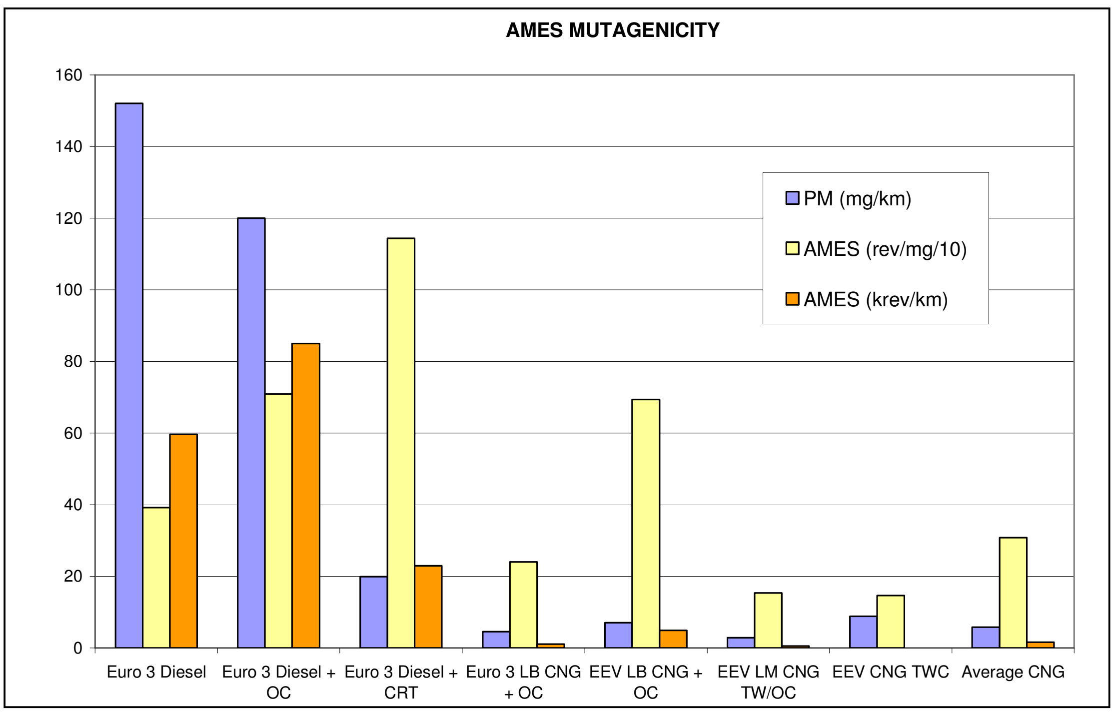

Figure 30. Graphic presentation of the Ames mutagenicity results (TA98-S9, BSC).

9 COMPARISON OF RESULTS

In general, the results obtained at VTT are much more favourable for natural gas than results of certain other studies. This is mostly due to the fact that some other studies have unfairly compared diesels equipped with exhaust after-treatment with CNG vehicles without catalysts. It is evident that all technologies benefit from effective exhaust after-treatment.

In the study at VTT, the best available European diesel technology was compared with the best available European CNG technology. Table 10 presents a comparison of the results of VTT's, ARB's and International's studies.

The VTT results for CNG vehicles are grouped into two categories, lean-burn and stoichiometric technology (the latter group includes the lean-mix technology). As for the ARB study, the results of the catalyst equipped CNG vehicles are combined. The results have to be considered indicative, as there are differences in the duty cycles used for testing. There might also be differences in individual compounds included in the sum of PAHs.

It can be noted that the general coherence is relatively good for many of the components. In the case of DPF equipped diesel, rather similar results have been obtained (PM 0.02/0.01/0.01, formaldehyde 5/3/5, 1,3-butadiene 0/0/1, benzene 1/0.4/0, PAHs 94/90/n.a., mutagenicity 23/20/n.a). The biggest differences can be found in the NO_2/NO_x ratio, 10 % for the measurements at VTT and roughly 50 % for the US studies).

Stoichiometric combustion, which is not used for heavy-duty vehicles in the US, gave the best results in the VTT study. On the other hand, a heavy-duty CNG vehicle without catalyst is not an option in Europe. In the case of CNG vehicles, lean-burn oxidation catalyst equipped CNG represents the common denominator. For this technology there are differences in the results of VTT and ARB for formaldehyde, sum of PAHs and mutagenicity. ARB' study shows higher values for these parameters

The results indicate that there are no big discrepancies in the measurements and analysis as such. The biggest differences arise from the choice of vehicles and how the results are interpreted.

Table 10. Comparison of results.

