BUS EMISSION EVALUATION: 2002 - 2004 SUMMARY REPORT

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VTT PROCESSES

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Summary

Within 2002 – 2004, VTT measured altogether 34 different Euro 1 – EEV certified city buses. All measurements were made on VTT's new chassis dynamometer. The output of the measurements is truthful emission factors in the form of g/km.

There were large variations in the regulated emissions. Diesel Euro 1 vehicles and EEV natural gas vehicles make up the extreme ends. The NO_x emission varied from some 20 g/km for Euro 1 diesel vehicles to around 2 g/km for the most advanced natural gas vehicles. For particulates, the spread was even greater, i.e., from 0.6 to 0.003 g/km, a difference of a factor of 200. Good news is that real-life emissions seem to be falling with advancements in Euro classes.

The work included PM emissions of low-emitting CRT diesel vehicles and natural gas vehicles. To stay operational, a CRT filter needs some service. Natural gas vehicles showed extremely low PM values independent of mileage. Older CNG vehicles show rather high THC or methane emissions.

For a detailed diesel/natural gas bus comparison, seven modern buses, three diesel-driven and four CNG vehicles, were tested for emission performance. The measurements included regulated emission components and a number of speciality measurements. A CRT type particle filter improves the emission performance of a diesel vehicle in many ways. However, with current technology the best natural gas buses outperform the CRT diesel vehicle in most respects.

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ABSTRACT

Within 2002 – 2004, VTT measured altogether 34 different Euro 1 – EEV certified city buses. The buses within the National Bus Project were measured for regulated emissions and CO_2 only. In parallel with the National Bus Project, a comprehensive study on emissions from top-of-the-line diesel and natural gas buses was conducted.

All measurements were made on VTT's new chassis dynamometer. The output of the measurements is truthful emission factors in the form of g/km. These emission factors reflect typical driving patterns and the properties of the complete vehicles.

There were large variations in the regulated emissions. Diesel Euro 1 vehicles and EEV natural gas vehicles make up the extreme ends. The NO_x emission varied from some 20 g/km for Euro 1 diesel vehicles to around 2 g/km for the most advanced natural gas vehicles. For particulates, the spread was even greater, i.e., from 0.6 to 0.003 g/km, a difference of a factor of 200.

Good news is that real-life emissions seem to be falling with advancements in Euro classes. On an average, Euro 2 vehicles, thus, demonstrate lower NO_x and PM values than Euro 1 vehicles, Euro 3 lower than Euro 2, and finally EEV lower than Euro 3. For diesel vehicles, the spread from brand to brand and individual to individual seem to decline with advancements in engine technology. CO_2 emissions and energy consumption vary by a factor higher than 1.5. The lowest CO_2 equivalent emissions were measured for a stoichiometric CNG bus, the highest for a diesel bus with rather high mileage.

The work included PM emissions of low-emitting CRT diesel vehicles and natural gas vehicles. Altogether five CRT vehicles were measured, and of these only three were in good or relatively good working order. To stay operational, a CRT filter needs some service. Natural gas vehicles showed extremely low PM values independent of mileage. Older CNG vehicles show rather high THC or methane emissions. Methane, however, is neither toxic nor reactive and, thus, of little relevance for urban air quality, even though a quite strong greenhouse gas.

The effects of fuel quality on emissions were tested with one Euro 2 and one Euro 3 diesel bus. The baseline fuel was Finnish commercial diesel fuel with less than 50 ppm S, the test fuel low-aromatic Swedish MK1 fuel with less than 5 ppm S. MK1 reduced NO_x emissions by some 5 % and PM emissions by 15 – 25 %. The reduction in PM emissions is quite substantial.

For the detailed diesel/natural gas bus comparison, seven modern buses, three diesel-driven and four CNG vehicles, were tested for emission performance. The measurements included regulated emission components and a number of speciality measurements. A CRT type particle filter improves the emission performance of a diesel vehicle in many ways. However, with current technology the best natural gas buses outperform the CRT diesel vehicle in most respects.

PREFACE

There is a clear need for objective emission data from buses. A lot of confusing and contradictory data on the emissions 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. As emission certification for heavy-duty vehicles is based on testing of stand-alone engines, there is a general lack of good distance based (g/km) emission data.

VTT commissioned a new heavy-duty vehicle emission laboratory in 2002. The key piece of equipment in the new laboratory is a heavy-duty transient type chassis dynamometer. Generation of truthful emission factors for city buses has been one of the focal activities within 2002 – 2004. As a result of more than 200 tests on 34 different buses, VTT has now acquired solid knowledge on the emissions performance of various bus technologies.

The measurements at VTT show that emission trends are moving downwards, and that huge emission reductions could be achieved by replacing the oldest vehicles with new vehicles, either diesel or CNG. VTT will continue its measurements. With the oncoming Euro 4 and Euro 5 requirements, new vehicles and new technical solutions will enter the market. Hopefully, further emission reductions in real-life service will be seen for the new generation diesel vehicles, as well.

The report at hand is the 2002 – 2004 summary report of the bus studies at VTT. In parallel with the National Bus project of VTT, a comprehensive study on emissions from top-of-the-line diesel and natural gas buses was conducted. The results of this study were published in a separate report in October 2004, and only some examples of the results will be presented in this summary report.

The sponsors of the bus projects were:

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

This report was compiled by a team at VTT Processes consisting of Dr. Nils-Olof Nylund and Mr. Kimmo Erkkilä.

CONTENTS

1 BACKGROUND

There is a lack of good distance based emission and fuel consumption figures for heavy-duty vehicles. For light-duty vehicles, both emission and fuel consumption values are readily obtainable. This situation is due to the fundamental differences in the emission certification of light- and heavy-duty vehicles.

The emission certification of light-duty vehicles is done by running complete vehicles on a chassis dynamometer. The output of the testing is emission and fuel consumption values relative to the driven distance, i.e., g/km or litre/km. The test method takes into account the properties of the vehicles, i.e., performance of engine and transmission, vehicle weight, driving resistance etc. Even though the European test cycle for light-duty vehicles is artificial and drawn using a ruler, it provides reasonable estimates of the performance of vehicles.

Emission certification of engines for heavy-duty vehicles is based on running stand-alone engines in test benches. The European methodology for heavy-duty emission certification is described in Directive 1999/96/EC. The Directive contains, among other things, a description of the apparatus, load cycles and emission limit values. The output of the testing is specific emissions in the form of g/kWh at the engine crankshaft. The rationale for running stand-alone engines and not complete vehicles is that the same engine can be used in a variety of vehicles, e.g., buses, trucks and even in some speciality vehicles. The drawback is that the testing does not in any way take into account the properties of the vehicle itself or the real-life service conditions.

Directive 1999/96/EC gives two test cycles for heavy-duty engines, the European Steady Cycle ESC and the European Transient Cycle ETC. In addition, there is the European Load Response Test ELR for acceleration smoke. Table 1 summarizes current and oncoming emission regulations for heavy-duty on-road vehicles both for Europe and the US. 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. 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 ETC Cycle. Starting 2005 (Euro 4), 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 1. 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 2010			0.19	0.27	0.014	

*) CH_4 for natural gas engines only

(A= Euro 3, B1= Euro 4, B2= Euro 5, in the US phase in of NO_x and NMHC values, US 2007 requirement for NO_x is 1.6 g/kWh, 50 % of sales have to fulfil 2010 requirement in 2007 - 2009, 100 % in 2010, no phase in for PM as 0.014 g/kWh applies starting 2007)

It is easy to perceive that a steady-state test does not correlate very well with true driving conditions, especially with urban-type driving. It is therefore debatable whether ECE R49 or ESC emission certification values reflect the true emission performance of heavy-duty vehicles. The introduction of the ETC test for Europe is a step in the right direction, especially for more truthful particle emission values.

Certain municipalities have systems involving bonuses for bus operators providing services with clean vehicles. For the time being, the only possibility is to base these bonus systems upon the official emission certification values or emission classes. However, for the reasons stated above, the fact that the engine of a bus is, e.g., Euro 3 certified does not unambiguously describe the true emission performance of the vehicle.

Engine testing is not at all suited to checking in-service performance of heavy-duty vehicles. Thinking about testing for vehicle emission stability or monitoring the emissions from certain vehicle fleets, taking out engines from the vehicles for engine dynamometer testing would be extremely laborious and expensive.

The obvious solution for monitoring field tests and vehicle fleets and for generating truthful distance based emission factors is to conduct either on-board measurements on the road or to perform chassis dynamometer tests. In both cases, both the properties of the vehicle and the true running conditions can be taken into account. At VTT, a decision was taken to build an emission laboratory comprising a heavy-duty chassis dynamometer.

2 HEAVY-DUTY VEHICLE RESEARCH AT VTT

2.1 GENERAL

In 2000, VTT initiated a research integrate on heavy-duty vehicles. This integrate included the creation of a new heavy-duty vehicle test facility within 2000 – 2001, and the first stage of research and testing activities related to buses and trucks within 2002 – 2004. A second stage of research is now under way.

As for the test facility, the following objective was written down in the master plan of the research integrate:

To create an up-to-date research and test facility with the provisions to conduct transient-type measurements on both stand-alone test engines and complete heavy-duty vehicles. The test facility comprises the following equipment:

- *a heavy-duty transient-type chassis dynamometer*
- *a transient-type engine dynamometer*
- *an exhaust emission measurement system including a full-flow CVS system*

Within 2002 – 2004, several projects making use of the new test facility were carried out. During this period, more than 1,000 chassis dynamometer tests with heavy-duty vehicles were run. The activities included e.g.:

- emission factors for buses
- emission factors for trucks
- fuel savings for heavy-duty vehicles
- development of bio-diesel fuels
- development of exhaust after-treatment systems
- testing of lubricants
- development of particle sampling techniques

Chassis dynamometer testing provides many advantages over engine testing. When conducting measurements with a complete vehicle instead of a stand-alone engine, much less installation work is needed. This means that the delivery cycle is much shorter and the number of test objects can be higher, opening up the possibilities for, e.g., in-use compliance type of testing and fleet monitoring even for heavy-duty vehicles.

The dynamometer is programmed to simulate the properties of the total vehicle. Any real-life driving cycle can relatively easily be transferred to laboratory conditions. In the case of the chassis dynamometer of VTT, it is even possible to include the road gradient in the simulation of the road load. Thus, it is possible to generate truthful emission factors in the form of g/km for both buses and trucks. In the case of buses, as the routes and schedules are fixed, it is easy to generate emission inventories based on distance specific emission factors.

Compared with on-road measurements, chassis dynamometer measurements provide more closely controlled conditions, as the effects of weather and disturbance by other traffic can be eliminated. In addition, a set-up with the vehicle on the chassis dynamometer and a fixed instrumentation provides a better framework both for accuracy and special emission measurements involving complex instrumentation compared with on-road measurements.

2.2 EQUIPMENT AND GENERAL METHODOLOGY

The new facility with its heavy-duty transient chassis dynamometer, transient engine dynamometer and full-flow CVS-emission system also has versatile instrumentation for special emission analysis, including detailed measurements of particles. Information on the facilities can be found at: http://www.vtt.fi/pro/pro3/pro31/indexe.htm

The chassis dynamometer of VTT, 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 within the range of 2 500 to 60 000 kg.

The regulated emissions are 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 is carried out using transient driving cycles, the emission measurements are basically performed in the same way as for passenger car chassis dynamometer tests or transient ETC type engine tests.

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, Figure 1).

The method covers both emission and fuel consumption measurements. In June 2003, the Finnish Centre for Metrology and Accreditation granted accreditation for the method of VTT (T125, In-house method, VTT code MK02E). Figure 2 shows an emission test of a bus on the chassis dynamometer, including instrumentation for special emission analyses, and an insert showing the size of the dynamometer rollers.

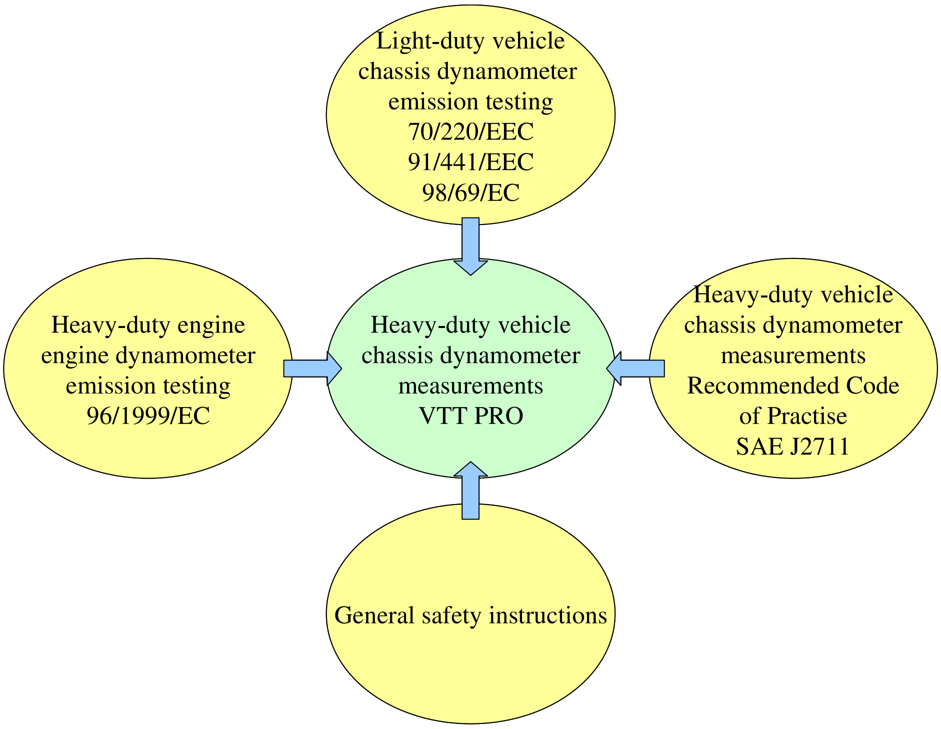

Figure 1. *The elements of the accredited in-house method of VTT for measuring emissions and fuel economy of heavy-duty vehicles.*

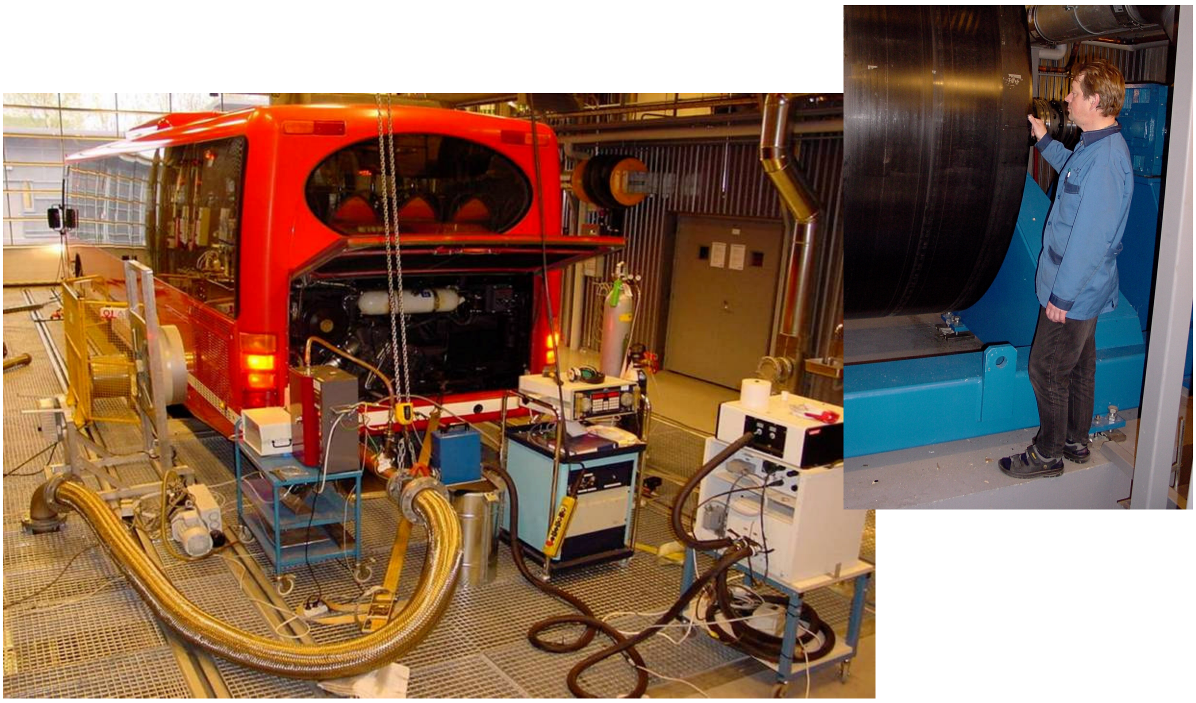

Figure 2. *Emission testing of a bus on the chassis dynamometer and a detail of the dynamometer.*

3 2002 -2004 BUS EMISSION EVALUATION

3.1 GENERAL

Within the research integrate of VTT on heavy-duty vehicles, the emissions from the urban bus fleet was one of the focal points. The plan described the bus evaluation part as follows:

"The primary motivation for the work is to promote the implementation of new low-emission and energy efficient bus technologies, thus improving the competitiveness and attractiveness of public bus transport. Methodology to assess the performance (exhaust emissions, energy consumption, possibly noise) of buses will be developed. The methodology will be used to assess the true emission performance of both new vehicles and vehicles already in service. The unbiased information on the performance of various types of vehicles and exhaust gas after-treatment devices will be helpful for the municipalities responsible for the procurement of bus services in defining emission criteria. It is also expected that the data to be generated will have an impact on vehicle procurement by the transport companies."

