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Emissions and Fuel Consumption of Clean City Bus Concepts

Elaborated by order of

BMLFUW, BAFU, GVB, STGW

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Summary:

Since the type approval test cycles ESC and ETC do not sufficiently cover the engine loads occurring in city operation, emission levels of city buses cannot be assessed in a reliable way by the type approval data. For this reason different city buses with low emission concepts were tested on the roller test bed for heavy duty vehicles. The emissions and fuel consumption for four CNG buses and for one diesel bus with a SCRT system were measured in real world city bus cycles. The results showed quite low emissions for all of the buses tested, but considerable differences between the individual models.

The measurement program and the report should serve as a support for authorities dealing with low emission city bus concepts. Updates are planned when more low emission vehicles are made available.

Key Words: Low emissions, city buses, emission measurement, roller test bed for HDV

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List of abbreviations

CNG .... Compressed Natural Gas
CRT .... Continuous Regenerating Trap
EEV ……..…Enhanced Environmentally Friendly Vehicle
ESC................ European Stationary Cycle (steady state type approval cycle for HDE)
ETC .... European Transient Cycle (transient type approval cycle for HDE)
EU.................. European Union
HDV .... Heavy Duty Vehicles (>3.5t gross vehicle weight)
HDE............... Heavy Duty Engine (engine of a vehicle with >3.5t gross vehicle weight)
LPG .... Liquefied Petrol Gas
NOx .... Nitrogen oxides (NO + NO_2)
PC .... Particle Counts (i.e. particle number emissions)
PM .... Particulate Matter
SCR .... Selective Catalytic Reduction
TU-Graz .... Graz University of Technology

1 Introduction

Cities and communities are interested in city buses with low exhaust gas emissions due to air quality problems. The main topic in terms of exceeding air quality targets is PM 10 and NO_x exhaust gas components, for which conventional diesel engines are a relevant source. For this reason, alternative propulsion systems like Compressed Natural Gas (CNG) and Liquefied Natural Gas (LPG) as well as improved diesel buses with exhaust gas after treatment are of special interest since they promise the lowest pollutant emissions. While several CNG driven HDV are already certified according to EEV (Enhanced Environmentally Friendly Vehicle), diesel engines with EEV certification are just starting to enter the market. Table 1 shows the relevant limit values for the exhaust gas emissions of HDE in the European Union. The main demand on diesel engines for meeting EEV is the lower limit for particle matter in the ETC cycle (0.02 g/kWh for EEV instead of 0.03 g/kWh for EURO V).

Table 1: Exhaust gas emission limits for heavy duty engines in the EU

Date	Name	Test Cycle	CO	HC	NO_x	PM
			[g/kWh]			
1995	EURO II	ECE R 49	4	1.1	7.0	0.15
2000	EURO III	ESC	2.1	0.66	5.0	0.1
		(ETC)	5.45	0.78	5.0	0.16
2005	EURO IV	ESC	1.5	0.46	3.5	0.02
		ETC	4.0	0.55	3.5	0.03
2008	EURO V	ESC (1)	1.5	0.46	2.0	0.02
		ETC	4.0	0.55	2.0	0.03
-	EEV	ESC (1)	1.5	0.25	2.0	0.02
		ETC	3.0	0.40 (NMHC(2))	2.0	0.02

(1) ESC is not mandatory for gas driven engines

(2) Non Methane Hydrocarbons

What is most relevant for diesel engines are the emission levels of NO_x and of particulate matter (PM). The limits for those exhaust gas components are also shown in Figure 1.

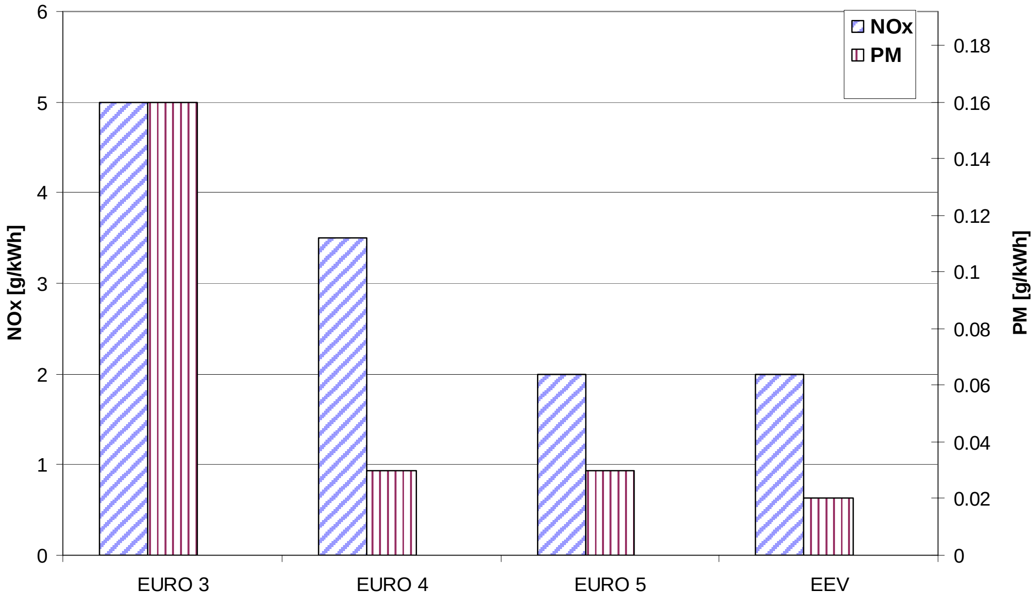

Figure 1: Exhaust gas emission limits of NOx and PM for heavy duty engines in the EU (values given for the ETC cycle)

New registered vehicles have had to fulfil EURO IV since 1.10.2006 (mandatory for all new type approvals since 1.10.2005). Compared to EURO IV, the EEV engines have to meet lower NO_x emissions and lower PM emissions in the type approval.

However, measurements on Heavy Duty Vehicles (HDV) showed that emission behaviour in real world driving can differ substantially from the emission level in the type approval cycle[1]. This is especially true for urban driving since the type approval test cycles ESC and ETC do not sufficiently cover the engine loads occurring in city operation.

Figure 2 compares the engine loads in the type approval cycle (ETC) and in a real world city bus cycle. The most frequent loads in the ETC are normalized engine speeds of approximately 70% (0% is idling, and 100% is rated speed) with varying engine power. This load pattern is representative for highway driving at various road gradients and phases of acceleration and deceleration. Full load also occurs quite frequently. In city buses, on the other hand, engines are usually driven at lower engine speeds and the engine load covers a rather broad range, which is typical of city driving with frequent starts and stops. The automatic gear box of city buses certainly contributes to the different engine loads of buses, too.

[1] E.g. tests on more than 100 engines and vehicles in the project ARTEMIS (**A**ssessment and **R**eliability of **T**ransport **E**mission **M**odels and **I**nventory **S**ystems, http://www.trl.co.uk/ARTEMIS)