Study/ Component	NO_x (g/km)	NO_2 (g/km)	PM (g/km)	Formaldehyde (mg/km)	1,3-butadiene (mg/km)	Benzene (g/km)	PAHs (µg/km)	Mutagenicity PM phase (krev/km)
VTT								
Diesel w/o	8	0.1	0.17	37	8	3	613	59
Diesel OC	8.5	0.3	0.12	16	0	1	427	85
Diesel CRT	9	0.8	0.02	5	0	1	94	23
LB CNG OC	7	0.3	0.01	6	0	0	8	3
SM CNG	2	0.05	0.005	0.1	0	0	7	1
ARB								
Diesel OC	19	-	0.08	?	0	2	250	100
Diesel DPF	20	10	0.01	3	0	0.4	90	20
LB CNG w/o	11	-	0.02	500	1	2	110	250
LB CNG OC	8	-	0.01	30	0	0.6	30	50
International								
Diesel w/o	9	1	0.12	25	0	3	-	-
Diesel DPF	6	3	0.01	5	1	0	-	-
LB CNG w/o	10	1	0.03	300	3	3	-	-

10 CONCLUSIONS

Seven modern buses, three diesel and four CNG vehicles, were tested for emission performance. The measurements included regulated emission components and a number of speciality measurements. Two different duty cycles were used, the European Braunschweig cycle and the US Orange County cycle. It turned out that both cycles gave practically identical results, with the exception of CO_2, which was slightly higher in the Orange County cycle.

A CRT type particle filter improves the emission performance of a diesel vehicle in many ways, including significantly reduced emissions of PM mass, particle numbers, PAHs and aldehydes. However, there are also drawbacks associated with CRTs, e.g., increased fuel consumption and increased direct emission of NO_2. The increase in direct NO_2 emission was, however, smaller than seen in some other studies.

Natural gas is a fuel with many advantages. Methane is not toxic, and the combustion of methane is free from soot. It is often claimed that CNG gives significant benefits for both PM and NO_x emissions. The first statement is certainly valid, even for vehicles that have accumulated a lot of mileage. In terms of NO_x, the LB CNGs are not necessarily superior to diesel. However, CNG engines using stoichometric or mixed combustion demonstrated NO_x levels 75 % below Euro 3 diesel levels.

The current heavy-duty CNG engines are spark-ignition engines operating on the Otto cycle. For this reason, the thermal efficiency of gas engines is lower than for diesels. Fuel chemistry, with less carbon and more hydrogen in natural gas than in diesel fuel, compensates for the lower efficiency resulting in almost equal tailpipe CO_2 emissions for CNG and diesel. A common view is that lean-burn combustion is more fuel efficient than stoichiometric combustion. However, in the category of CNG vehicles, the full-time stoichiometric vehicle demonstrated the best fuel efficiency, with a tailpipe CO_2 emission lower than for the diesels.

When striving for low emissions, the comparison or choice of vehicles should be made between CRT equipped diesel vehicles running on high-quality diesel fuel and sophisticated catalyst equipped CNG vehicles. None of the conducted measurements or analyses pointed out clear drawbacks of CNG technology versus diesel plus CRT.

Table 11 presents a comparison of performance between diesel CRT and stoichiometric CNG for all items covered in the CNG bus study (combined performance of the LM and SM CNG vehicles using stoichiometric combustion).

Table 11. Comparison between CRT diesel and CNG.

Emission component	Significance of component *)	Diesel CRT	CNG SM
CO	low	lower	
THC	low	lower	
NMHC	high/moderate	similar	similar
NO_x	moderate		much lower
NO_2	high		much lower
PM mass	high		lower
CO_2	moderate	similar	similar**)
Engine efficiency	moderate	better	
Total particle numbers	high	similar	similar***)
Nanoparticle numbers	high	similar	similar***)
Total PAH	high/moderate		much lower
Carcinogenic PAH	high		lower
Mutagenicity	high		much lower
Aldehydes	high		much lower

*) For urban buses, giving priority to toxic emissions
**) Lower for SM, higher for LM
***) Similar for the LM vehicle, higher for the SM vehicle with roof mounted catalyst

Figure 31 shows a graphic comparison for diesel without after-treatment, diesel with CRT and LM CNG. The worst result for each category is set at 100. The properties considered are NO_x, NO_2, CO_2, mutagenicity (Ames), formaldehyde, particle mass, nanoparticle numbers (PM #), carcinogenic PAH and NMHC.

CRT diesel is slightly worse compared with the baseline diesel for NO_x and CO_2, but significantly worse for NO_2. In all other respects the CRT diesel is significantly better than the baseline diesel. With the exception of CO_2, LM CNG is better than or similar to the CRT diesel in all other aspects. If the comparison were made between CRT diesel and the SM CNG vehicle, nanoparticle numbers would be higher and CO_2 lower compared with CRT diesel.

The authors believe that the emission performance (mainly unburned methane, PM mass and particle numbers) of the SM CNG vehicle could be further enhanced by improving catalyst performance by, e.g., securing a higher catalyst temperature.