The overall programme for buses was set to cover a number of different aspects:

- comparison of alternative vehicle technologies
    - new vehicles/vehicles in prime condition, different fuel and exhaust gas after-treatment options
    - e.g., diesel, diesel + particle filter, diesel + EGR, diesel + SCR, natural gas
- truthful emission factors for in-use vehicles and deterioration factors for various technologies
- effect of duty cycles on emissions
    - static and dynamic emission factors
    - emissions on various bus routes
    - response of various technologies to driving conditions

All the items listed in the plans have been followed up, with the exception of noise. In fact, work with buses took place in four complementary projects:

1. National Bus Project 2002 - 2004
2. Transient Bus Study: Comparison of Emissions from Diesel and Natural Gas Buses 2002 - 2004
3. Energy Savings for Heavy-Duty Vehicles 2003 – 2005
4. Evaluation of Duty Cycles for Heavy-Duty Urban Vehicles (IEA AMF Annex XXIX) 2004 - 2006

The National Bus Project (1) has produced two Annual Reports, 2002 and 2003, the latter one also available in an English version.

A separate report on the comparison between diesel and natural gas buses (2) was issued in 2004. This report can be downloaded at the website of VTT at:

http://www.vtt.fi/inf/pdf/jurelinkit/VTTNylund.pdf

For this project, comprehensive emission analyses were carried out for three diesel and four natural gas buses.

Information about the project of energy savings for heavy-duty vehicles (3) can be found in Finnish at:

www.motiva.fi/raskaskalusto

The main objective of the IEA project (4) is to compare a number of duty cycles with several heavy-duty vehicles (buses) aiming at the following goals:

- to generate understanding of the characteristics of different duty cycles
- to produce a key for cross-interpretation of emission results generated with different cycles
- to study the interaction between vehicle, exhaust after-treatment and fuel technologies and test procedures
- to pin-point the need for international harmonization in emission testing

A description of this project can be found at:

http://www.vtt.fi/virtual/amf/annex-xxix.html

The report at hand brings together the findings of the National Bus Project and the study to compare emissions from diesel and natural gas buses (hereafter Bus Fleet Emission Evaluation). More than 200 emission tests were carried out with 34 individual buses. The National Bus Project focused on regulated emissions only, and provided emission data for a number of vehicles representing different emission certification classes, age and mileage. In the case of the comparative study, all vehicles were low-mileage vehicles in prime condition. The emission analyses also included unregulated components and special measurements for particles.

3.2 PARTNERS

The sponsors of the National Bus Project were:

- 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

In the Helsinki Metropolitan Area, the Helsinki Metropolitan Area Council and the Helsinki City Transport Planning Department are responsible for the procurement of bus services. Both parties have a system in place differentiating the fares based on the technical and environmental qualities of the buses. Thus both parties are very interested in the true emission performance of buses.

The Swedish Road Administration was invited to participate in the project, and took a decision to join in 2004. As the bus fleets in Finland and Sweden are quite similar, the emission results generated by VTT are of relevance for Swedish conditions as well.

The International Association for Natural Gas Vehicles IANGV also teamed up with the Finnish bus project. The National Bus Project was scheduled to cover 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 representing top-of-the-line technologies and certified for the most stringent European emission class, EEV (Enhanced Environmentally Friendly Vehicle). In addition, the IANGV involvement made it possible to expand upon the diesel vehicle measurements, thus providing a sound base for the comparison of emission performance of diesel and natural gas buses.

3.3 TEST VEHICLES

For the Bus Fleet Emission Evaluation, VTT performed in total more than 200 emission measurements with 34 different buses (Table 1). Three vehicles, two diesel buses and one natural gas bus, were subjected to a follow-up program to study emission stability and deterioration. These vehicles were measured three times.

The emission certification of the diesel buses varied from Euro 1 to Euro 3. In 2004, no Euro 4 certified was yet available for testing in Finland. The natural gas vehicles represented Euro 2 (unofficial), Euro 3 and EEV emission classes.

Table 1. Buses measured within 2002 – 2004.

	2002	2003	2004	Total
Diesel	7	10	9	26
Natural gas	4	3	1	8
Total	11	13	10	34
Diesel – follow-up	(2)	2	2	2
NG – follow-up	(1)	1	1	1

The comparison of diesel and natural gas buses involved the following vehicles (new or low-mileage vehicles):

- Euro 3 diesel without exhaust after-treatment
- Euro 3 diesel + oxidation catalyst (OC)
- Euro 3 diesel + continuously regenerating trap (particle filter, CRT)
- Euro 3 CNG
- EEV CNG (three different brands and combustion technologies)
  - lean-burn (LB, oxidation catalyst)
  - lean-mix (LM, mixed combustion, three-way catalyst)
  - stoichiometric (SM, three-way catalyst)

In this case, the three diesel vehicles were of the same brand and model. The exhaust after-treatment devices were OEM installed.

Most of the Euro 2 and Euro 3 diesel vehicles in the base matrix are also equipped with oxidation catalysts (with a few exceptions). These catalysts are normally integrated into the muffler and cannot be distinguished form the outside. As the documentation of the vehicles is seldom unequivocal, it is impossible to make a separation between non-catalyst and catalyst equipped vehicles, so these vehicles are treated as a single group. CRT filters, on the other hand, are easily detected.

The mileage of the vehicles in the general test matrix varied between 4 800 and 847 000 km. The tested vehicles were on loan either from transport companies, vehicle importers or vehicle manufacturers. The vehicles were not served especially for the testing. It was agreed not to identify vehicle brands or models in the public reporting, so the vehicles are identified by codes (brands A, B, C etc.).

The separate report on the comparison of diesel and natural gas buses contains technical data on the test vehicles. However, for this summary report it was not considered functional to list technical data on 34 individual vehicles. This report will classify the results mainly by emission certification class, but to some extent by vehicle brand, as well.

3.4 TEST FUELS AND LUBRICANTS

The vehicles within the National Bus Project were tested with the commercial fuel in the tank of the vehicle. Thus, the fuel quality is not accounted for, but the assumption is that the sulphur content of the fuel is clearly below 50 ppm (Finnish fuel specification).

For the three diesel vehicles used in the detailed diesel/natural gas comparison, the same batch of diesel fuel was used, i.e., reformulated, low sulphur diesel fuel fulfilling the oncoming European 2005 specifications (Directive 2003/17/EC, Amending Directive 98/70/EC). This fuel batch was analysed for sulphur, and the sulphur content was 23 ppm.

At request of the Swedish Road Administration, two vehicles were also tested with Swedish Environmental Class 1 diesel fuel (MK1). The very light MK1 fuel has a sulphur content of less than 5 ppm and very low aromatics content.

The natural gas used in Finland originates from Siberia, Russia. 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).

3.5 TEST PROCEDURES

3.5.1 Chassis dynamometer

All vehicle testing was carried out in the new heavy-duty test facility of VTT Processes, Finland. 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 utilised to compile the resistance coefficients for the measurements.

The control system of the dynamometer makes it possible to freely simulate the driving resistance of any vehicle. The vehicle matrix included both two- and three-axle vehicles, plus one articulated bus. However, the majority of the buses were two-axle conventional city buses.

Basically, all vehicles were tested simulating the weight of the vehicle itself plus 50 % of maximum load. In the case of two-axle buses the results are unequivocal. Some of the three-axle vehicles were measured simulating both two-axle and three-axle vehicles.

The single articulated bus within the test vehicle matrix was, in fact, also measured simulating a two-axle and a three-axle bus.

All the results for the diesel/natural gas comparison were generated simulating the weight of two-axle vehicles. As the CNG vehicles are slightly heavier than their diesel counterparts, this was taken into consideration.

During the chassis dynamometer test, the driver follows a given speed vs. time profile. All vehicles were tested at least using the highly transient Braunschweig bus cycle. Some vehicles were also tested using other cycles (Orange County, ECE 15 urban part etc.). Table 2 presents data on most commonly used cycles and Figure 3 the speed profile of the Braunschweig cycle. VTT has established that the Braunschweig duty cycle also represents well driving in downtown Helsinki. For the diesel/natural gas comparison, both Braunschweig and Orange County cycles were used. It was found out that the differences in emission results are rather small.

Table 2. 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
ECE 15	3.976	780	18.4	50	25

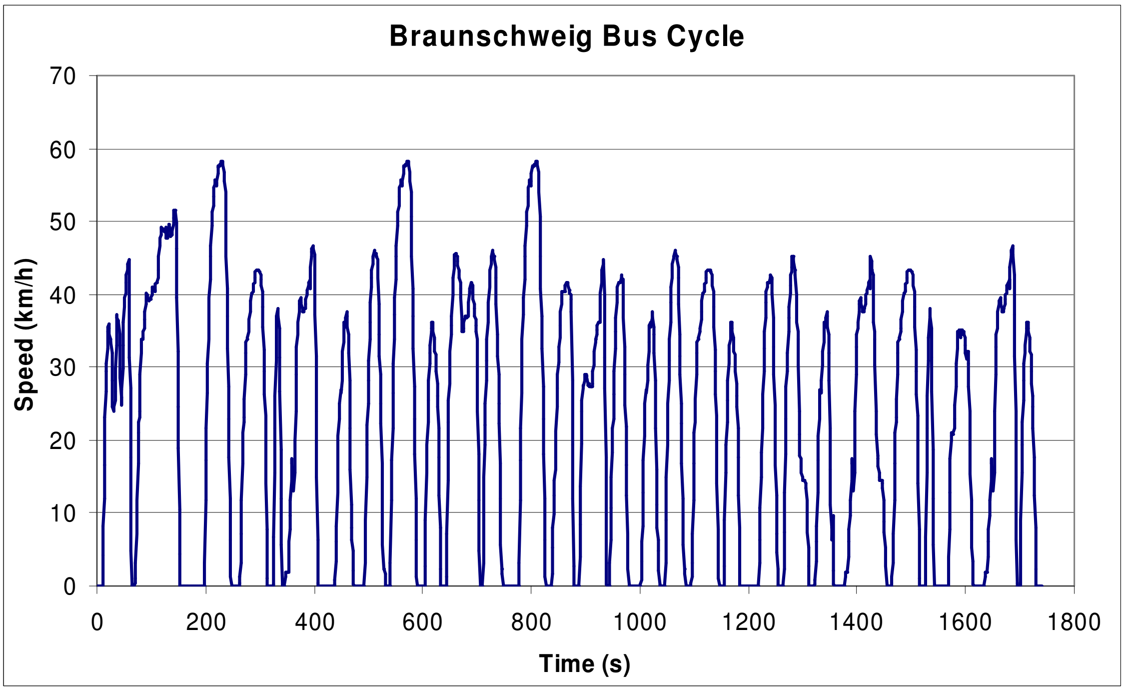

Figure 3. Speed vs. time of the Braunschweig (BSC) bus cycle.

3.5.2 Exhaust emissions

The regulated emissions (CO, THC, NO_x, PM) of all vehicles were measured using the full-flow CVS system (Pierburg CVS-120-WT) and the analyzer set (Pierburg AMA 4000). The apparatus conforms to the requirements of Directive 1999/96/EC for the measurement of exhaust emissions of heavy-duty on-road engines. For the measurements on the chassis dynamometer, the specific emissions were calculated per driving distance (g/km).

For the diesel/natural gas comparison (7 vehicles), a number of special emission analyses was 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:

- particle number size distribution
- PAH compounds (collected on filters, GC-MS (SIM))
- Ames mutagenicity of the particle matter (*Salmonella* strains TA98 –S9 and +S9)

The report at hand will not go into details regarding special emission measurements. More information can be found in the full report of diesel/natural gas bus comparison:

http://www.vtt.fi/inf/pdf/jurelinkit/VTTNylund.pdf

4 RESULTS AND DISCUSSION

4.1 GENERAL

For the bulk of the vehicles, only regulated emissions were measured. Therefore, this presentation will mainly focus on regulated emissions. The separate report on the diesel/natural gas comparison contains a detailed discussion about the special emission measurements. This discussion will not be repeated here. However, some examples of the results will be presented.

The separate report also contains a summary of the relevance of the different emission components. This summary has been added as an appendix to this report.

The results are presented as follows:

- regulated emissions and CO_2
- the effect of mileage on emission results of Euro 2 and Euro 3 diesel buses
- particle emissions from CRT filter equipped diesel buses and natural gas buses
- the effect of vehicle weight (two-axle, three-axle) on emission results
- the effect of diesel fuel quality on emissions
- examples of the results of the special emission measurements for the diesel/natural gas comparison

4.2 REGULATED EMISSIONS AND CARBON DIOXIDE

Figures 4 – 7 present CO, THC, NO_x and PM results (g/km, Braunschweig cycle) for all the buses measured within 2002 – 2004. The most important pollutants regarding urban air quality are NO_x (especially NO_2) and particles, CO and THC are of lesser importance (see Appendix 1).

The vehicles are grouped together in the following way:

- Euro 1 diesel (only two vehicles)
- Euro 2 diesel
- Euro 3 diesel
- Euro 2 and Euro 3 diesel with CRT
- Euro 2 and Euro 3 CNG
- Euro 5/EEV CNG

The Figures include denotes for vehicle information. "n" is used for the number of parallel vehicles. Certain manufacturers offer two or more versions of a vehicle, differing from each other, e.g., through engine size. The different versions are identified through "mod.1" or "mod.2". In the case of CRT equipped diesels, as there are huge variations in the performance of the CRT filter, each measured vehicle is identified ("ind.1", "ind.2"). As a consequence, the Figures contain individual, vehicle specific results and average values for a certain type of vehicle.

The average CO emission is approximately 1.5 g/km (Figure 4). The highest CO values are found among Euro 2 vehicles, both diesel and CNG. The average THC value for diesel vehicles is below 0.5 g/km (Figure 5). The average THC emission of CNG vehicles in good working order is around 1 g/km. For older CNG vehicles with a malfunctioning catalyst, the THC emission can increase from this value by a factor of 10. This is especially true for vehicles utilizing lean-burn technology. However, it should be noted that the THC emission from a CNG bus is more than 95 % methane and methane is neither toxic nor reactive. Methane is a strong greenhouse gas, and should be taken into account when calculating total greenhouse gas emissions. Neither CO, nor THC is priority pollutants for buses.

The range for NO_x emissions is from some 20 g/km (Euro 1 and Euro 2 diesel buses) to 2 g/km (EEV certified CNG vehicles, Figure 6). Looking at diesel vehicles, the variation is greater for Euro 2 vehicles than for Euro 3 vehicles. Electronic injection control provides better accuracy and performance than older totally mechanical injection systems.

The greatest variations can be found in particle emissions (Figure 7). The particle mass emission varies from some 0.6 g/km (Euro 1 diesel) to practically zero (the best CNG vehicles). All CNG vehicles perform well in this respect, as do the diesel vehicles equipped with a properly functioning CRT filter.

Figures 8 (NO_x) and 9 (PM emissions) summarise the emission trends found in this study. 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.

At an 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 advanced exhaust after-treatment. Average NO_x and PM values obtained on the chassis dynamometer seem to be in coherence with the emission limit values of the various vehicle classes.