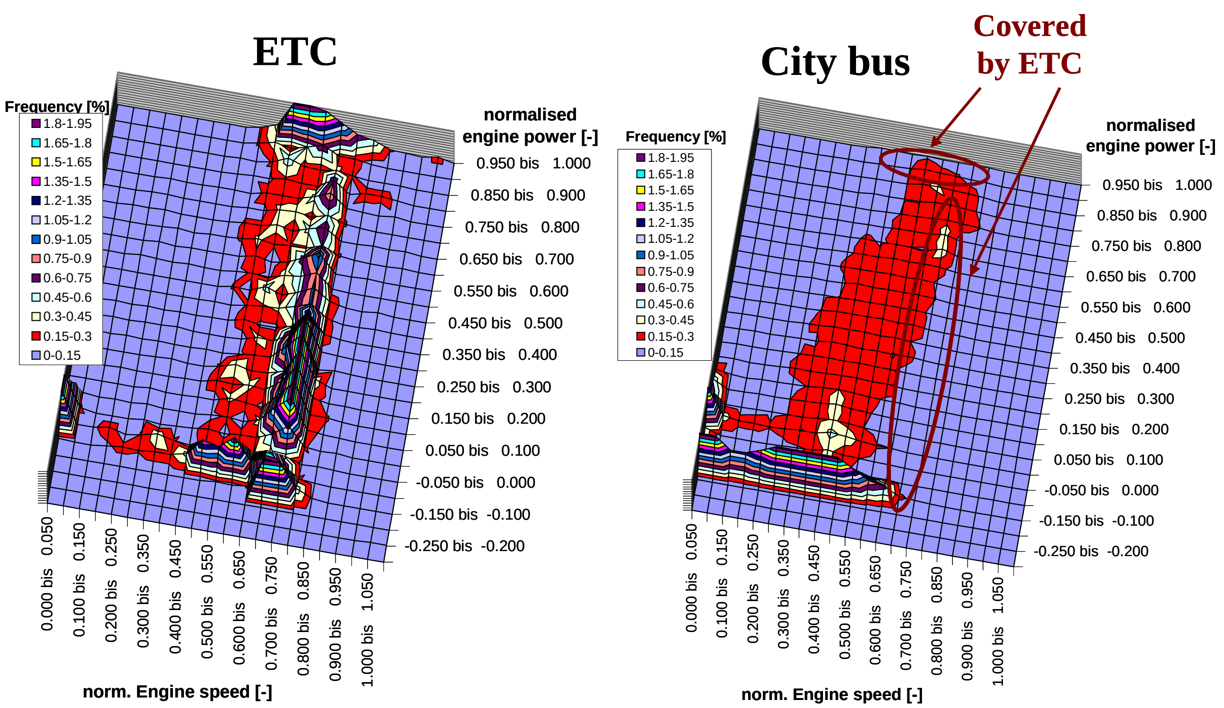

Figure 2: Comparison of the engine loads driven in the ETC (European Transient Cycle) and in a real world city bus cycle (Braunschweig cycle)

Due to the shortcomings of the type approval cycles, manufacturers are not forced to optimise the engines at the typical operation points of city buses for low emission levels. Certainly several other targets for the development of bus engines exist (low fuel consumption, drivability, durability, noise,…). A trade off exists, in particular, between fuel efficiency and NO_x emissions, which leads to a conflict of targets in the application of engines. A given engine can be tuned towards lower specific fuel consumption which then results in the drawback of increasing NO_x emission levels[2]. Since the NO_x emissions of buses are not directly recognised by the owner, but better fuel economy significantly lowers costs, an incentive exists for optimising engines outside of the type approval cycle for high fuel efficiency, but not for low NO_x emissions. Due to the flexible electronic engine control systems of modern engines, the engine can demonstrate quite different emission behaviour in the type approval cycle and in typical bus driving. Thus the emission levels in real world bus driving cannot be concluded from the type approval levels.

To test modern city buses with low emission levels under real world driving conditions, Switzerland, Austria (in the D.A.CH.-NL cooperation), the GVB and the STGW have launched the present project, in which buses are measured on the roller test bed in real world driving cycles.

If the work proves to be a useful tool, a continuation of the tests with further clean city bus concepts is foreseen to provide information and an extended database of potential low emission concepts for decision makers.

[2] Such measures are, for example, an earlier fuel injection or, for CNG engines in particular, a lean burn concept, in which a 3-way catalyst does not reduce NOx emissions.

2 Test program

An overview on the roller test bed, the vehicles tested, the test cycles and the standard sequence of test runs is described in this chapter. Details for the individual vehicles and the corresponding tests are given in chapter 4.2.

3 Roller test bed

The mechanical test stand unit is built in the form of a steel frame construction, in which the roller set, flywheel and electrical brake unit are installed. The frame is integrated into the building by anti-vibration elements. The brake is a thyristor-controlled d.c. machine, which can be driven as generator (brake operation) and motor (motoring operation). The brake control is appropriate for stationary and transient driving. Figure 3 shows a picture of the test bed.

Figure 3: Transient roller test bed at TU-Graz for HDV up to 38 tons and 360 kW with full flow CVS system (CVS system not in the picture)

The determination of the traction force at the point of tyre-contact takes place via measurement of the torque at the brake machine by means of a load cell, which operates according to the DMS principle. The simulated vehicle speed is recorded by measuring the roller speed.

The test stand is equipped with a wind simulator to achieve thermal engine cooling conditions that are comparable to real driving.

Technical specifications:

max. traction force	27 kN
max. braking power:	360 kW
max. drag power:	290 kW
max. speed:	120 km/h
vehicle mass range:	3.5t to 38t

diameter of the rolls: 0.5m
max. axle weight: 12t

CVS system

The CVS (Constant Volume Sampling) system, together with the exhaust gas analysing system, is a complete measuring system to record the limited emissions of heavy duty engines. The system can be used for steady state and transient conditions. The system is automatically controlled by the software TORNADO from Kristl&Seipt Engineers. For measurement of the gaseous emissions, a AVL CEB II bench is used. The exhaust gas measurement system fulfils the current regulations for HDE in the EU and the US.

Particle number measurement

Proper sampling is essential for an accurate, repeatable and meaningful measurement of the particulate number and size distribution. At the FVT, a special system was developed which also fulfils the current definitions of the PMP group (Particle Measurement Programme Working Group):

- Variable dilution (1:1 to 1:1000, usually set between 1:25 and 1:100) to meet the measurement range of the CPC
- Heating of the probe to eliminate nucleation particles without carbon core (effect of heating and dilution)
- Antistatic materials and short length to minimise losses in the system.

The system is shown in Figure 4 for the set up in combination with a CVS tunnel. A set up for measurement in undiluted exhaust gas is also possible.

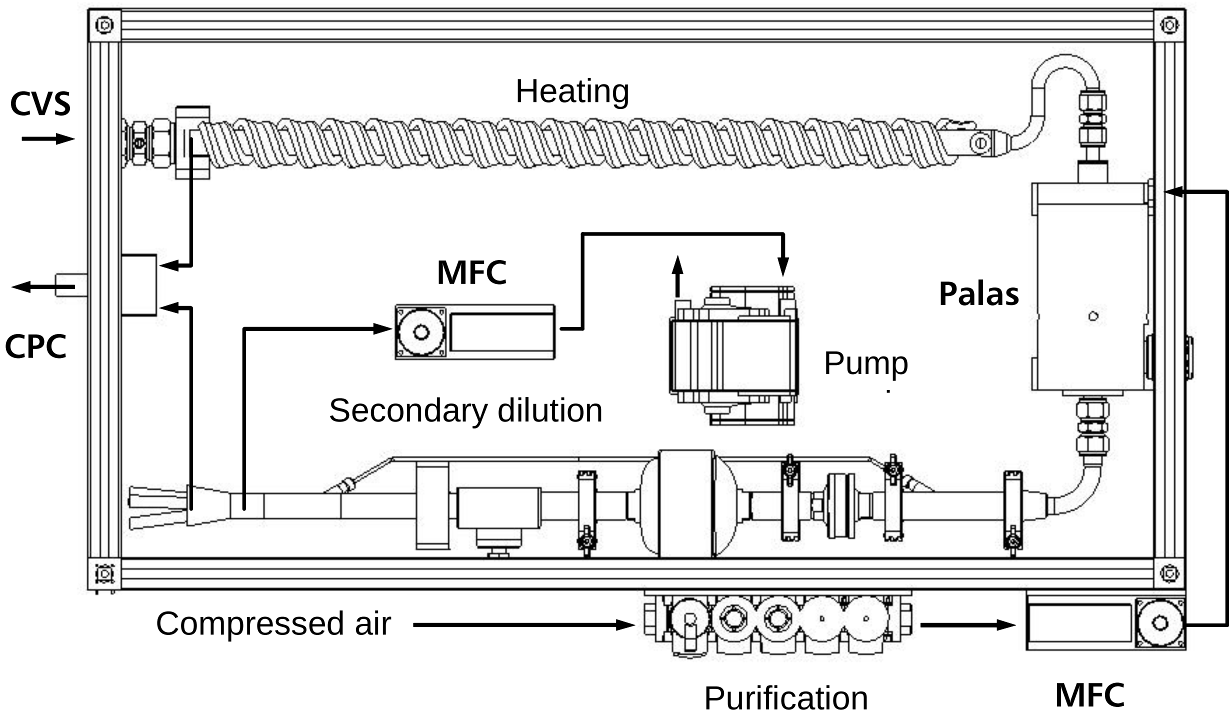

Figure 4: Schematic picture of the PM number and size distribution measurement system

CVS........... Constant Volume Sampling (CVS-Tunnel of the test bed)
CPC........... Condensation Particle Counter
MFC .... Mass Flow Controller

The following measurement devices were used to measure the particulate number concentration and the size distribution:

- SMPS (TSI): a combination of an "Electrostatic Classifier", a "Differential Mobility Analyzer (Model 3081)" and a condensation particle counter (CPC 3010)
- Condensation particle counter (CPC 3010 or CPC 3070) for total particle number

The measurement system used and the preconditioning system are described, for example, in (Schmölzer, 2006).