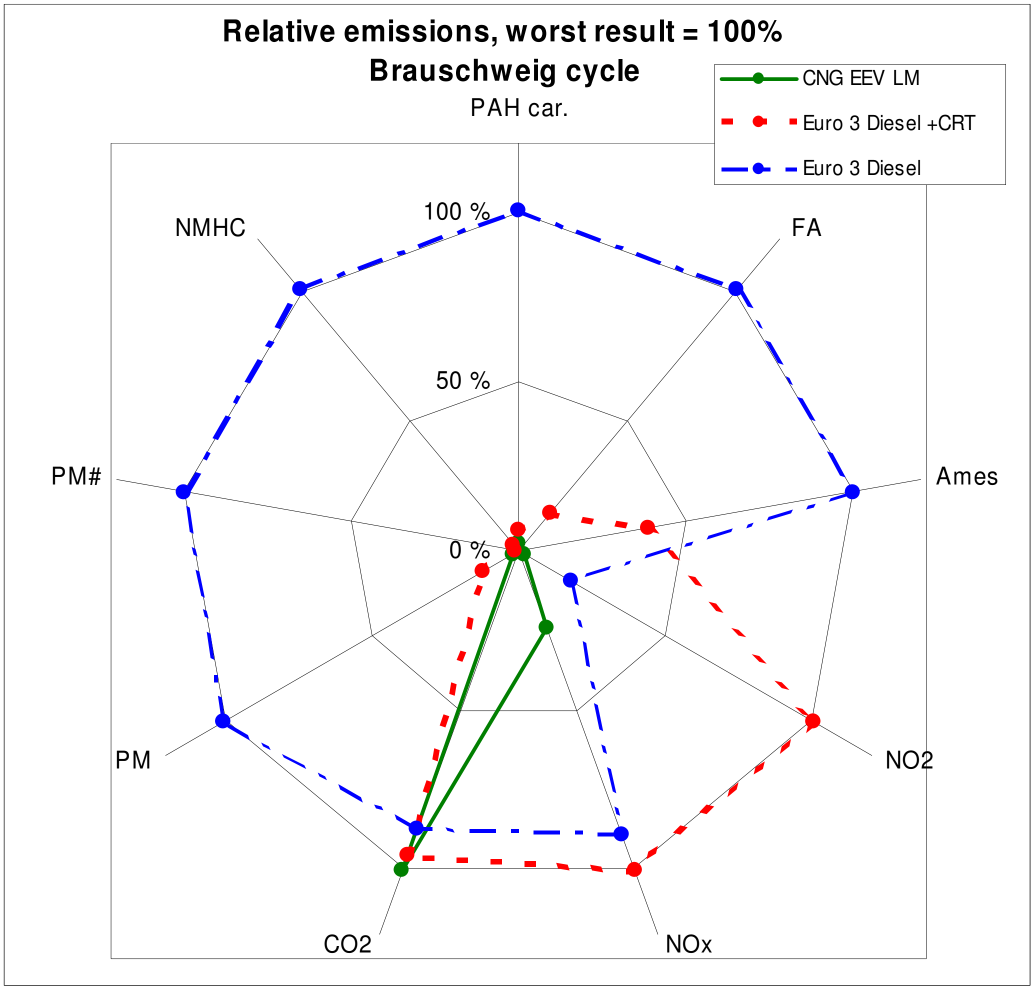

Figure 31. A comparison between diesel without after-treatment, CRT diesel and LM CNG. The worst result is given the index 100.

11 ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

AA	acetaldehyde
BSC	Braunschweig driving cycle
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CPC	condensation particle counter
CRT	continuously regenerating trap (particle filter)
CVS	constant volume sampler
DNPH	dinitrophenylhydrazine
DOC	diesel oxidation catalyst
DPF	diesel particle filter
ECE	Economic Commission of Europe, ECE test method
EEV	enhanced environmentally friendly vehicle
ELPI	electrical low-pressure impactor
EPA	Environmental Protection Agency (US)
FA	formaldehyde
FTIR	Fourier transformation infra-red (spectrometer)
GC	gas chromatograph
HC	hydrocarbons
HPLC	high pressure liquid chromatograph
IANGV	International Association for Natural Gas Vehicles
IARC	International Agency for Research on Cancer
LB	lean-burn (combustion)
LM	lean-mix (combustion)

MS	mass spectrometer
MSAT	mobile source air toxic
MSHA	US Mine Safety and Health Authority
MY	model year
NETL	National Energy Technology Laboratory
NMHC	non-methane hydrocarbons
NO	nitrogen oxide (nitric oxide)
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NSSGA	US National Stone, Sand and Gravel Association
OC	oxidation catalyst
OCC	Orange County driving cycle
OEM	original equipment manufacturer
PAH	polyaromatic hydrocarbons
PM	particle matter
PM#	particle number
PUF	polyurethane foam
SIM	single ion monitoring
SM	stoichiometric
TAC	toxic air contaminant
THC	total hydrocarbons
TW, TWC	three-way, three-way catalyst
US	United States
VTT	Technical Research Centre of Finland
WVU	West Virginia University