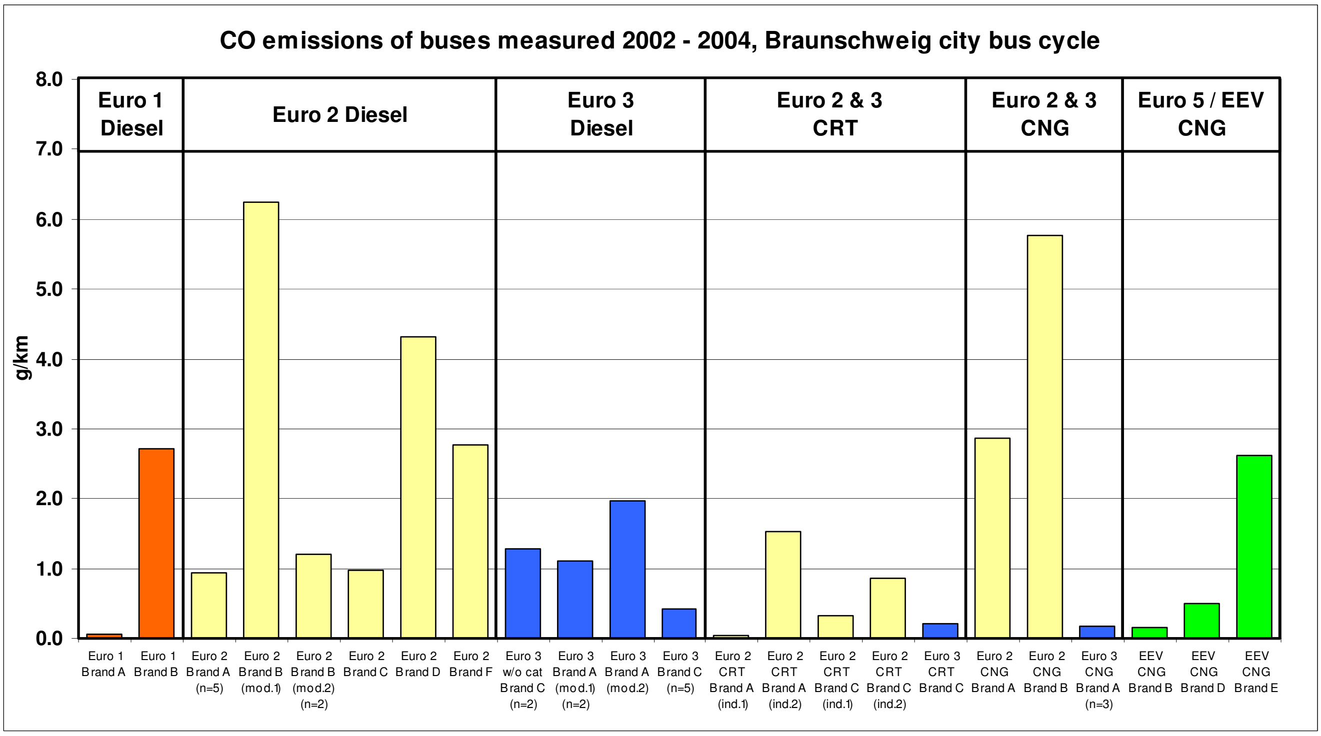

Figure 4. CO emission results.

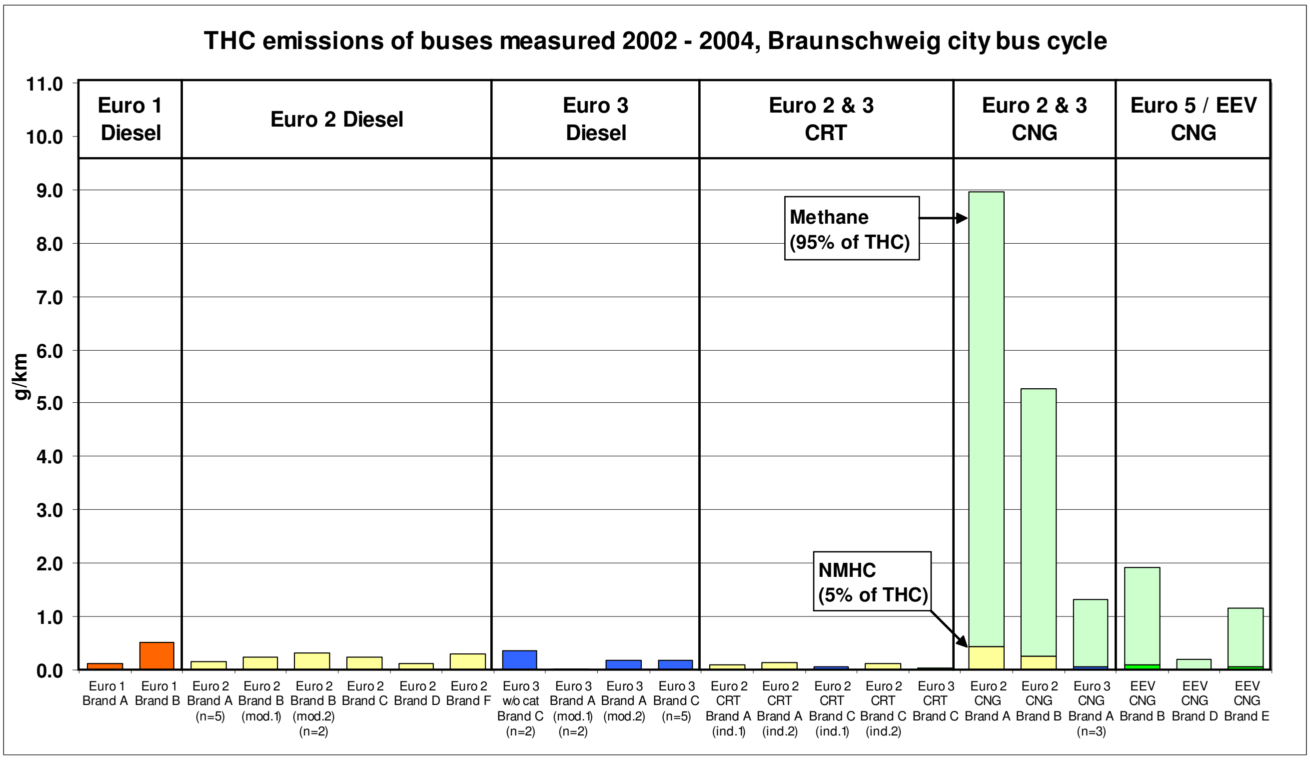

Figure 5. THC emission results (NMHC of NGVs estimated at 5 % of total HC).

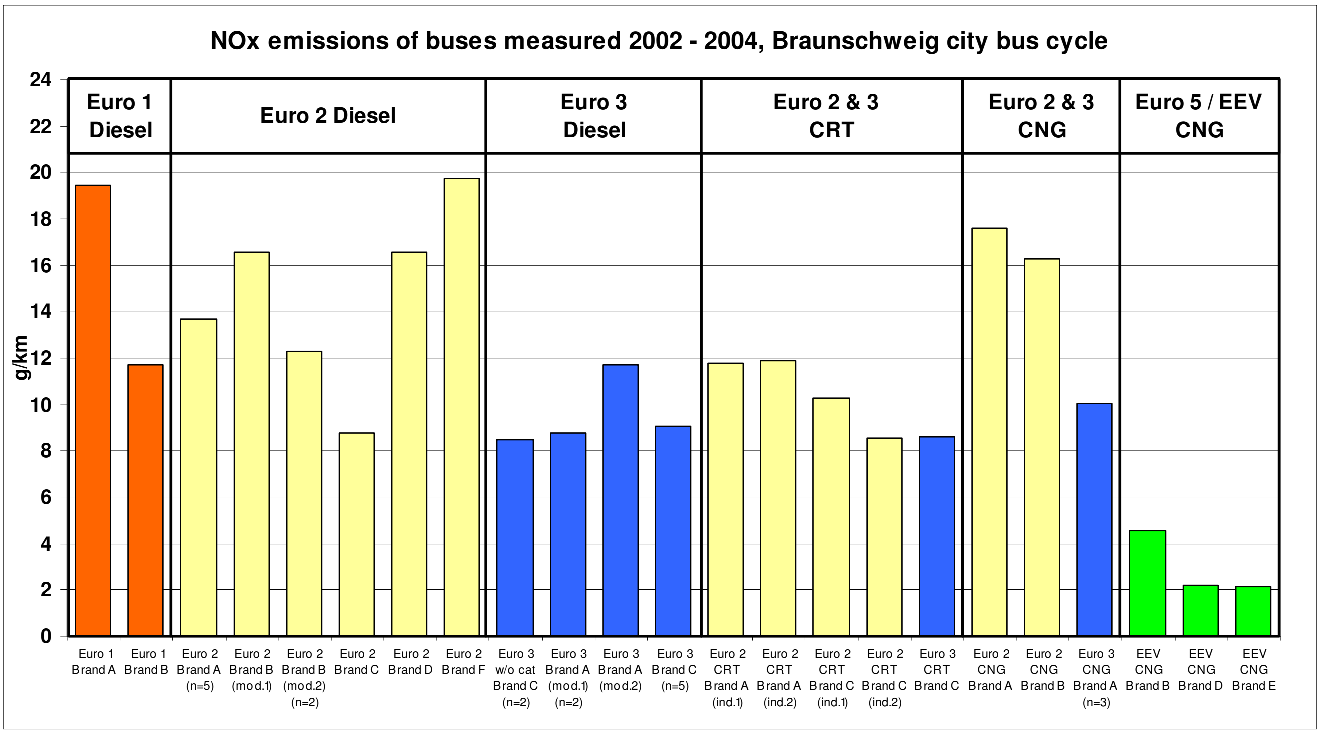

Figure 6. *NO_x emission results.*

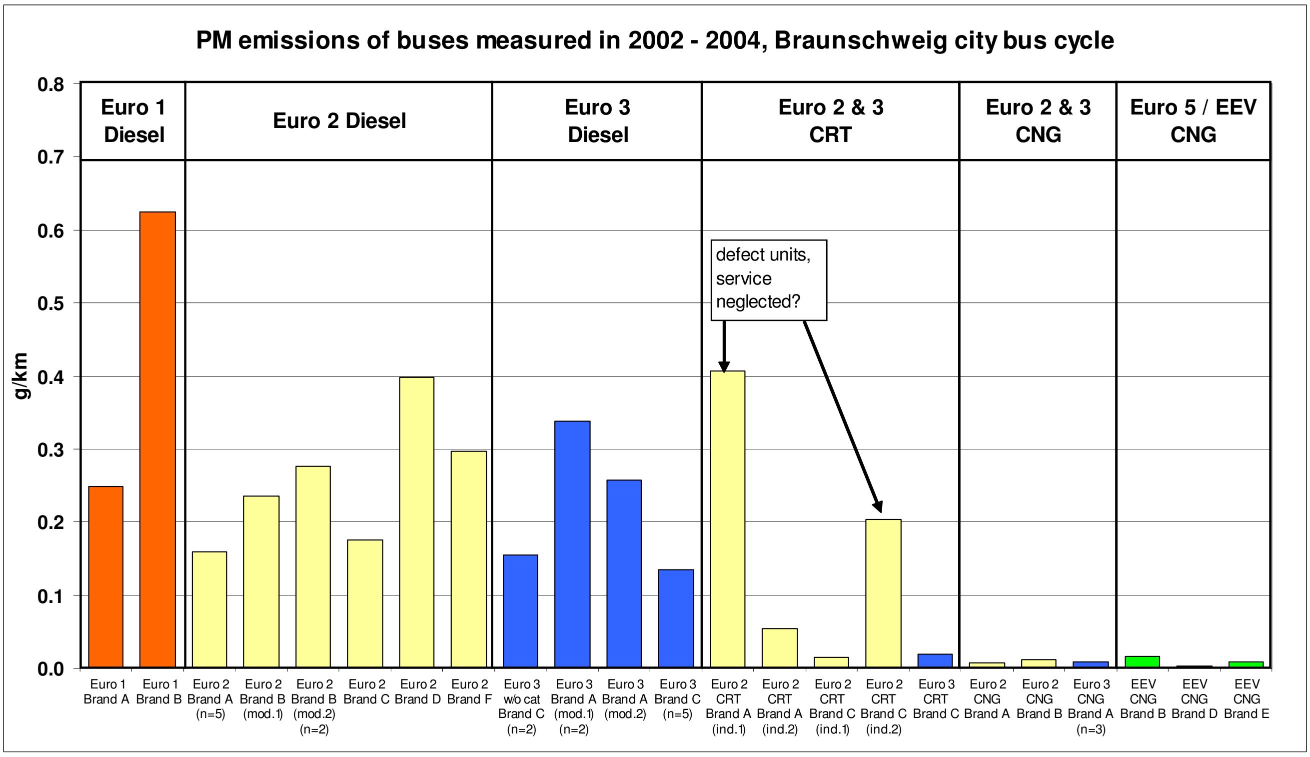

Figure 7. *PM emission results.*

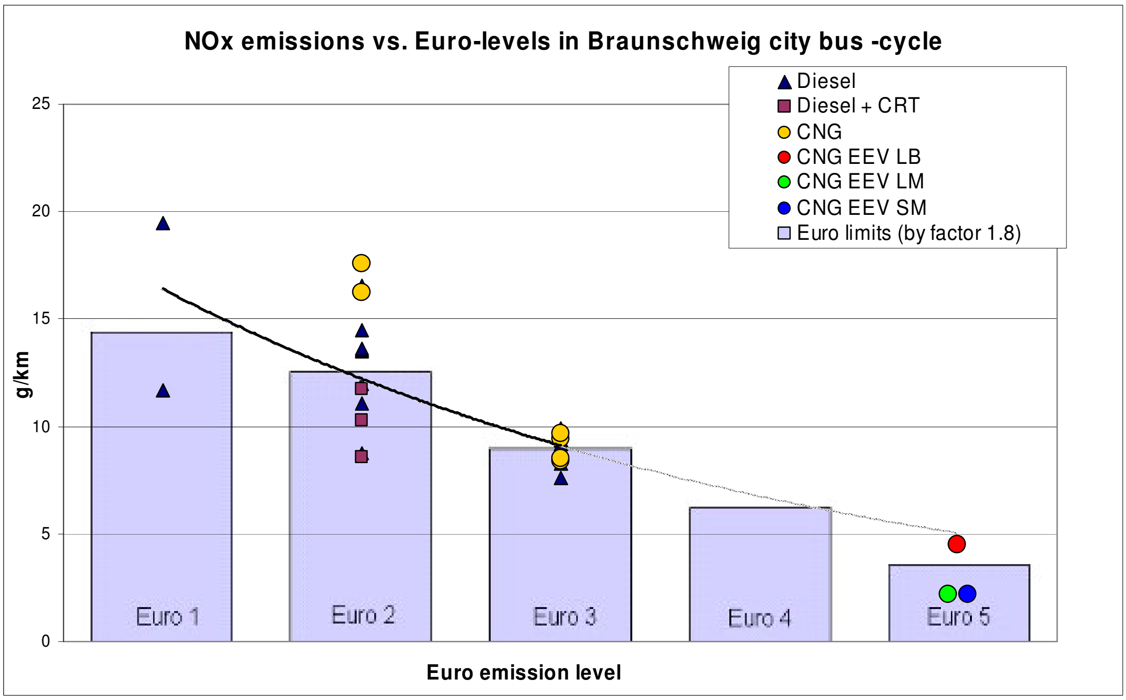

Figure 8. NO$_x$ emission trends.