3.1 Test vehicles

Table 2 shows a list of the vehicles included in this report. The Mercedes Citaro EURO III buses were measured in earlier projects for the bus company "Grazer Verkehrsbetriebe, GVB" and are included for comparison here.

Table 2: City buses measured

Vehicle	Fuel	year of constr.	Emission level	Exhaust gas aftertreatment
Diesel buses				
Mercedes Citaro / O 530 N3	Diesel	2002	Euro III	none
Mercedes Citaro / O 530 N3	Biodiesel	2003	Euro III	none
Mercedes Citaro / O 530 N3	Biodiesel	2003	Euro III	PM-Kat (PECS)
Irisbus-CITELIS S-Diesel	Diesel	2006	EEV	SCRT
CNG buses				
Mercedes 0405 N2-Gas	CNG	1999	Euro II	3-way catalyst
Mercedes O530 CITARO CNG EEV	CNG	2004	EEV	Oxicat
Volvo 7000 CNG Bus	CNG	2004	Euro IV	3-way catalyst
Irisbus- CITELIS S-CNG	CNG	2003	EEV	3-way catalyst

During the tests, the total vehicle weight was always set to the sum of the empty weight of the vehicle plus 3 tons to simulate passengers on board. The driving resistance values were obtained by coast down tests. The coast down tests were performed on the same test course for all buses.

3.2 Test cycles

A standard program, comprised of two real world bus cycles and three constant speed tests, was measured for all the buses. Special cycles were added for some buses on the suggestion of the manufacturer if they were necessary for internal comparison.

One real world cycle was obtained from the "Handbook on Emission Factors, HBEFA", (e.g. Keller, 1995). This "9040 cycle" represents bus driving in urban centre areas with short distances between the stations and high traffic volume (Figure 5). The acceleration levels in this cycle are rather low and represent driving situations, in which acceleration is limited by the traffic flow and not by the maximum vehicle power.

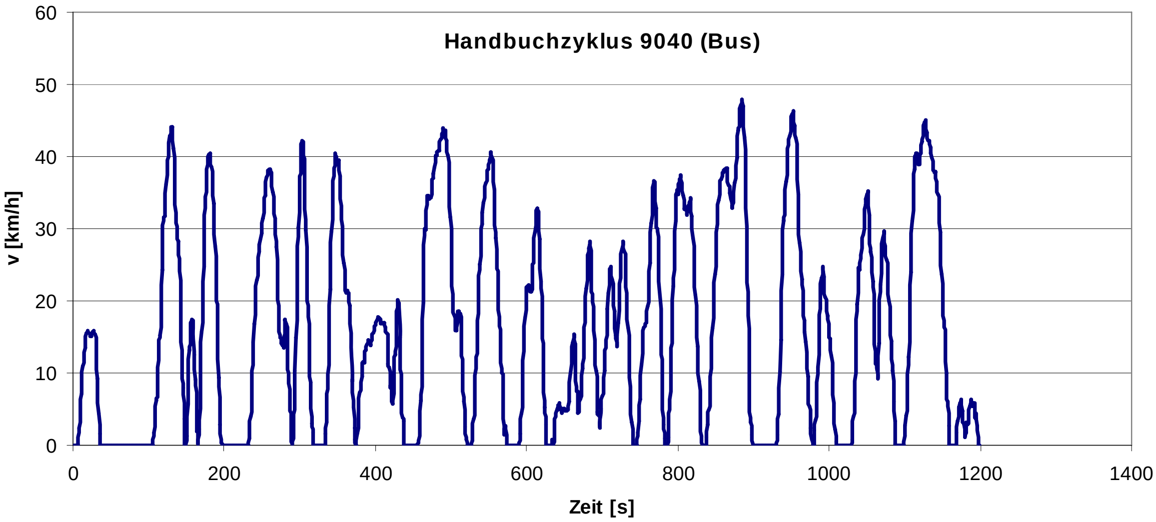

Figure 5: Real world city bus cycle 9040 from HBEFA

The “Braunschweig cycle” was used as a second real world cycle (Figure 6). The cycle was measured in the city of Braunschweig and is used for tests on city buses quite frequently in Europe, e.g. (Nylund, 2004).

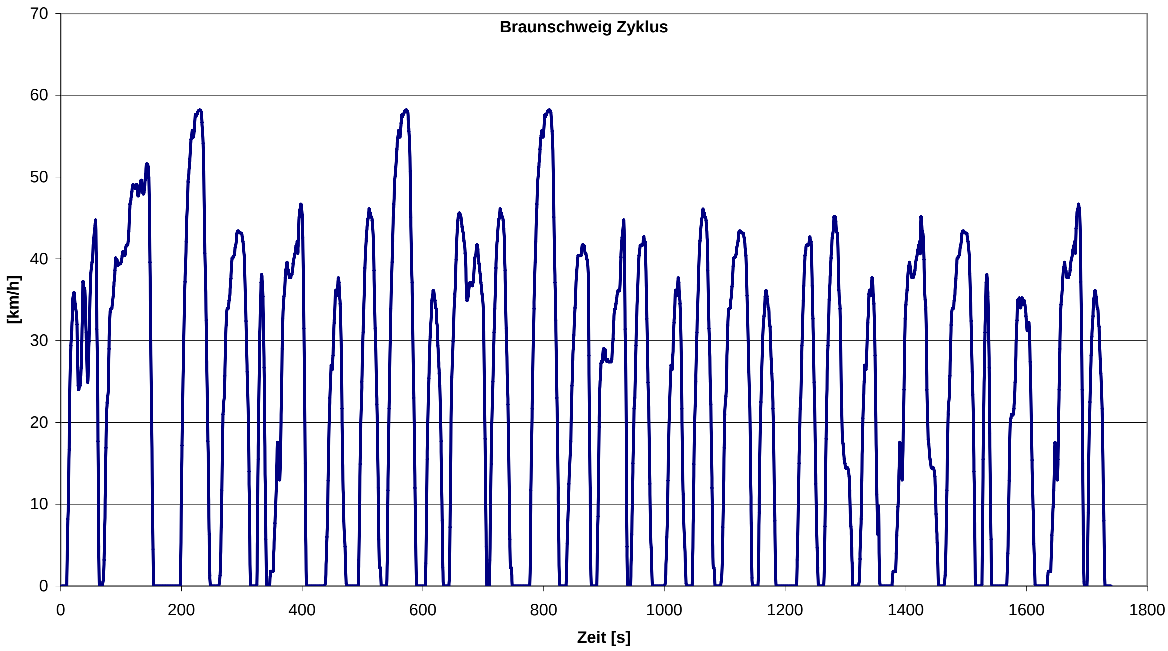

Figure 6: Braunschweig cycle

The Braunschweig cycle has higher vehicle speeds and higher acceleration values, and thus an approx. 70% higher average engine load than the 9040 cycle. The average positive engine power in the Braunschweig cycle is approx. 50% higher than in the 9040 cycle. Table 3 summarises the main parameters of the real world test cycles used.

Table 3: Data of the test cycles

	9040 cycle	Braunschweig cycle
Length [km]:	5.19	10.87
Average velocity [km/h]:	15.6	22.5

Each cycle was measured at least two times. If the results of the two repetitions did not match, a third test was performed. In this case, outliers in the emissions measured were then eliminated before averaging the results. All the values given below are the average of at least 2 repetitions of the cycle if not explicitly defined in a different way.

4 Results

In this chapter, the energy consumption and exhaust gas emissions of all buses measured are listed first to get an overview (chapter 4.1). The results for some EURO III and EURO II diesel buses, which have been measured in the same tests cycles, and which have already been made public by being published, are listed in this chapter as benchmark results. Then the results for each bus tested are given in more detail (chapter 4.2).

4.1 Overview

Table 4 gives the average energy consumption and the exhaust gas emissions of the buses in the tested cycles. Figure 7 to Figure 13 show the corresponding graphs.

When reading the figures, one has to consider that all the buses tested had different vehicle weights and also offered different numbers of seats and standing room. A different test weight influences fuel consumption and emissions. Thus, a certain percentage of the differences measured between the buses can result from the different driving resistance values and vehicle masses. However, the buses belong to the same size class and the different vehicle weights and driving resistance values occur in real world driving, too. Thus, the complete bus concepts are compared here and not only the engines.

Furthermore, all the buses tested have automatic gear boxes, in which the gear change strategy can be controlled electronically. Setting the gear shift points earlier can save fuel, but it reduces the maximum power output. During the measurements, the set up of the gear box control was the same as it was when it was delivered by the manufacturers.

As expected, the specific energy consumption of the CNG buses is higher than that of the diesel buses (+20% MJ/km on average, Figure 7). This results from worse engine efficiency and higher vehicle mass, which is due to the heavier tank system. Since the costs per energy content are usually lower for CNG than for diesel, the overall fuel costs for the CNG buses can be lower than for diesel buses. If and when the higher investment costs for a CNG bus will be amortized due to lower fuel costs depends on the current fuel price levels and the existing infrastructure for CNG.

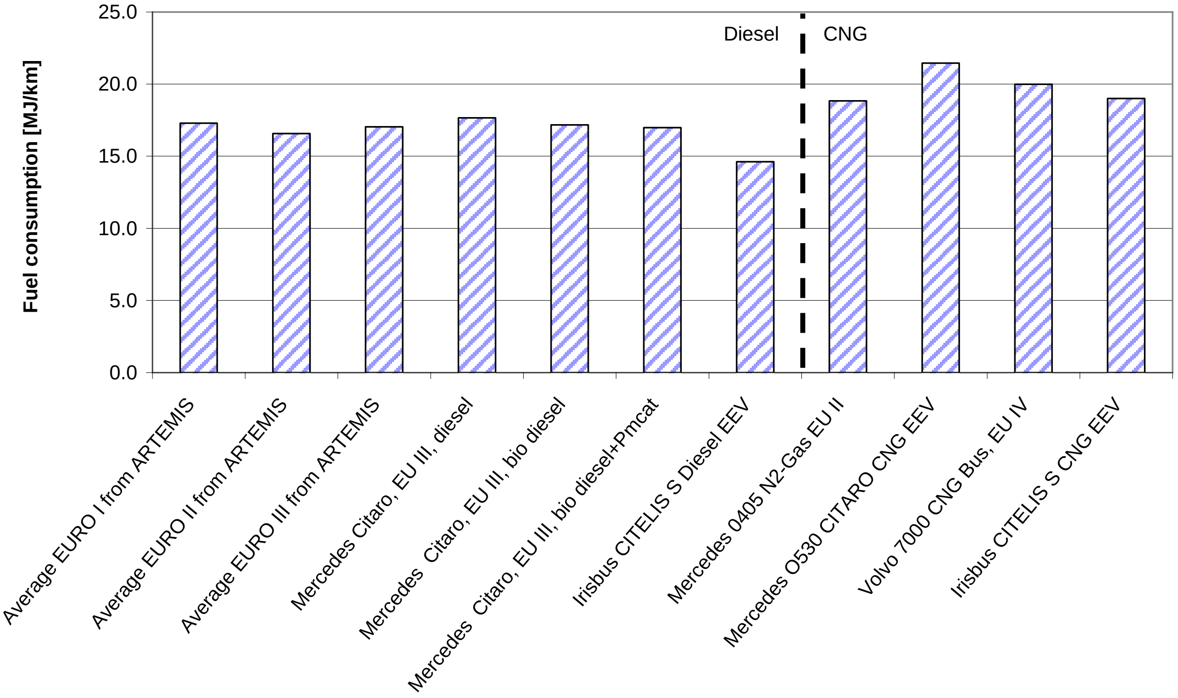

Figure 7: Measured fuel consumption in the "Braunschweig city bus cycle"

Due to the lower Carbon content of CNG, the CO_2 exhaust gas emissions are approx. 10% lower for the CNG buses than for diesel (Figure 8). The higher share of CH_4-Emissions in the total HC (THC) emissions of the CNG-buses does not significantly influence the greenhouse gas balance, since THC emissions are very low.

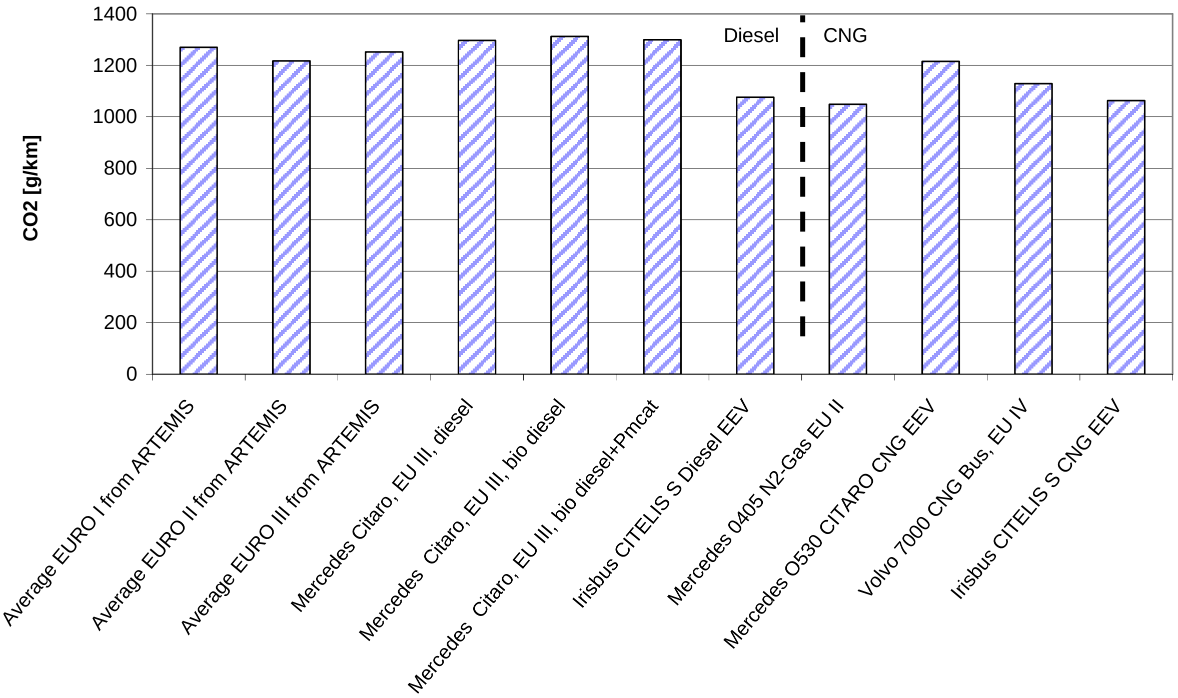

Figure 8: Measured CO_2-emissions in the "Braunschweig city bus cycle"

Looking at the NO_x-emissions (Figure 9), the engines tested in ARTEMIS show a rather constant level from EURO I to EURO III for the city bus cycles. The EURO IV and EEV buses tested had significantly lower NO_x emission levels. The CNG buses generally show a wide variety of results. One EURO II certified CNG bus had NO_x emissions in real world driving that were similar to diesel EURO II buses, and the Volvo CNG bus, which was EURO IV certified, had approx. 40% lower NO_x levels than EURO III diesel. Of all the buses tested so far, the CNG-Irisbus clearly showed the lowest NO_x emissions, which are also below the type approval limit value of 2g/kWh in the real world bus cycles[3].