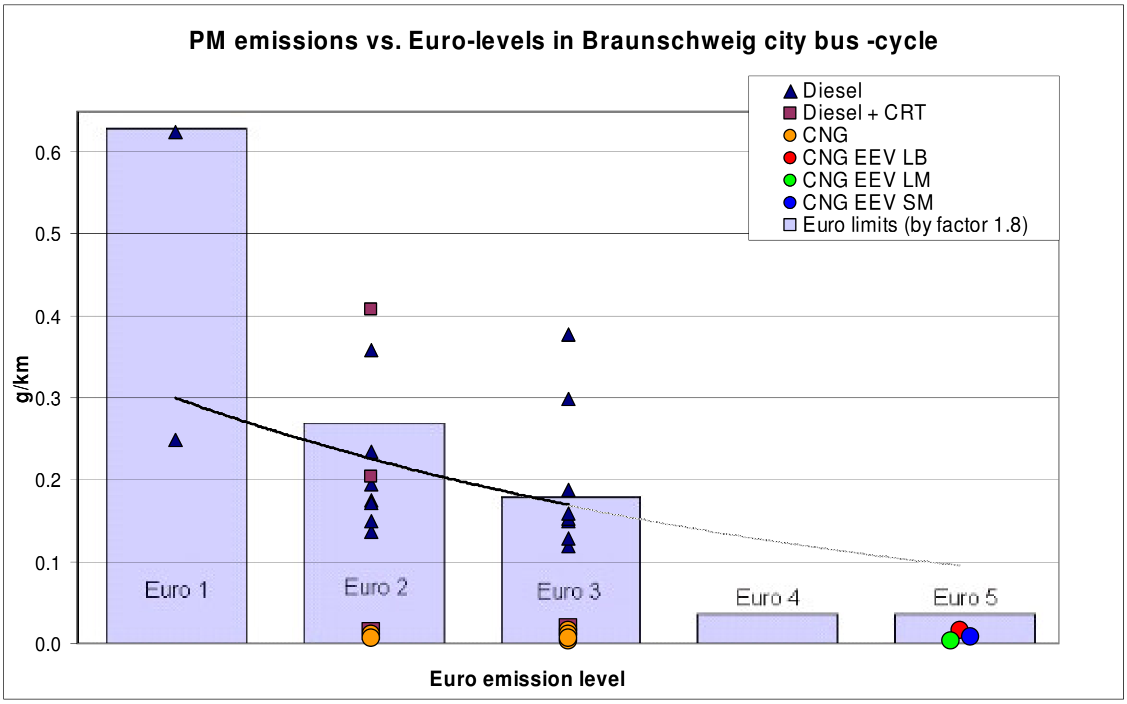

Figure 9. PM emission trends.

Figure 10 shows a different kind of summary in the form of a NO_x vs. PM plot. This Figure accentuates the differences between vehicle classes, but also the big differences within the classes (i.e., differences between the vehicle brands).

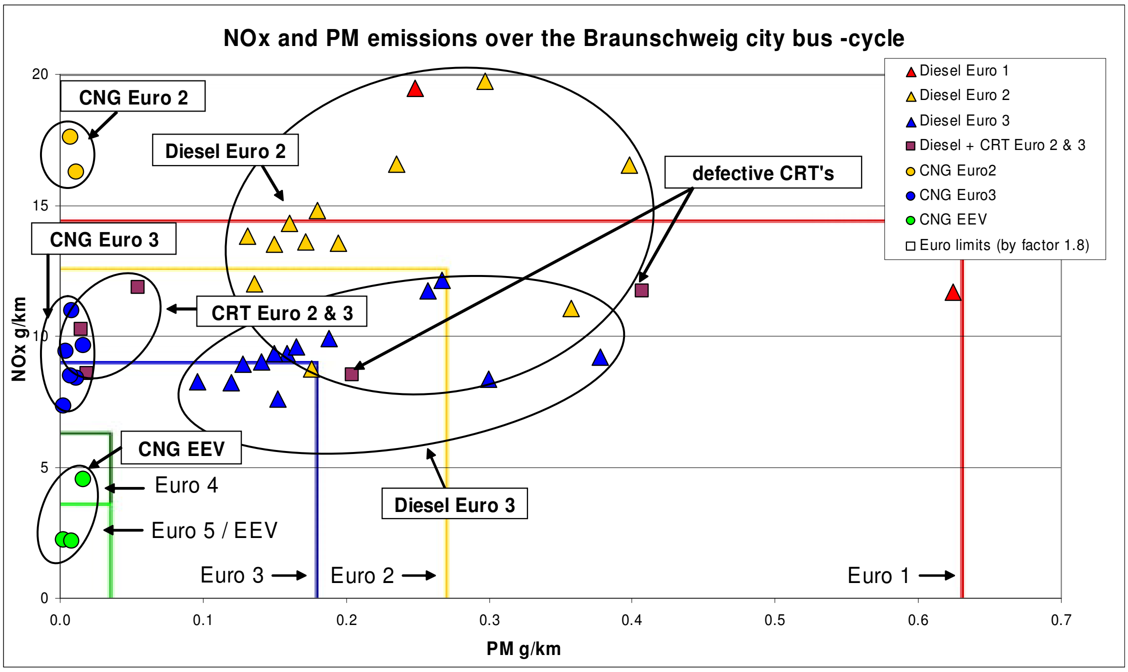

Figure 10. NO_x vs. PM emissions.

In addition to NO_x and PM, CO_2 emissions are also of general interest. CO_2 is the most important greenhouse gas. For a given fuel, e.g., diesel fuel oil, the CO_2 emission correlates to fuel consumption and vehicle efficiency. The specific CO_2 emission, expressed in g CO_2/MJ_{fuel}, on the other hand, varies from fuel to fuel. Natural gas or methane is a hydrogen rich fuel which benefits from its chemistry. The specific CO_2 emission of methane is 25 % lower compared with diesel fuel.

On the other hand, the current heavy-duty natural gas engines, which basically are diesel engines converted into spark-ignition engines, have lower efficiency compared with diesel engines, and this in most cases mitigates the possible CO_2 advantage.

There is one additional issue related to the greenhouse gas emissions of natural gas engines, and that is the emission of unburned methane. Methane is a strong greenhouse gas, with an effect of some twenty-fold compared with CO_2. For this reason, the emission of unburned methane multiplied by a factor of 21 is often added to the CO_2 emission to delineate the total equivalent CO_2 emission.

Figure 11 presents the equivalent tailpipe CO_2 emissions. The values for the CNG vehicles have been corrected for unburned methane. In the case of CNG vehicles in prime condition (methane emission around 1 g/km), methane stands for only some 2 % of the equivalent CO_2 emission, whereas in the case of high methane emitters (10 g/km) methane is some 15 % of the CO_2 equivalent.

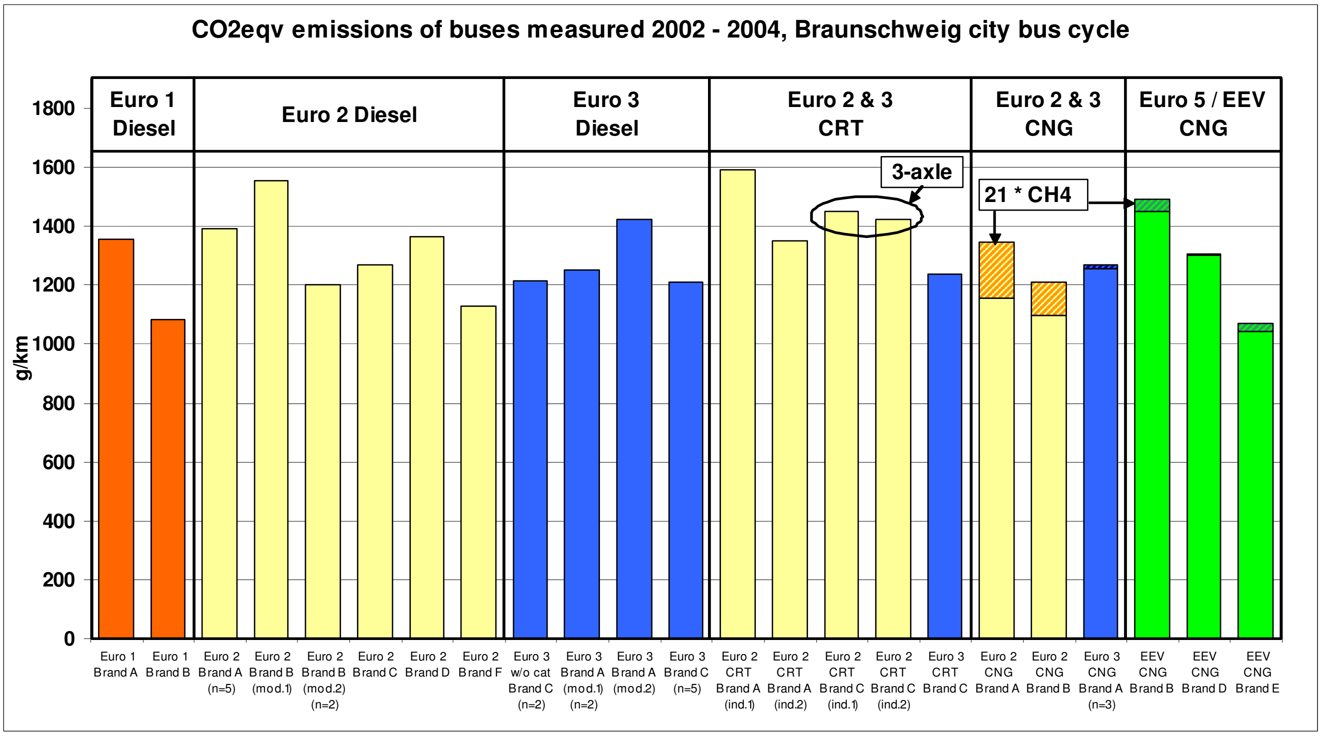

Figure 11. Equivalent CO_2 emissions.

For two-axle diesel vehicles, the CO_2 emission varies from some 1100 (Euro 1 w/o exhaust after-treatment) to 1600 g/km (Euro 2 + CRT), a difference of some 45 %. For two-axle natural gas vehicles, the equivalent CO_2 emission is between 1100 (stoichiometric EEV) and 1500 g/km (lean-burn EEV).

Figure 12 presents a NO_x vs. CO_2 plot for the 7 vehicles included in the diesel/natural gas comparison. The effect of methane is not included in this Figure, as the contribution from methane is rather small for vehicles in prime condition. Figure 12 shows that adding exhaust after-treatment onto diesel vehicles increases not only CO_2 emission (due to increased fuel consumption), but also NO_x emissions slightly. 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.

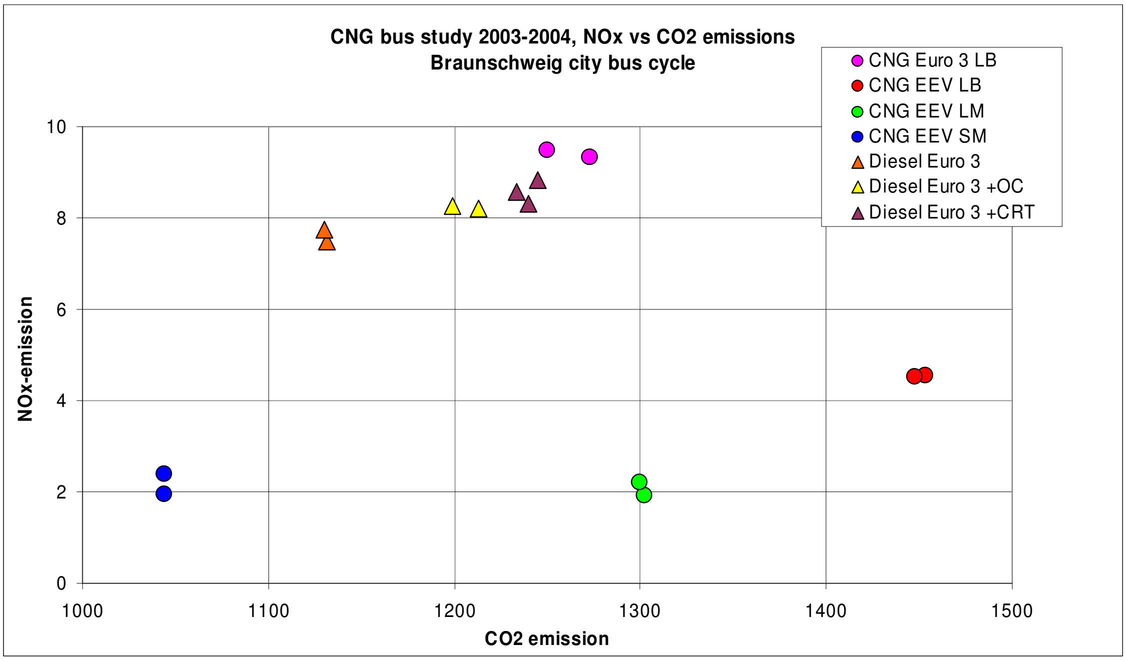

Figure 12. NO_x vs. CO_2 emissions (diesel/natural gas comparison).

The average CO_2 and NO_x values for the Euro 3 certified vehicles equipped with exhaust after-treatment (diesel and natural gas, oxidation catalyst or CRT) are some 1250 and 9 g/km, respectively. The EEV certified CNG vehicles scored NO_x values between 2 and 4.5 g/km and CO_2 values from 1050 to 1450 g/km. Somewhat surprisingly, the lowest CO_2 emission was recorded for a stoichiometric EEV CNG vehicle.

Energy and fuel consumption can be calculated on basis of the CO_2 emission. Figure 13 shows energy consumption for the different vehicle categories. For two-axle diesel buses, the energy consumption is between 14.6 – 21.4 MJ/km. These values correspond to some 41 – 60 l/100 km, a difference of some 45 %. The average value for diesel vehicles without CRT is 17 MJ/km, corresponding to 48 l/100 km. The average value for CRT diesels (estimated for two-axle vehicles) is 18.5 MJ/km (52 l/100 km).

The average energy consumption of Euro 2 and Euro 3 CNG vehicles is 21 MJ/km. For Euro 5/EEV CNG vehicles, it is 22 MJ/km. This means that the energy consumption of the natural gas vehicles is on an average 25 – 30 % higher compared with diesel vehicles without CRT and 15 – 20 % higher compared with CRT equipped diesels.

The variation in energy consumption within the group of EEV certified CNG vehicles is rather large. Looking at the vehicles included in the diesel/natural gas comparison, the EEV certified CNG vehicles consumed 10 - 50 % more energy compared with the diesel with CRT, 15 -55 % more compared with the diesel with oxidation catalyst and 20 – 65 % more compared with the diesel without exhaust after-treatment. Translated into diesel equivalent, the most efficient EEV CNG vehicle consumed 51 l/100 km, the least efficient 71 l/100 km.

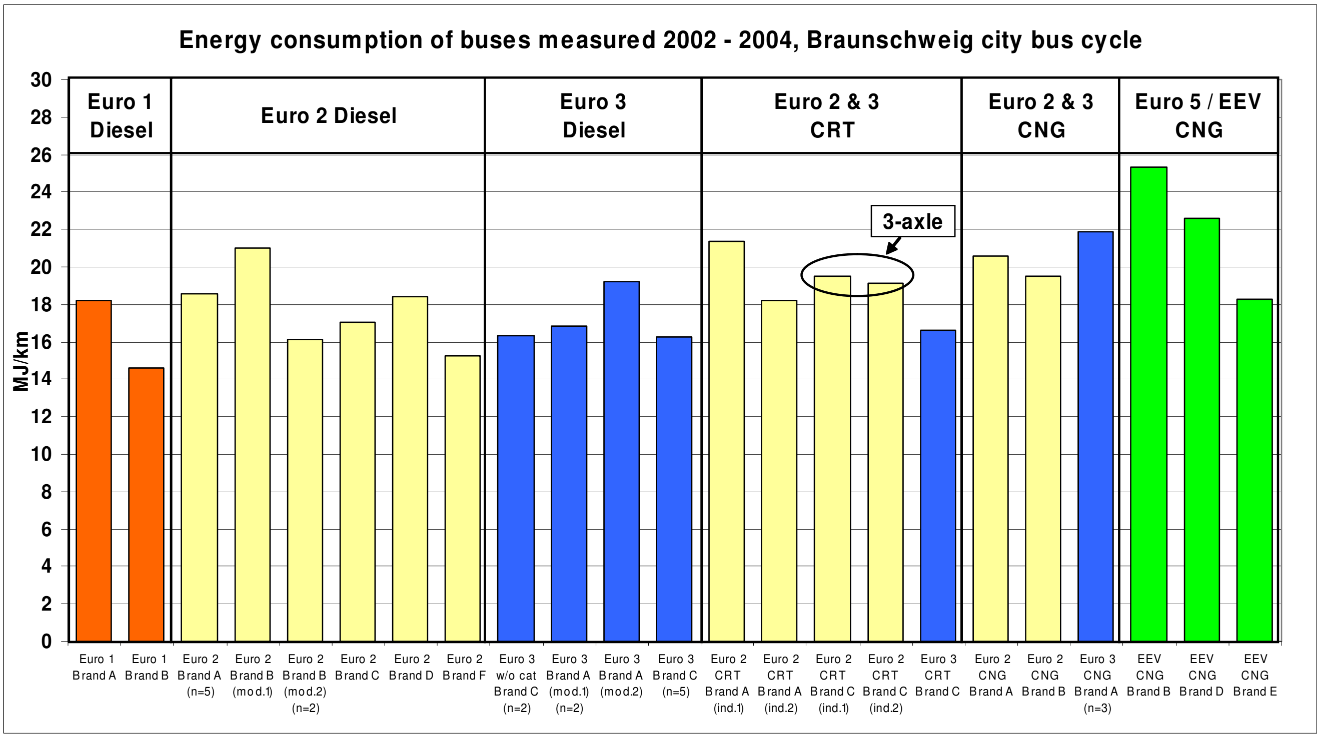

Figure 13. Energy consumption.