The EEV diesel Irisbus with SCRT exhaust gas after treatment had similar NOx levels to the EEV-CNG Mercedes. The SCRT system kept NO_x emissions low as long as the exhaust gas temperature was hot enough to keep the SCR catalyst active. At exhaust gas temperatures below approx. 200°C, the SCR is not active and the NO_x raw emissions are not reduced. Such driving conditions result in NO_x emissions at the EURO III level. Table 4 shows results for the SCR bus with warm SCR (bus preconditioned with the city cycle) and results achieved when the bus started after 10 minutes of idling, during which the SCR cooled down. After approx. 15 minutes of driving in the 9040 cycle, the SCR was fairly warmed up after the cool start. Thus, low SCR temperatures will have remarkable real world effects for this bus only if the bus stops for longer periods several times a day and will then drive in rather low load cycles after the stops.

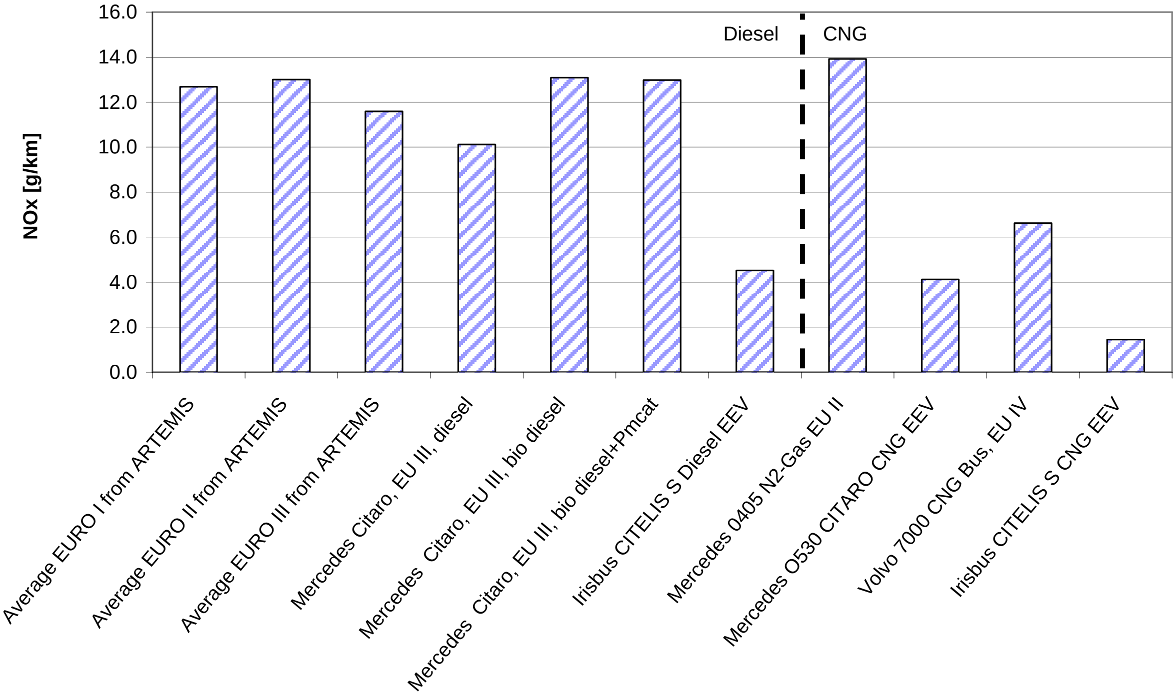

Figure 9: Measured NOx-emissions in the “Braunschweig city bus cycle”

The 30% higher NOx-emissions for the diesel bus with biodiesel compared to the fossil diesel can be explained by the influence of biodiesel, but also by differences in the buses tested. Although they were the same make and model, a remarkable scattering in the emission level

[3] On average, roughly 1.9 kWh/km work is necessary per bus-km in the real world cycles.

between the buses was found. The influence of biodiesel was found in other HDV to be approx. +20% NO_x emissions

Looking at the particulate emissions, the engines tested in the ARTEMIS project show a reduction of 60% from EURO I to EURO III (Figure 10). The lowest particulate mass emissions were measured for the diesel Irisbus with particle filter (SCRT system). The EEV certified CNG buses showed slightly higher PM mass emissions than the diesel bus with the SCRT, but were still at a very low level. The reason for the difference between CNG and SCRT-diesel is most likely particles resulting from lube oil combustion in the CNG engines, while the filter in the diesel bus removes nearly 100% of all the particles in the exhaust gas. Using biodiesel in combination with a particulate catalyst can reduce particulate emissions by approximately 75% compared to fossil diesel. The resulting PM mass emission level for the biodiesel & PM-Catalyst combination was similar to the EURO IV CNG bus tested.

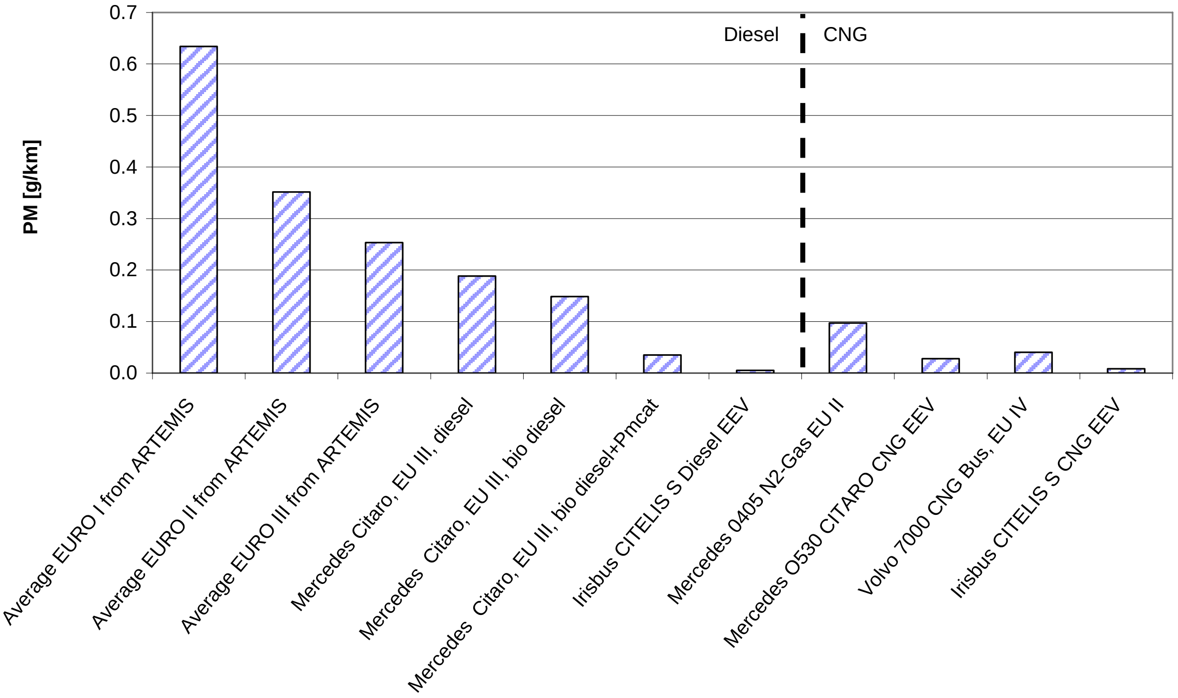

Figure 10: Measured particulate mass emissions in the “Braunschweig city bus cycle”

However, the particulate number emissions for the EURO IV CNG bus were about two orders of magnitude lower than for biodiesel with PM catalyst (Figure 11).