Figures 14 (Euro 3 diesel with oxidation catalyst) and 15 (CNG Euro 3) show the effect of the test cycle on emission results. The three test cycles shown are Braunschweig, Orange County and ECE 15. The last one is a synthetic cycle consisting of elements of idle, constant acceleration, constant speed and constant retardations.

CO_2 correlates to average load, and the order from the lowest to the highest is ECE 15, Braunschweig and Orange County. For the diesel vehicle, NO_x and PM also follow the same order. In the case of the CNG vehicle, the Braunschweig and Orange County cycles give roughly equal NO_x and PM values. The light load of the ECE 15 cycle increases CO for the diesel, but reduces THC for the CNG vehicle.

In general, the effect of the duty cycle on emissions is relatively small. This is true especially for NO_x.

The Annual Reports 2002 and 2003 of the National Bus Project featured a Table with typical specific emissions values (g/km) for transient-type driving for vehicles representing different emission certification classes.

In a similar way, Table 3 presents a summary of all the results from 2002 – 2004. Compared with the previous Tables, more columns (vehicle categories) have been added. In the case of CRT equipped diesel vehicles, one abnormally high PM value has been left out (damaged filter). It should be noted that the values in Table 3 are from vehicles of different age and mileage and, for this reason, the results contain "built-in" deterioration factors, especially for vehicles in Euro 1 and Euro 2 categories.

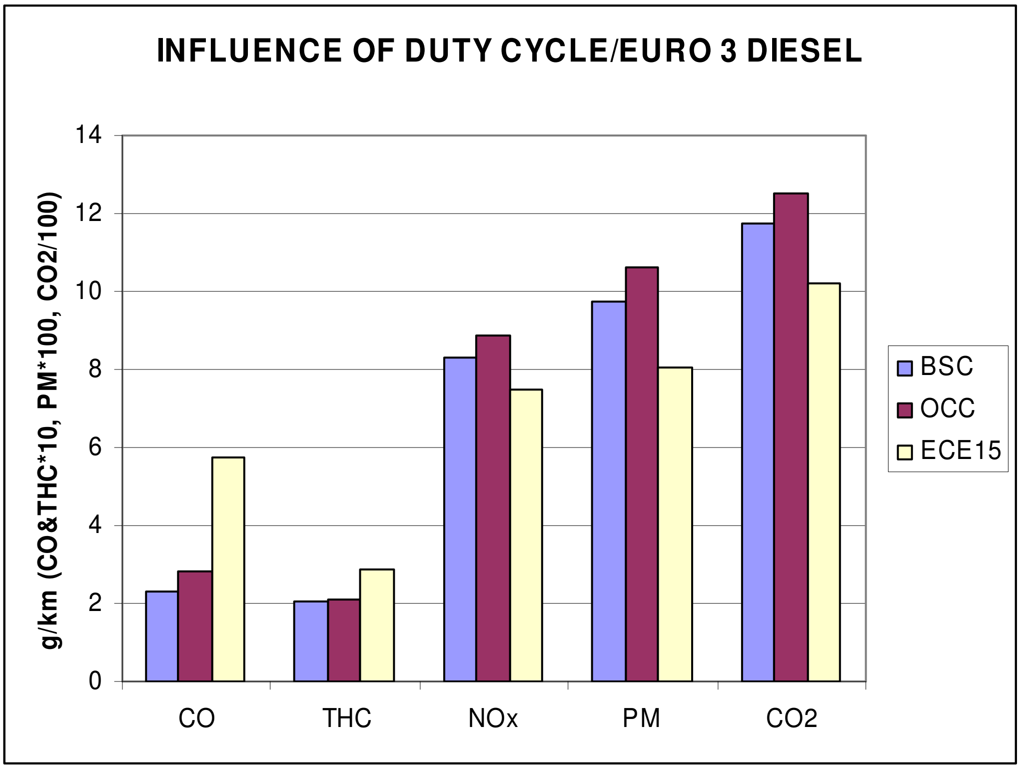

Figure 14. *Effect of duty cycle on emission results, Euro 3 diesel vehicle.*

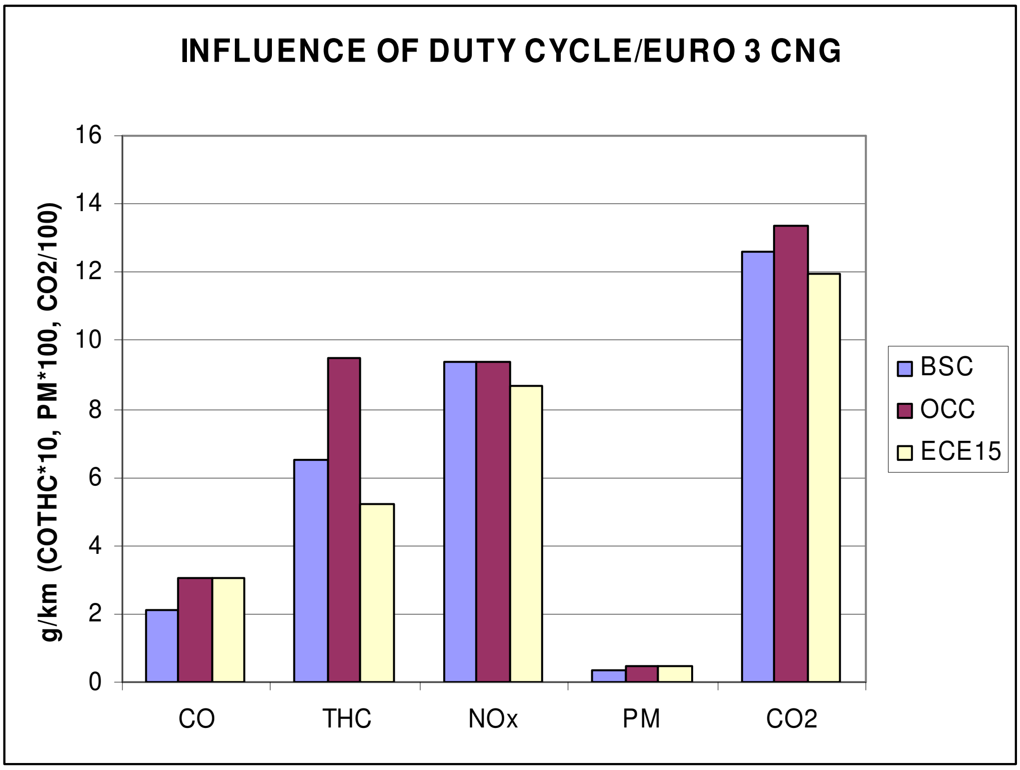

Figure 15. *Effect of duty cycle on emission results, Euro 3 CNG vehicle.*

Table 3. Summary of dynamic emission factors (g/km, round figures).

	Euro 1 diesel	Euro 2 diesel	Euro 3 diesel	Euro 2/3 diesel CRT	Euro 2 CNG	Euro 3 CNG	Euro 5/EEV CNG
CO	1.5	1.5	1.0	0.5	4.0	0.2	1.0
THC	0.3	0.2	0.15	0.1	7.0	1.0	1.0
NO_x	16	14	9.0	9 – 14	17	10	3.0
PM	0.45	0.20	0.18	0.03	0.01	0.01	0.01
CO_2	1200	1350	1250	1400	1100	1250	1250
CO_2 eqv.					1300	1300	1300

4.3 EFFECT OF MILEAGE ON EMISSION RESULTS

It is possible to estimate the effect of mileage on emissions for brand “A” Euro 2 and brand “C” Euro 3 diesel vehicles and brand “A” Euro 3 CNG vehicles. Several individuals have been measured in these categories, including one vehicle subjected to continuous follow-up. The older Euro 2 vehicles have had the possibility to accumulate more mileage than the other vehicles.

Figure 16 shows NO_x and PM emissions as a function of mileage for brand “A” Euro 2 diesel vehicles. Four individuals were measured, one of these three times.

It is interesting to see that NO_x and PM values form pairs; a high NO_x value goes hand in hand with a high PM value. One might expect a high NO_x value resulting in a low PM value and vice versa.

Variations are at maximum for the follow-up vehicle, which displays both the highest and the lowest NO_x and PM values. Generally speaking, this vehicle type seems to be rather stable as the emission results at approximately 700 000 km do not differ significantly from the results at approximately 200 000 km. The average NO_x value is 13.8 g/km and average PM value 0.16 g/km.

Figure 17 shows the results for brand “C” Euro 3 diesel vehicles. In this case, four individuals were also measured, one of these three times. Here the picture is somewhat different. The scatter is smaller, but there is a clear upward trend for PM emissions, although the maximum mileage is much lower than in the previous case. The average NO_x value is 9.0 g/km and average PM value 0.14 g/km. Taking into account the differences in mileage the results indicate that brand “C” Euro 3 vehicles will provide an advantage over brand “A” Euro 2 vehicles for NO_x, but not necessarily for particles.

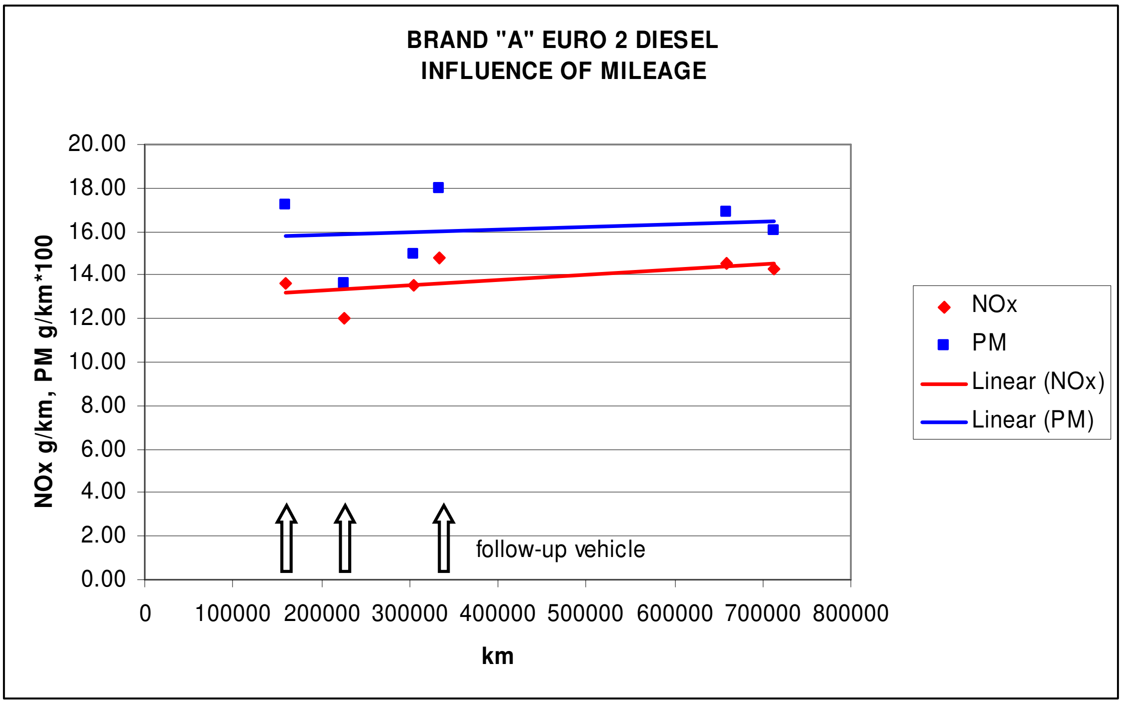

Figure 16. *NO_x and PM emissions as a function of mileage for brand "A" Euro 2 diesel vehicles.*

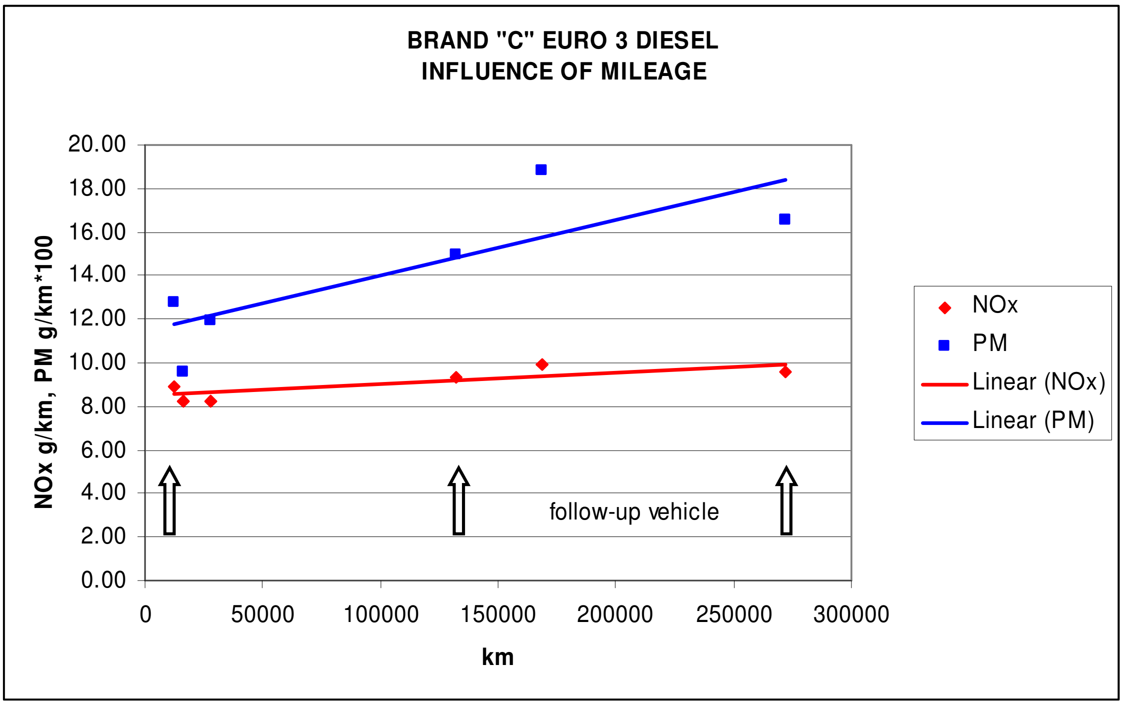

Figure 17. *NO_x and PM emissions as a function of mileage for brand "C" Euro 3 diesel vehicles.*

Figure 18 shows the results for brand "A" Euro 3 CNG vehicles. Three individuals were measured, one vehicle only once, one vehicle twice and one, the actual follow-up vehicle, three times. The follow-up vehicle was a two-axle bus, the two others were three-axle buses. In Figure 18, all these vehicles are treated as one category. For the CNG vehicles, THC has also been added to the Picture.

The CNG vehicles are stable for both NO_x and particles. As for particles, the mass emission values for CNG are very close to the detection limit. As the measurements for the National Bus Project were made using the ordinary diesel dilution tunnel, the results should be considered indicative, not absolute.

THC emissions (in the case of CNG vehicles more than 95 % methane) increase over time, mainly due to reduced efficiency of the oxidation catalyst. The average NO_x value is 9.1 g/km, average PM value 0.01 g/km and average THC value 1.2 g/km. A THC value of 2 g/km is reached around 150 000 km.

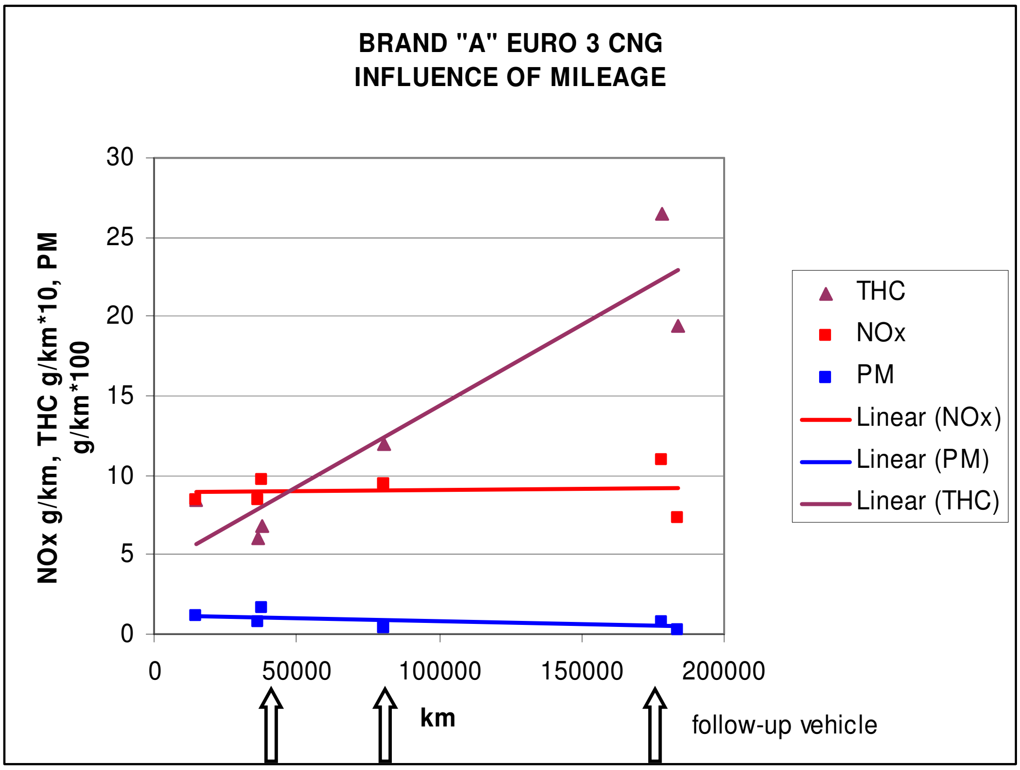

Figure 18. NO_x, PM and THC emissions as a function of mileage for brand "A" Euro 3 CNG vehicles.

4.4 PARTICLE EMISSIONS OF LOW-EMISSION VEHICLES

Particle emissions are of special interest as particles are considered the most harmful emission components in urban air. Compared with baseline diesel vehicles, CRT equipped diesel vehicles and natural gas vehicles reduce particle mass emissions by a factor of 10.

Figure 19 shows particle mass results from the diesel/natural gas comparison. The values were within the range of 0.2 (diesel without after-treatment) to 0.002 (lean-mix 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 still lower PM mass emissions than the CRT equipped diesel.

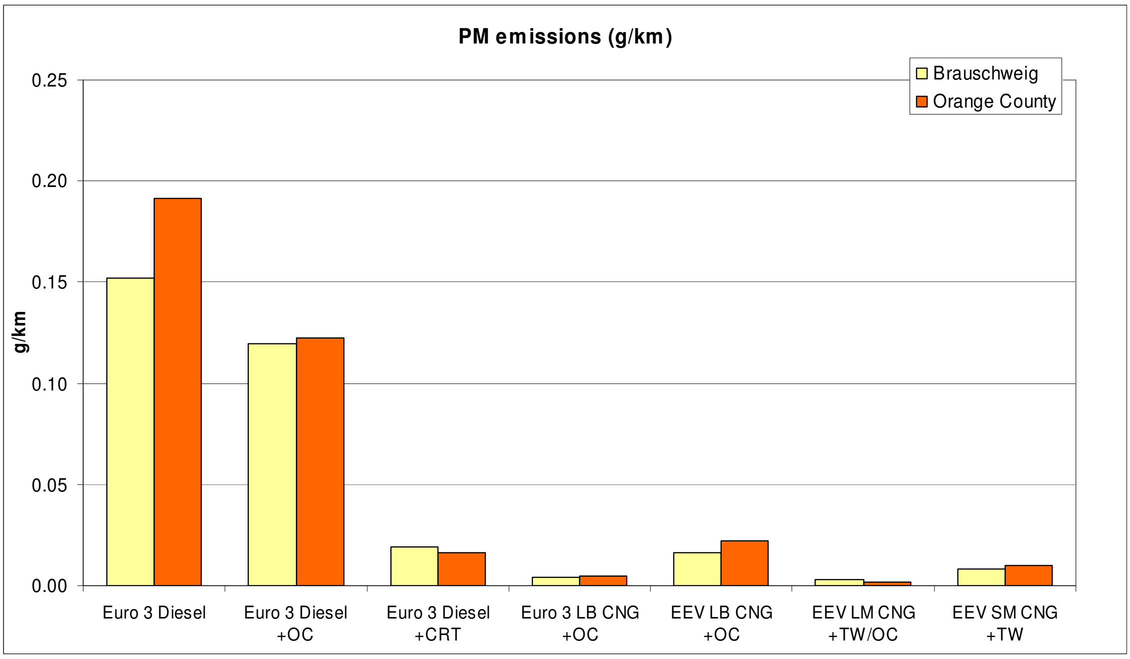

Figure 19. PM mass results from the diesel/natural gas comparison. LB = lean-burn, LM = lean-mix (mixed combustion system), SM = stoichiometric.

It can be debated how stable these low particle emitters are. Altogether five CRT equipped buses were measured. In three of these buses the CRT filter was in good working order. The lowest PM value obtained with CRT was some 0.015 g/km. The average PM value for diesel vehicles without filters is around 0.2 g/km.

One CRT filter did not reduce particles, and one filter actually increased particle emissions relative to the baseline vehicle (Figure 20). The latter phenomenon can only be explained by a disintegrating filter matrix of a totally damaged filter. In the case of the other damaged filter, the oxidation catalyst block upfront the actual filter had come unstuck and moved to partially block the filter. As a consequence, the efficiency of the filter was significantly reduced and the exhaust backpressure and, thus, fuel consumption increased.

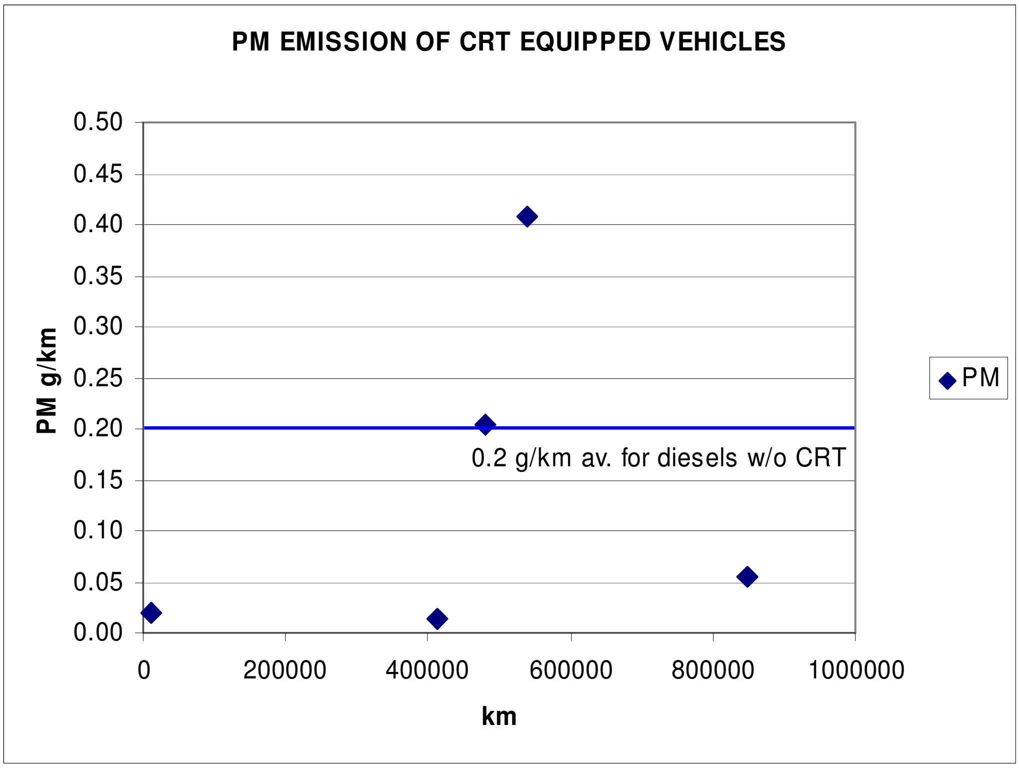

Figure 20. PM emission of CRT filter equipped diesel vehicles.

It is noteworthy that the bus with the highest mileage of all measured buses, a MY 1996 CRT bus with some 850 000 km, displayed good PM results, 0.05 g/km. The experience demonstrates that neglecting service will destroy the filters, but CRT filters can be long-lasting, when properly serviced.

Figure 21 depicts the particle emissions of CNG vehicles as a function of mileage. The highest driven distance was 673 000 km. The PM emissions of CNG vehicles seem to be very low and stable. In this respect, CNG vehicles perform better than CRT equipped diesel vehicles.

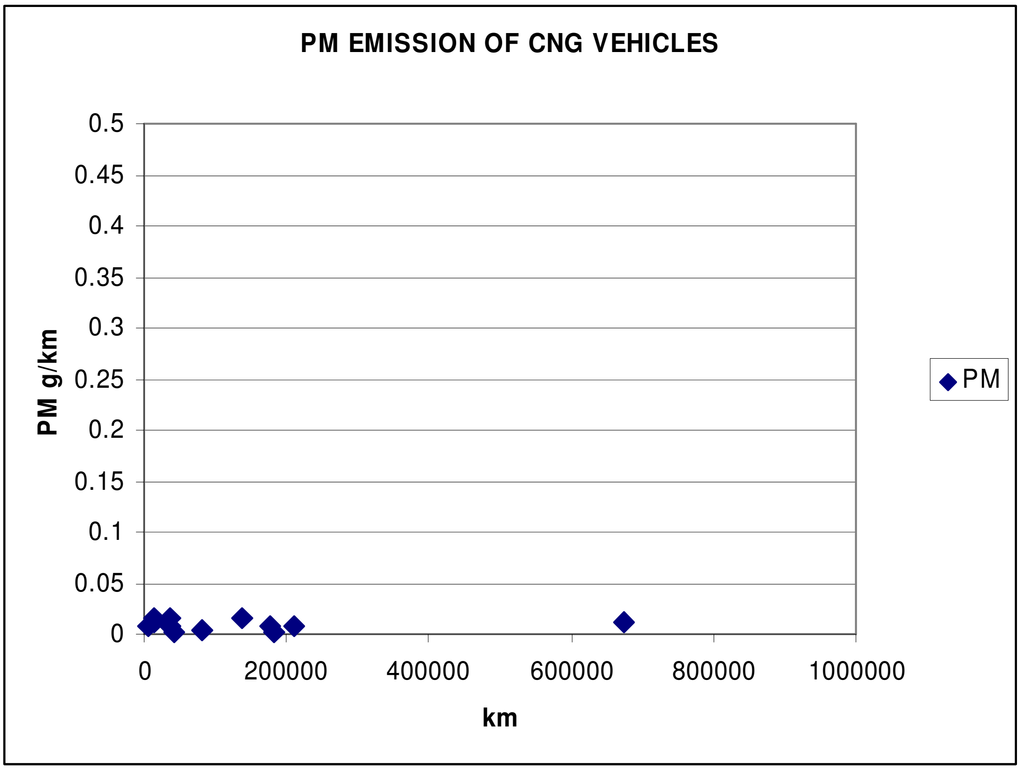

Figure 21. PM emission of CNG vehicles.

4.5 EFFECT OF VEHICLE WEIGHT ON EMISSIONS

Some vehicles were measured simulating both a two-axle and a three-axle vehicle. The load (half load in both cases) was around 3 000 kg for the two-axle vehicles and some 5 000 kg for the three-axle vehicles. Figure 22 (Euro 3 diesel) and 23 (EEV CNG) show examples of the absolute emission values for two- and three-axle vehicles. Figure 24 illustrates the emissions of the three-axle version relative to the two-axle version.

For the three-axle vehicles, relative emission are 83 – 133 % compared to the two-axle vehicles. The only emission component which is reduced with increasing load is CO in the case of the diesel vehicle, all other emissions increase. For the CNG vehicle, THC and PM values increase by some 30 %. It should, however, be kept in mind that the absolute PM values of the CNG vehicle are extremely low. For both vehicle types, NO_x increases by some 5 % and CO_2 (fuel consumption) by some 10 - 15 %.

A mass of 3 000 kg is equivalent to some 40 passengers, 5 000 kg to some 67 passengers. Hence, when emission and fuel consumption values are calculated per passenger kilometre, the three-axle buses are more advantageous. Energy consumption, for example, is 0.5 MJ per passenger kilometre for the two-axle diesel bus and 0.34 MJ per passenger kilometre for the three-axle diesel bus. If the calculations were performed for fully laden buses, the three-axle buses would be even better.