The particulate number emissions were lowest for the CNG buses measured. The diesel bus with SCRT had slightly higher particulate number emissions, but all the low emission concepts showed approx. 3 to 4 orders of magnitude lower particulate number emissions compared to EURO III diesel level. The measurements shown here for biodiesel resulted in lower particulate number emissions compared to the fossil diesel. Pronounced reductions like those found in the 9040 cycle (Table 4), which were due to a switch to biodiesel, were not seen in other tests, but the combination of biodiesel and exhaust gas after treatment was generally found to significantly reduce particle numbers in other projects due to the higher proportion of soluble mass in the PM.

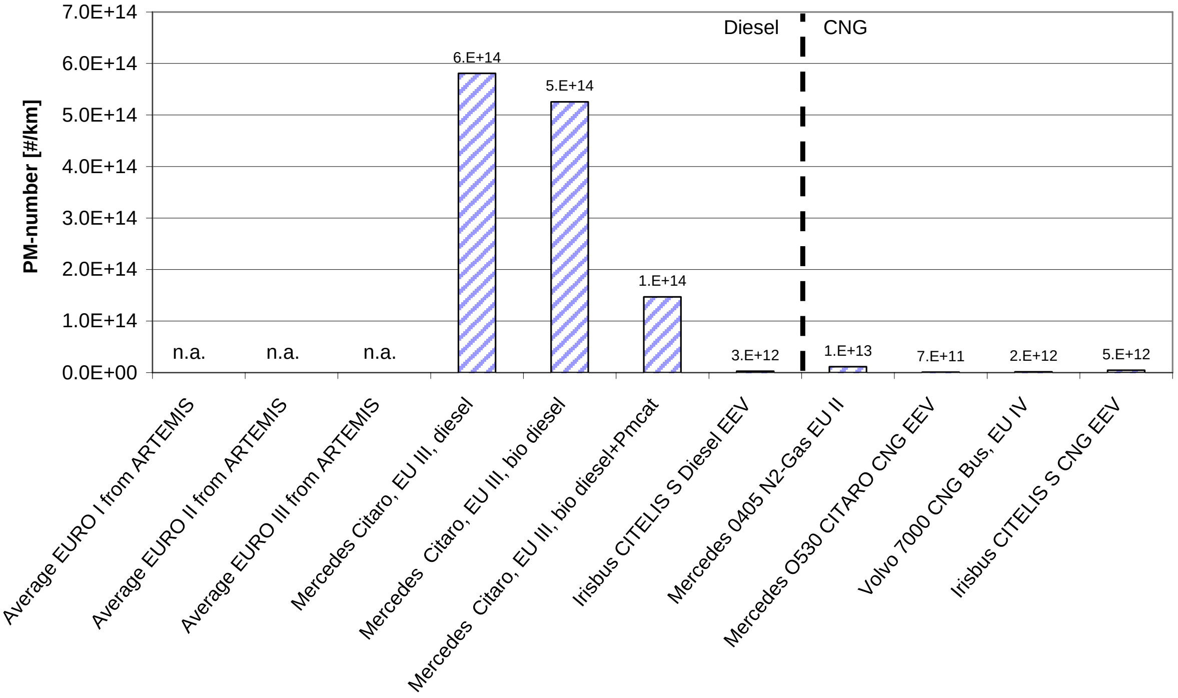

Figure 11: Measured particulate number emissions in the “Braunschweig city bus cycle”

The low emission concepts tested up to now have shown a lot of potential for operating city bus services at a very low emission level. However, the differences between makes and models are sometimes great and the influence of individual setups of the buses (e.g. strategy of the automatic gear box) can have a lot of influence on the resulting emission levels. Thus, the testing of modern buses on their real world emission behavior seems to be necessary if one of the main targets of renewing a bus fleet is lowering the pollutant emissions.

Durability tests of the buses are not a task of this project.

Table 4: Average results in the "9040 city bus cycle"

Vehicle	year of constr.	Emission level	[t] Vehicle Mass	Fuel	Exhaust gas aftertreatment	[g/km] FC	[MJ/km] FC	[g/km] CO2	[g/km] CO	[g/km] HC	[g/km] NOx	[g/km] PM	[#/km] PC
Emission values for diesel city buses for comparison													
Average EURO I from ARTEMIS	1997	Euro II	14.50	Diesel, 50ppm S	none	428	18.41	1350	3.69	1.15	14.27	0.651	n.a.
Average EURO II from ARTEMIS	1998	Euro II	14.50	Diesel, 50ppm S	none	407	17.48	1282	3.48	0.77	14.98	0.298	n.a.
Average EURO III from ARTEMIS	2001	Euro III	14.50	Diesel, 50ppm S	none	423	18.18	1333	3.55	0.66	13.66	0.270	n.a.
Mercedes Citaro, EU III, diesel	2002	Euro III	14.65	Diesel, 8ppm S	none	435	18.71	1372	1.47	0.68	12.14	0.239	1.3E+15
Mercedes Citaro, EU III, bio diesel	2003	Euro III	14.65	Biodiesel	none	511	18.90	1443	1.43	0.28	16.44	0.185	9.1E+13
Mercedes Citaro, EU III, bio diesel-	2003	Euro III	14.65	Biodiesel	PM-Catalyst	515	19.05	1457	0.31	0.05	16.95	0.056	6.0E+13
EURO V and EEV diesel buses													
Irisbus CITELIS S Diesel EEV	2006	EEV	14.30	Diesel, 8ppm S	SCRT-warm	343	14.8	1087	0.58	0.00	4.43	0.002	5.7E+12
Irisbus CITELIS S Diesel EEV	2006	EEV	14.30	Diesel, 8ppm S	SCRT-cold	367	15.8	1161	0.69	0.04	13.50	0.002	7.4E+11
Actual CNG city bus results													
Mercedes 0405 N2-Gas EU II	2003	Euro II	15.05	CNG	3-way catalysts	438	21.3	1179	3.00	6.79	13.83	0.071	8.4E+12
Mercedes O530 CITARO CNG EEV	2004	EEV	15.00	CNG	Oxikat	554	24.5	1384	0.85	3.08	6.34	0.019	1.6E+12
Volvo 7000 CNG Bus, EU IV	2004	Euro IV	16.38	CNG	3-way catalysts	473	22.9	1294	0.26	0.89	9.08	0.049	1.1E+12
Irisbus CITELIS S CNG EEV	2003	EEV	15.50	CNG	3-way catalysts	472	21.9	1225	0.56	0.11	1.51	0.010	3.7E+12

Vehicle mass……..vehicle empty weight + 3tons for passengers

Table 5: Average results in the "Braunschweig city bus cycle"

Vehicle	year of constr.	Emission level	[t] Vehicle Mass	Fuel	Exhaust gas aftertreatment	[g/km] FC	[MJ/km] FC	[g/km] CO2	[g/km] CO	[g/km] HC	[g/km] NOx	[g/km] PM	[#/km] PC
Emission values for diesel city buses for comparison													
Average EURO I from ARTEMIS	1997	Euro II	14.5	Diesel, 50ppm S	none	402	17.29	1269	3.85	0.90	12.68	0.634	n.a.
Average EURO II from ARTEMIS	1998	Euro II	14.5	Diesel, 50ppm S	none	385	16.57	1217	3.64	0.57	13.00	0.351	n.a.
Average EURO III from ARTEMIS	2001	Euro III	14.5	Diesel, 50ppm S	none	396	17.04	1252	3.82	0.49	11.59	0.253	n.a.
Mercedes Citaro, EU III, diesel	2002	Euro III	14.65	Diesel, 8ppm S	none	411	17.66	1297	0.97	0.27	10.12	0.189	5.8E+14
Mercedes Citaro, EU III, bio diesel	2003	Euro III	14.65	Biodiesel	none	465	17.17	1313	1.33	0.22	13.09	0.148	5.3E+14
Mercedes Citaro, EU III, bio diesel-	2003	Euro III	14.65	Biodiesel	PM-Catalyst	459	16.99	1299	0.23	0.03	12.98	0.035	1.5E+14
EURO V and EEV diesel buses													
Irisbus CITELIS S Diesel EEV	2006	EEV	14.30	Diesel, 8ppm S	SCRT	340	14.6	1076	0.70	0.01	4.52	0.005	2.7E+12
Actual CNG city bus results													
Mercedes 0405 N2-Gas EU II	2003	Euro II	15.05	CNG	3-way catalysts	389	18.8	1049	2.43	4.57	13.92	0.097	1.1E+13
Mercedes O530 CITARO CNG EEV	2004	EEV	15.00	CNG	Oxikat	484	21.5	1215	0.79	0.82	4.12	0.028	6.8E+11
Volvo 7000 CNG Bus, EU IV	2004	Euro IV	16.38	CNG	Catalyst	412	20.0	1129	0.22	0.60	6.62	0.040	1.7E+12
Irisbus CITELIS S CNG EEV	2003	EEV	15.50	CNG	3-way catalysts	410	19.0	1063	0.45	0.15	1.45	0.008	4.5E+12

Emission results for CO and HC are shown in Figure 12 and Figure 13. The HC emissions of the CNG buses are to more than 90% methane (CH_4) which is not a toxic component. HC and CO was at very low levels for all the low emission concepts measured.