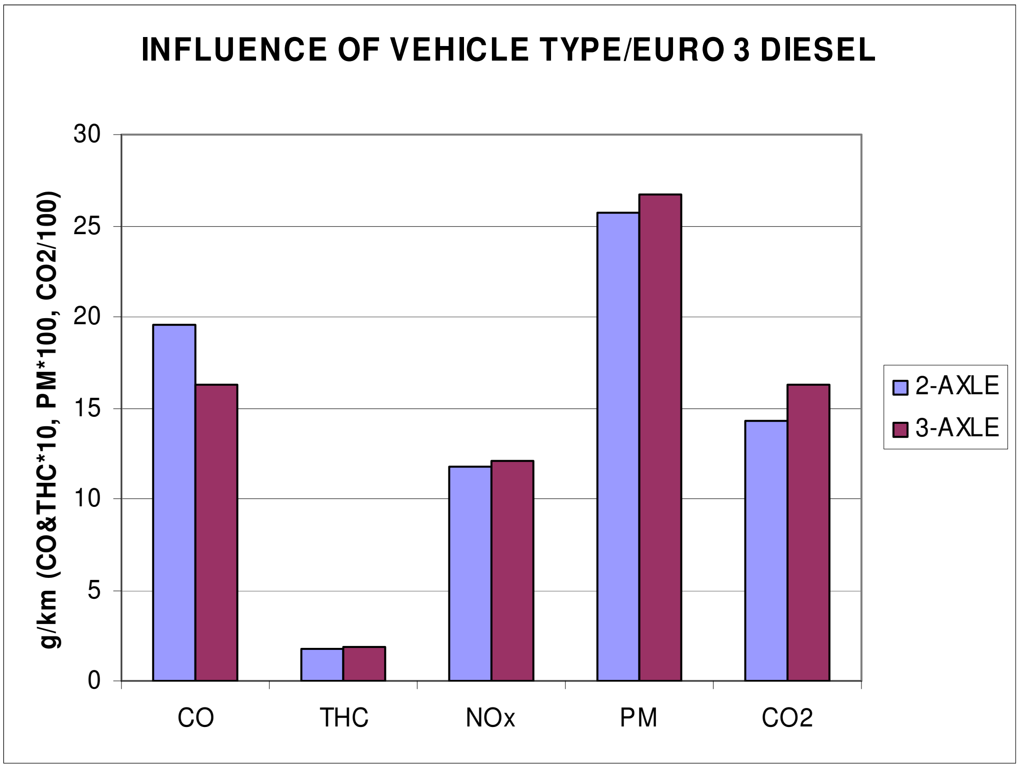

Figure 22. *Effect of vehicle weight on emissions, Euro 3 diesel, half load.*

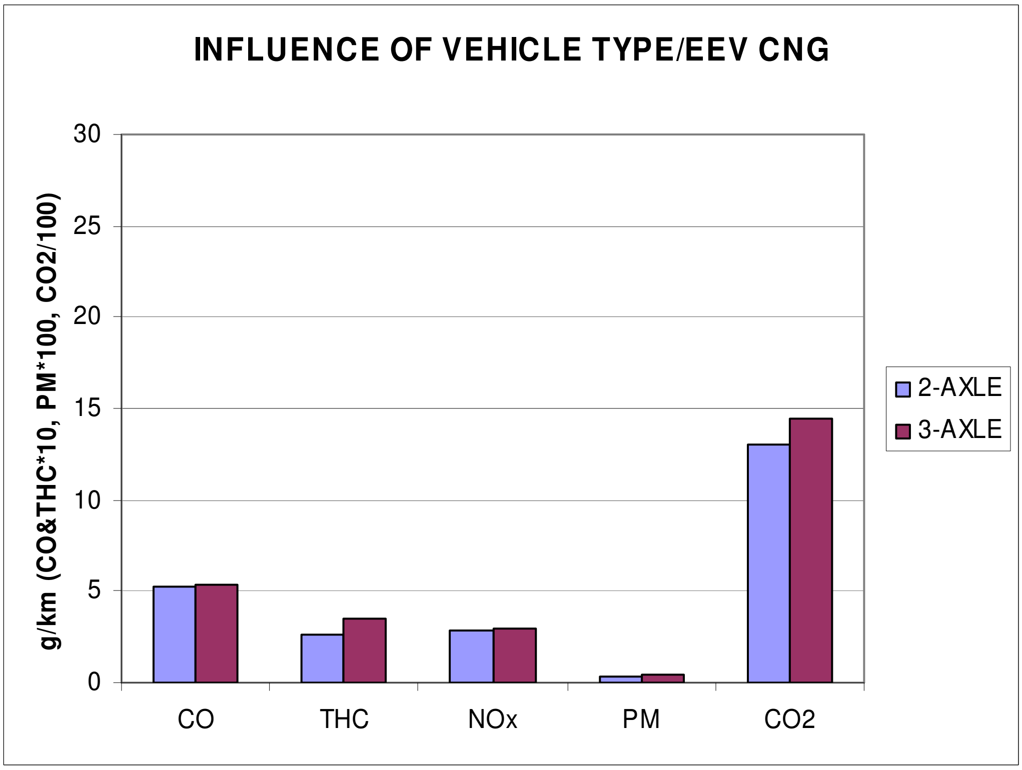

Figure 23. *Effect of vehicle weight on emissions, EEV CNG, half load.*

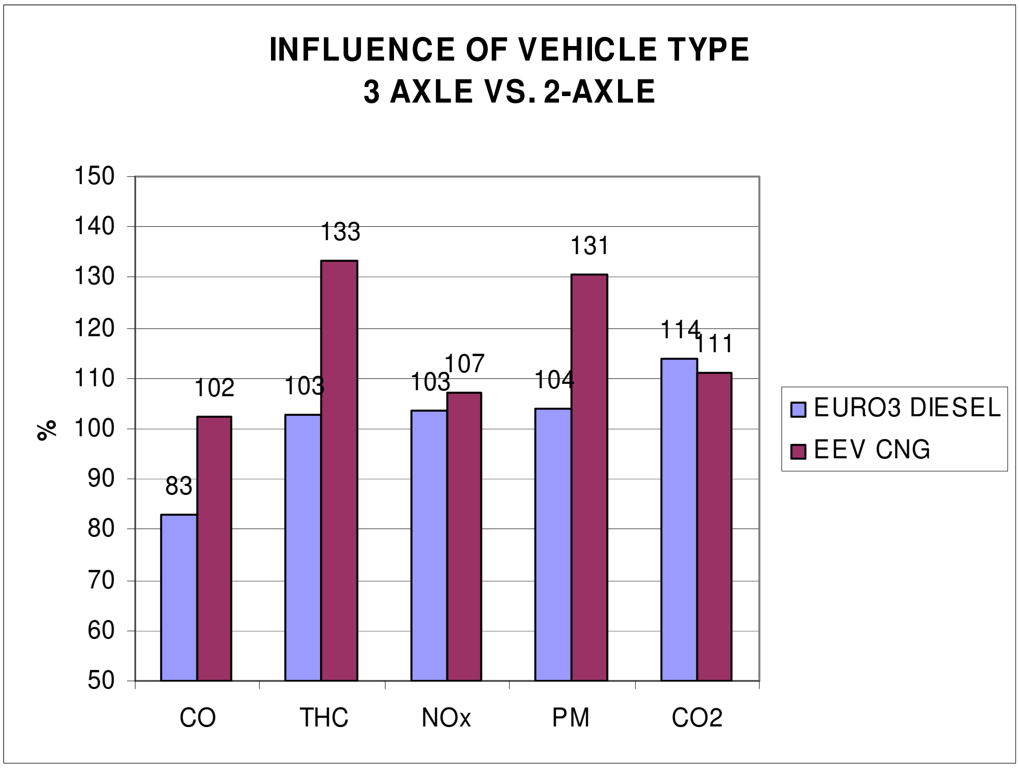

Figure 24. Relative emissions, three-axle vs. two-axle (two-axle marked as 100 %).

4.6 EFFECT OF DIESEL FUEL QUALITY ON EMISSIONS

On request of the Swedish Road Administration, two diesel vehicles, one Euro 2 and one Euro 3, were tested with both commercial Finnish diesel fuel and Swedish Environmental Class 1 fuel (MK 1). The results are presented in Figure 25.

MK 1 fuel reduced all other emission components, but not THC. For both vehicles, the NO_x reduction was some 5 %. The MK 1 fuel was more effective for PM reduction in the Euro 2 engine than in the Euro 3 engine, 25 vs. 15 % PM reduction. In fact, the Euro 2 engine with MK 1 fuel produced less particles than the Euro 3 engine with MK 1, whilst the Euro 2 engine had higher PM emissions with base fuel. A 25 % reduction in PM emissions must be considered significant. Tailpipe CO_2 emission was not affected.

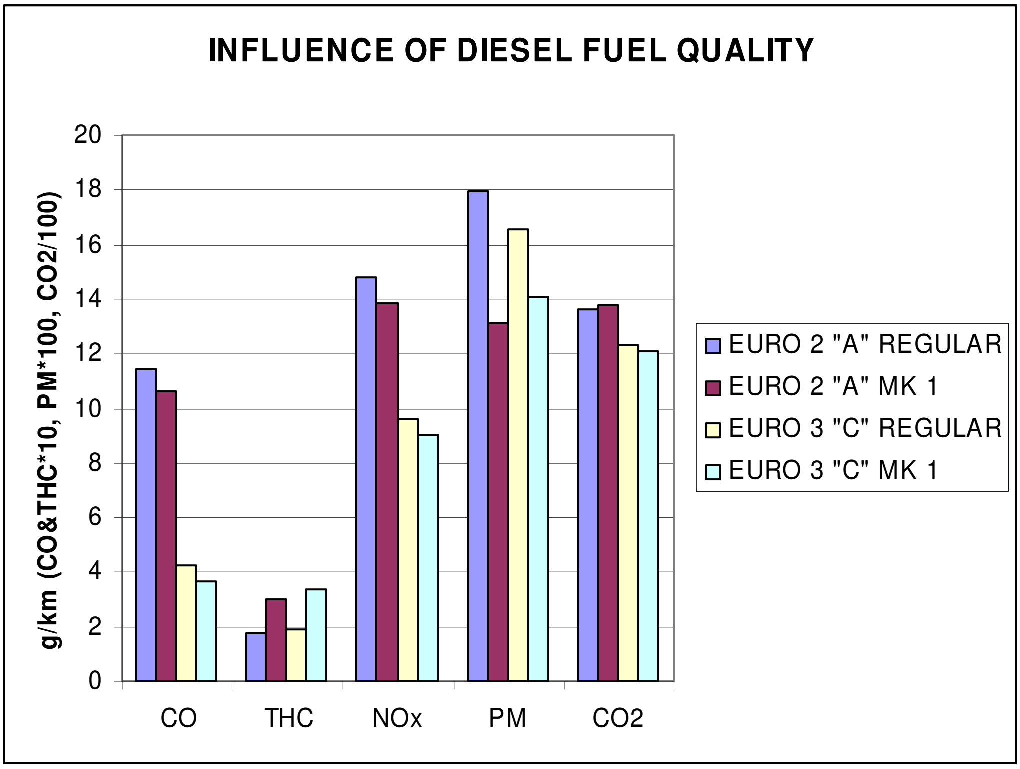

Figure 25. Effect of diesel fuel quality on emissions.

4.7 SPECIAL EMISSION MEASUREMENTS

4.7.1 General

For the diesel/natural gas vehicle comparison, VTT conducted a comprehensive program for special emission measurements. Seven out of the total of 34 vehicles were subjected to special emission testing (see 3.3 and 3.5.2). A full report on the diesel/natural gas comparison can be found at:

http://www.vtt.fi/inf/pdf/jurelinkit/VTTNylund.pdf

Here only some examples of the results are given (NO_2, aldehydes, particle numbers, PAH emissions).

4.7.2 NO and NO_2 emissions

Exhaust after-treatment affects the ratio of NO_2 to NO_x (Figure 26). 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 Appendix).

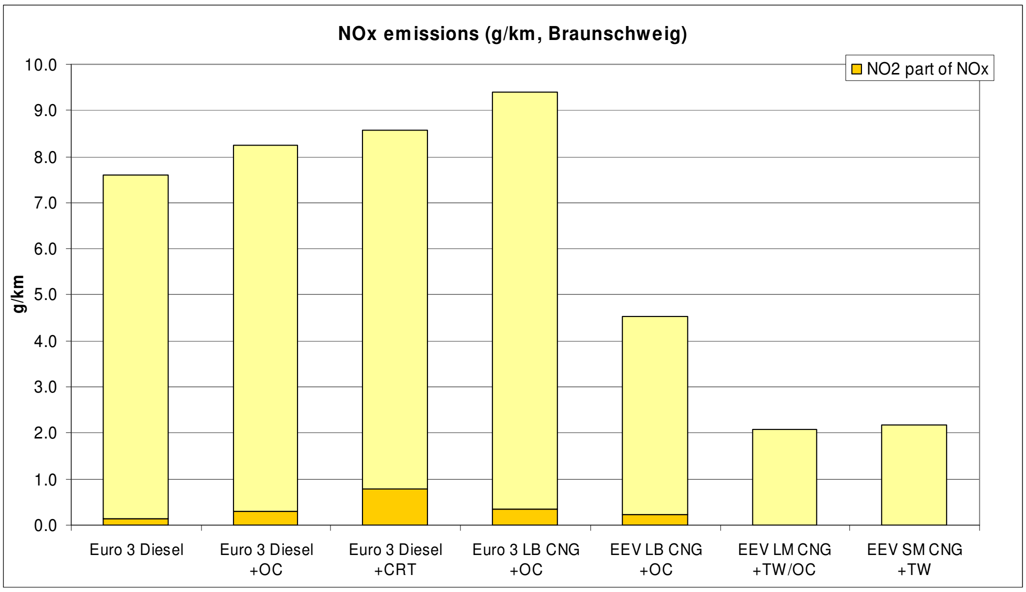

Figure 26. NO_x and NO_2 emissions (BSC).

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.

4.7.3 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 %. On an average, the LB CNG vehicles gave the same formaldehyde emission as CRT, some 5 mg/km. For the LM and SM CNG vehicles, aldehyde emissions were practically nil.

4.7.4 Particle size and number

The results shown are based on measurements with the ELPI (electrical low-pressure impactor) instrument. Figure 28 depicts particle size distribution over the BSC and OCC duty cycles. Please note that the Figure has a logarithmic scale.

Compared with the baseline diesel, the number of particles was reduced by two orders of magnitude both with CRT and in three of the four CNG vehicles (lower group of traces in Figure 28). 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. There are two possible explanations for this, oil consumption behaviour of the engine and catalyst performance. The latter is the most probable one, as the catalyst is mounted in a cool place on the roof of the vehicle.

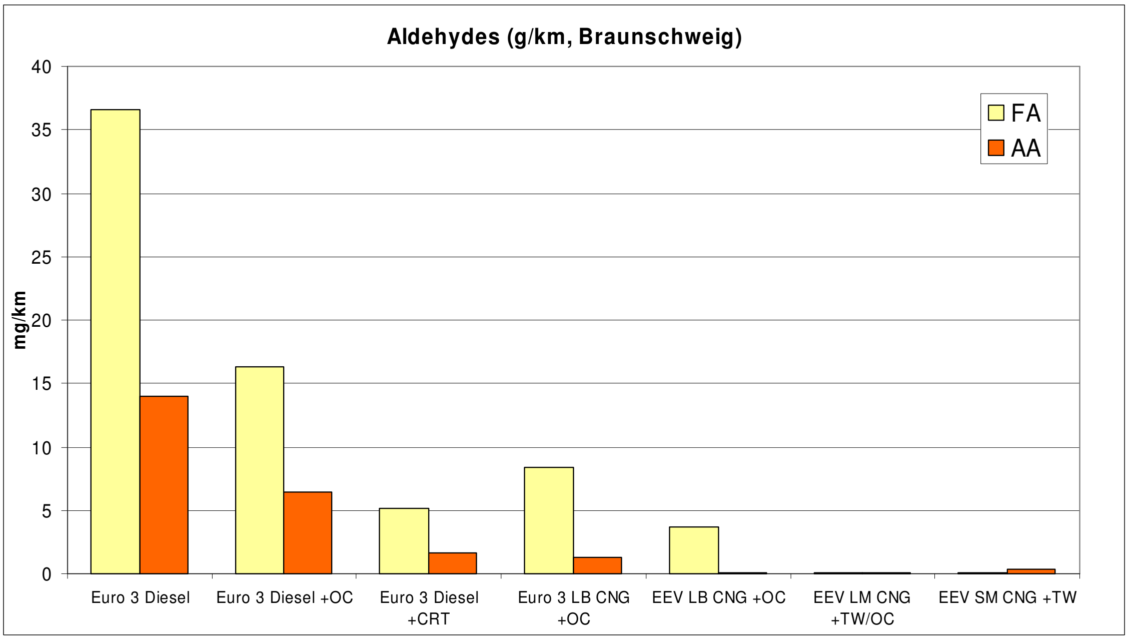

Figure 27. Form (FA)- and acetaldehyde(AA) emissions (BSC).

For the baseline diesel and diesel with catalyst, a clear particle accumulation mode peak was found at approximately 100 nm. The catalyst was able to reduce particle numbers somewhat in the smallest categories.

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.

4.7.5 PAH emissions

Regarding PAHs, 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. 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.

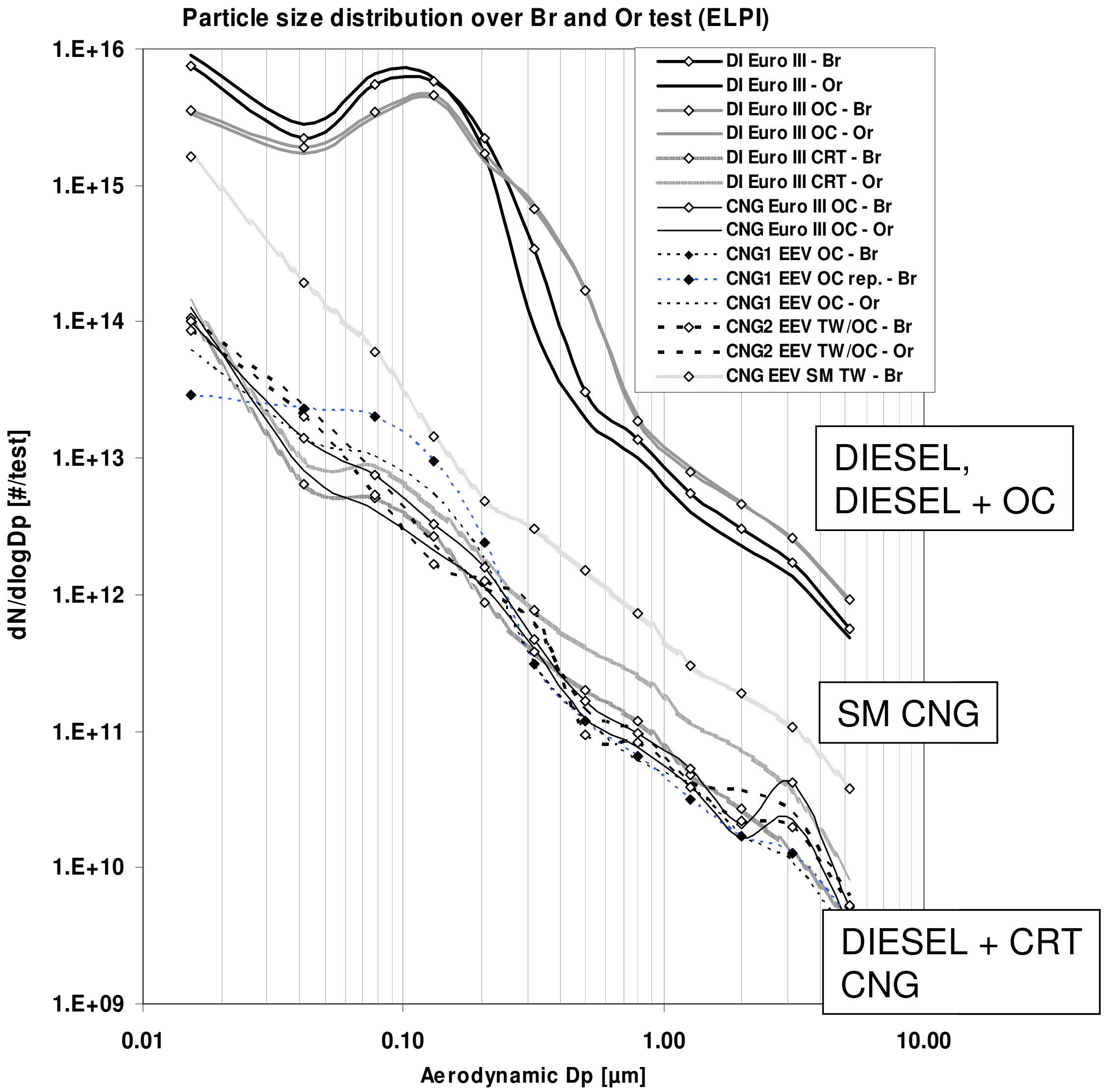

Figure 28. Particle size distribution.

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:

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

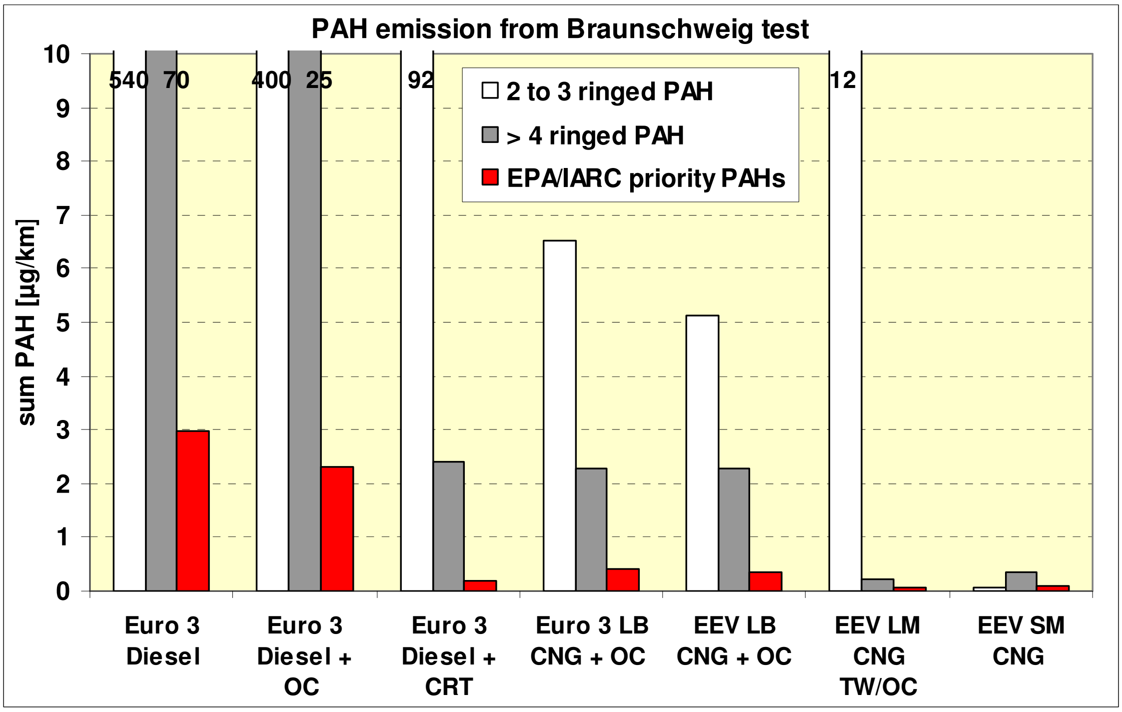

Figure 29. Sum of PAH compounds (BSC).

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 emissions of both 2 - 3 ringed and +4 ringed PAHs are smaller with an order of magnitude. The emission of priority PAHs is 50 - 70 % lower compared to CRT diesel.

4.7.6 Summary of special emission measurements

Figure 30 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.

CNG gave the best overall emission performance. Depending on the vehicle, CNG can even provide a reduction in CO_2 emissions.

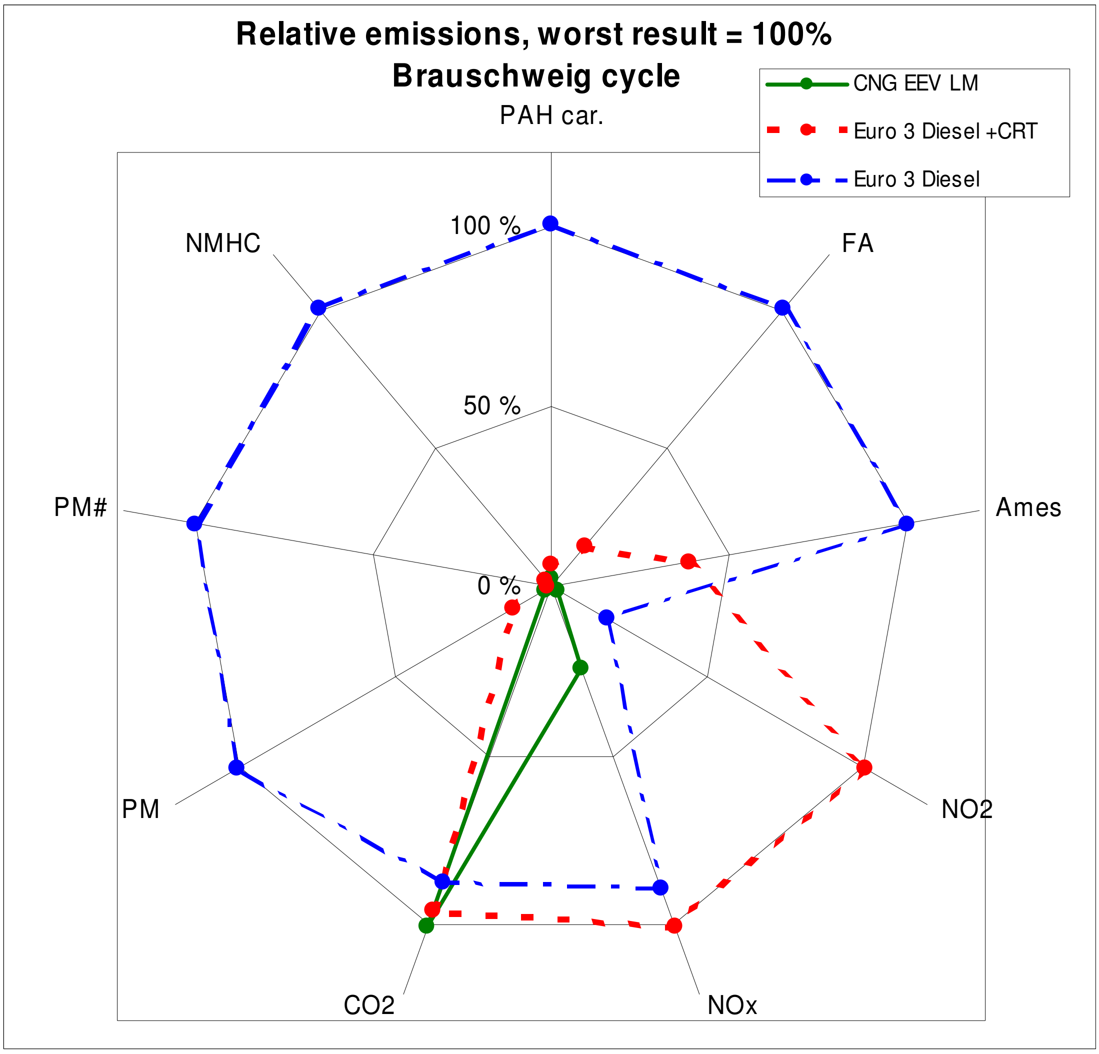

Figure 30. *Comparison between diesel without after-treatment, CRT diesel, and LM CNG. The worst result is given the index 100.*

5 SUMMARY

Within 2002 – 2004, Technical Research Centre of Finland (VTT) measured altogether 34 different Euro 1 – EEV certified city buses. The original project plan for the National Bus Project listed the following tasks:

- comparison of alternative vehicle technologies
- truthful emission factors for in-use vehicles and deterioration factors for various technologies
- effect of duty cycles on emissions

The buses within the National Bus Project were measured for regulated emissions and CO_2 only. In parallel with the National Bus Project, a comprehensive study of emissions from top-of-the-line diesel and natural gas buses was conducted. This study gave detailed information on both regulated and unregulated emissions from diesel and natural gas vehicles.

All measurements were made in the new chassis dynamometer at VTT. The output of the measurements is truthful emission factors in the form of g/km. These emission factors reflect typical driving patterns and the properties of the complete vehicles.

There were large variations in the regulated emissions. Euro 1 diesel vehicles and EEV natural gas vehicles make up the extreme ends. The NO_x emission varied from some 20 g/km for Euro 1 diesel vehicles to approximately 2 g/km for the most advanced natural gas vehicles. For particulates, the spread was even greater, i.e., from 0.6 to 0.003 g/km, a difference of a factor of 200.

Older CNG vehicles show rather high THC or methane emissions. Methane, however, in neither toxic nor reactive and, thus, of little relevance for urban air quality, even though a quite strong greenhouse gas.

Good news is that real-life emissions seem to be falling with advancements in Euro classes. On an average, Euro 2 vehicles demonstrate lower NO_x and PM values than Euro 1 vehicles, Euro 3 lower than Euro 2, and finally EEV lower than Euro 3. For diesel vehicles, the spread from brand to brand and individual to individual seems to decline with advancements in engine technology.

A two-axle city bus needs some 1.8 kWh of work (on the engine crankshaft) per kilometre when driven over the Braunschweig bus cycle. This relationship makes it possible to compare emissions values from chassis dynamometer tests and emission certification values based on engine tests (although the load patterns differ a lot). Average emission values for vehicles representing different emission certification classes seem to be in quite good coherence with the certification limit values.

CO_2 emissions and energy consumption vary by a factor higher than 1.5. The lowest CO_2 equivalent emissions were measured for a CNG bus, the highest for a diesel bus.

Due to fuel chemistry, methane provides an advantage of some 25 % in specific CO_2 emission compared with diesel fuel. However, due to lower engine efficiency the energy consumption of CNG vehicles is higher compared with diesel vehicles. On an average, the difference is 25 – 30 % compared with diesel vehicles without CRTs and 15 – 20 % compared with CRT equipped diesels. With current technology, this means that the benefit arising from fuel chemistry is more or less mitigated and CNG vehicles have roughly equivalent CO_2 emissions compared with diesel vehicles.

When evaluating a number of duty cycles it was found that the effect of duty cycle on emissions is rather small. However, no extreme cycles were included. CO_2 correlates to the average load. For the diesel vehicles, NO_x and PM also follow the same trend, whereas in the case of CNG the cycle has little effect on NO_x and PM values.

The numbers of measurements with brand "A" Euro 2 diesel vehicles, brand "C" Euro 3 diesel vehicles, and brand "A" Euro 3 CNG vehicles (lean-burn) are sufficiently high to estimate emission stability with vehicle mileage. Brand "A" Euro 2 diesel vehicles seem to be very stable for NO_x and PM emissions, whereas brand "C" Euro 3 diesel vehicles show a trend of increasing PM emissions with mileage. Taking into account the differences in mileage the results indicate that brand "C" Euro 3 vehicles will provide an advantage over brand "A" Euro 2 vehicles for NO_x, but not necessarily for particles in the long run. The Euro 3 CNG vehicles seem to be stable regarding NO_x and PM emissions. However, the increase in THC emissions is rather steep, indicating a need to replace the oxidation catalyst at around 200 000 km and to maintain the ignition and combustion systems in time.

It is interesting to study PM emissions of low-emitting CRT diesel vehicles and natural gas vehicles. Altogether five CRT vehicles were measured, and of these only three were in good or relatively good working order. To stay operational, a CRT filter needs some service. On the other hand, when properly maintained, a CRT can last more than 800 000 km.

Natural gas vehicles showed extremely low PM values independent of mileage. The highest mileage was close to 700 000 km.

At half load, a three-axle bus (67 passengers) consumes some 10 – 15 % more fuel compared with a two-axle bus (40 passengers). On an average, NO_x and PM emissions increase at the same rate. However, when calculating energy consumption and emissions per passenger kilometre, the three-axle bus naturally shows more advantageous results.

The effects of fuel quality on emissions were tested with one Euro 2 and one Euro 3 diesel bus. The baseline fuel was Finnish commercial diesel fuel with less than 50 ppm sulphur (S). The test fuel was low-aromatic Swedish MK1 fuel with less than 5 ppm S. MK1 reduced NO_x emissions by some 5 % and PM emissions by 15 – 25 %. The reduction in PM emissions is quite substantial.

For the detailed diesel/natural gas bus comparison, seven modern buses were tested for emission performance, three diesel and four CNG vehicles. The measurements included regulated emission components and a number of speciality measurements. 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.

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 stoichiometric or mixed combustion demonstrated NO_x levels of 75 % below Euro 3 diesel levels.

As a result of more than 200 tests with 34 different buses, VTT has now acquired solid knowledge of the emissions performance of various bus technologies. VTT’s measurements show that emission trends are moving downwards and huge emission reductions could be achieved by replacing the oldest vehicles with new vehicles, either diesel or CNG. VTT will continue its measurements. With the oncoming Euro 4 and Euro 5 requirements, new vehicles and new technical solutions will enter the market. Hopefully, further emission reductions will also be seen in real-life service of the new generation diesel vehicles.

6 ACKNOWLEDGEMENTS

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The tested vehicles were on loan from transport companies and vehicle manufacturer representatives.

Working in the test team at VTT Processes were Tom Eklund, Reijo Mikkola, Ari-Pekka Pellikka, Pekka Piimäkorpi, Hannu Vesala and Erkki Virtanen.

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APPENDIX 1

SIGNIFICANCE OF THE DIFFERENT EMISSION 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.

Carbon monoxide CO

Normally, CO emissions from a diesel engine are low, because diesel operates with 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.

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

In diesel engines, the exhaust contains hydrocarbons (HCs) derived from partly burned (or un-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 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 of 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)

Nitrogen oxides, NO_x

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 it irritates the respiratory organs. Therefore, ambient air quality regulations set limit values for 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.

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.

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.

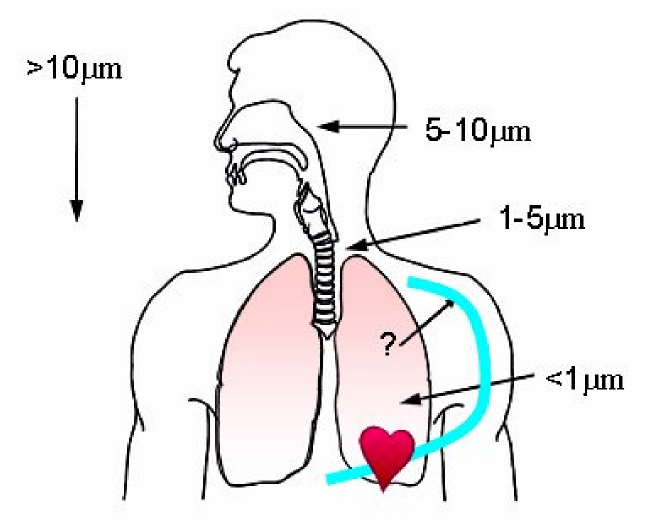

Figure 1. Particles entering the human body (Altshuler 2002).

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 the 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.

Other components

Sulphate and nitrate may have some adverse health effects, 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).