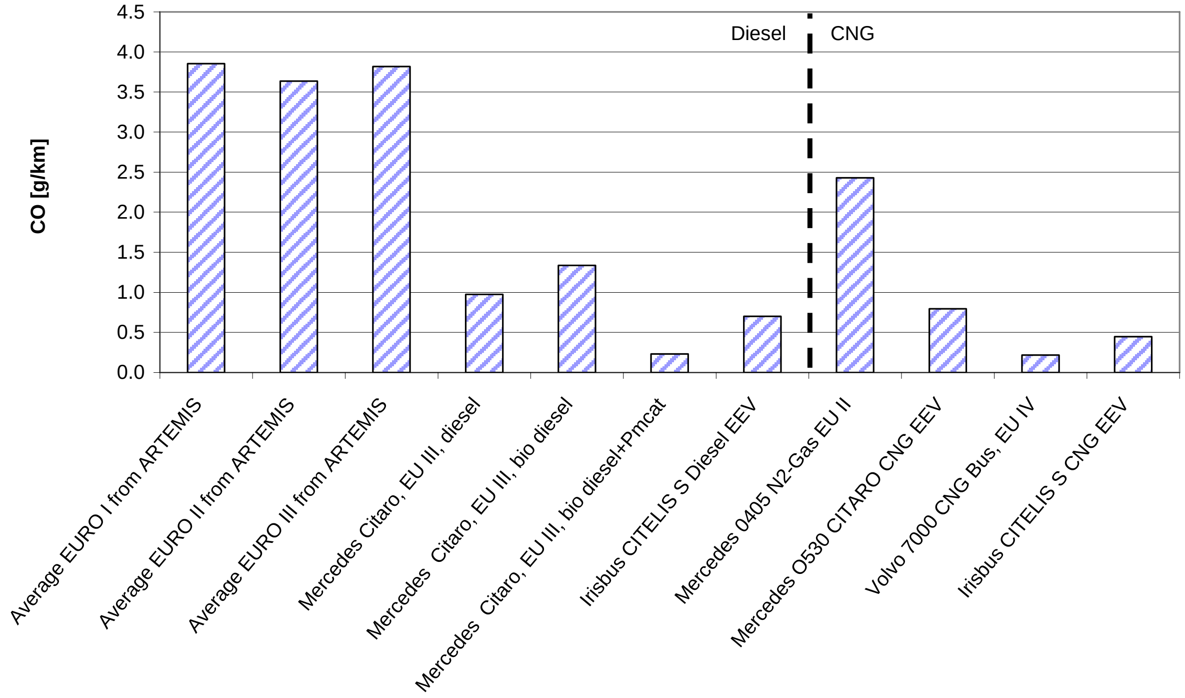

Figure 12: Measured CO-emissions in the “Braunschweig city bus cycle”

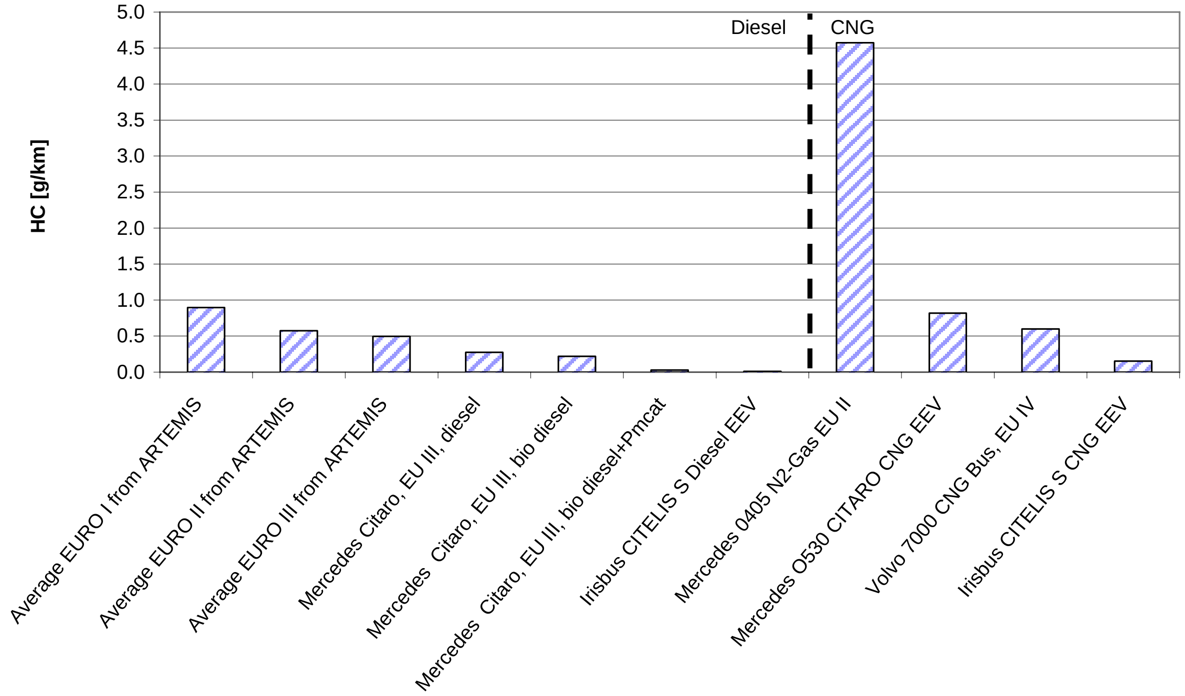

Figure 13: Measured HC-emissions (NMHC + CH_4) in the “Braunschweig city bus cycle”

4.2 Results for the individual vehicles tested

In this chapter, details on each individual vehicle measured within this project are described.

4.2.1 Mercedes /O/405 N2-Gas, EURO II

The Mercedes /O/405 N2-Gas is a EURO II certified city bus which was tested in Graz on behalf of the GVB. It was the first CNG bus measured as part of this project and gave the impetus for the test series on low emission city bus concepts. Table 6 summarises the technical data of this bus. The O 405 N CNG was only built up to 1999 and was then replaced by the Citaro Gas O 530, which was certified to EURO IV or alternatively to EEV (see 4.2.2).

Table 6: Vehicle data Mercedes / O/405 N2-Gas, EURO II

Vehicle category	2-axle / low-floor bus
Manufacturer / Model	Mercedes / O/405 N2-Gas
Year of first registration	1998
Km-driven at test start	300
Propulsion system	CNG / central CNG injection / Lambda 1 concept / 3-way catalyst
Vehicle empty weight	11650 kg
Total vehicle weight for testing	14650 kg
Maximum allowed gross weight	17800 kg
Seats	31
Standing room (persons)	58
Highest axle load front/rear	6300 / 11500 kg
Engine	4-stroke / 6 cylinder
Gear box	4 gear automatic
Engine capacity	11967 cm^3
Rated power	175 kW at 2200 rpm
Length / width / height	11795 / 2500 / 3300 mm
Emission class	Euro II

The average results for the bus cycles and for the steady state tests are given in Table 7.

Table 7: Results from the measurements on the roller test bed for the Mercedes / O/405 N2-Gas, EURO II

	Verbr.C-Bil.	Verbr. C-Bil.	CO_2	CO	HC	NO_x	PM	PM
	g/km	MJ/km	g/km	g/km	g/km	g/km	g/km	#/km
Idling [g/h]	1890.0	91.7	5045.4	-0.24	50.32	21.60	-	2.4E+13
20km/h	260.6	12.6	707.1	0.05	2.77	7.76	-	2.0E+12
60km/h	231.3	11.2	631.9	0.00	0.83	10.78	-	3.0E+16
9040_cycle	438.5	21.3	1179.1	3.00	6.79	13.83	0.071	8.4E+12
Braunschweig	388.5	18.8	1049.1	2.43	4.57	13.92	0.097	1.1E+13

4.2.2 Mercedes O530 CITARO CNG, EEV

The Citaro O530 Gas is the successor to the Mercedes /O/405 N2-Gas. The version tested in this project was equipped with an engine certified according to EEV standard. Table 8 summarizes the technical data of the bus.

Table 8: Vehicle data Mercedes O530 CITARO N3, EEV

Vehicle category	2-axle / low-floor bus
Manufacturer / Model	Mercedes / O/530 Citaro N3
Year of first registration	New vehicle
Km-driven at test start	900
Propulsion system	CNG / central CNG injection / lean burn engine / oxidation catalyst
Vehicle empty weight	11 500 kg
Total vehicle weight for testing	15 000 kg
Maximum allowed gross weight	18 000 kg
Seats	31
Standing room (persons)	58
Highest axle load front/rear	6900 / 11500 kg
Engine	4-stroke / 6 cylinder
Gear box	6 gear automatic
Engine capacity	11967 cm^3
Rated power	185 kW at 2000 rpm
Length / width	11950 / 2550
Emission class	EEV (Enhanced Environmentally Friendly Vehicle)

The average results for the bus cycles and for the steady state tests are given in Table 9.

Table 9: Results from the measurements on the roller test bed for the Mercedes O530 CITARO CNG, EEV

	Fuel consumption		CO_2	CO	HC	NO_x	PM
	g/km	MJ/km	g/km	g/km	g/km	g/km	g/km
9040_ cycle	554.0	24.5	1384.0	0.85	3.08	6.34	0.019
Braunschweig	484.4	21.5	1215.3	0.79	0.82	4.12	0.028

The emissions are kept at a low level most of the time in the cycle. NO_x peaks occur at the beginning of several high load phases. As an example, Figure 14 shows the first part of a Braunschweig cycle.

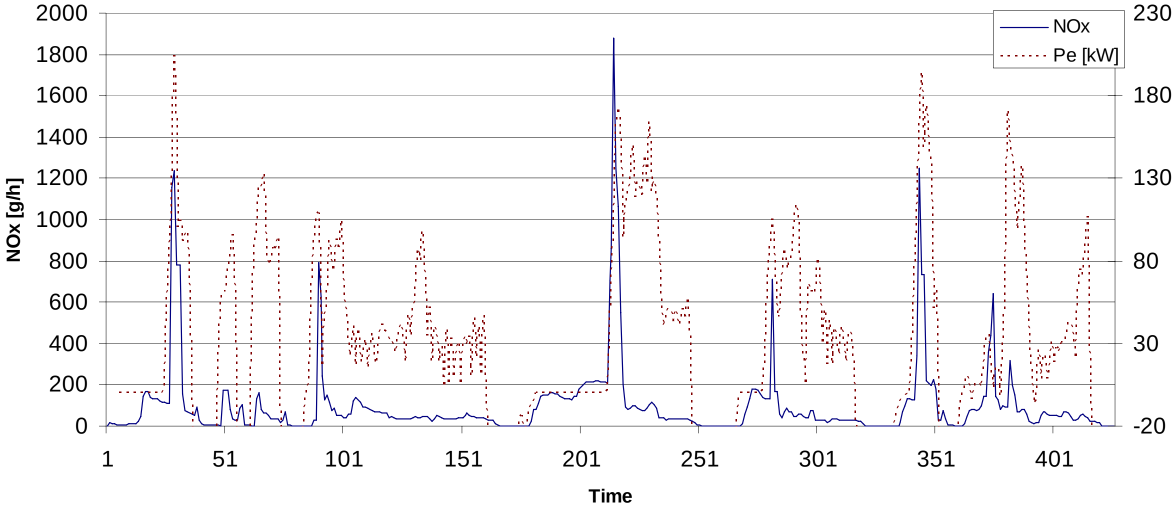

Figure 14: Measured instantaneous NOx emission levels for the Mercedes O530 CITARO CNG, EEV bus in the first 450 seconds of the "Braunschweig cycle"

However, the overall emission result is not heavily influenced by these emission peaks and the high load phases of the NO_x emissions are at quite low levels most of the time. As an example, Figure 15 shows the NO_x emissions measured in 1 Hz in a Braunschweig cycle plotted over the actual engine power.

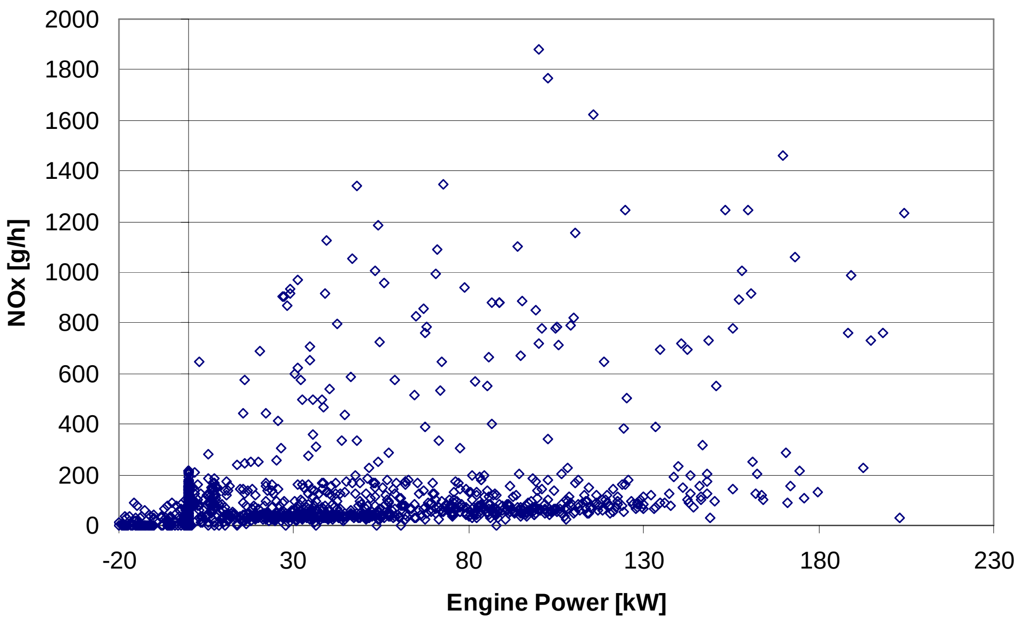

Figure 15: Measured NOx emission levels for the Mercedes O530 CITARO CNG, EEV bus in the "Braunschweig cycle" in 1 Hz as a function of the actual engine power

No particle size distribution was measured for the Mercedes O530 CITARO N3 by SMPS during the constant speed cycles due to a failure of the measurement equipment in the period of the measurement campaign.

4.2.3 Volvo 7000 CNG Bus, EURO IV

The technical data of the Volvo 7000 CNG bus is given in Table 10. The bus fulfils the EURO IV limit values in the ETC test cycle and uses a lean burn concept together with an oxidation catalyst.

Table 10: Vehicle data for the Volvo 7000 CNG Bus, EURO IV

Vehicle category	2-axle / low-floor bus
Manufacturer / Model	Volvo 7000
Year of first registration	02/2002
Km-driven at test start	95860
Propulsion system	CNG / turbo charged/ central CNG injection / lean burn concept/ oxidation catalyst
Vehicle empty weight	13 380 kg
Total vehicle weight for testing	16 380 kg
Maximum allowed gross weight	18 000 kg
Seats	45
Standing room (persons)	25
Highest axle load front/rear	6500 / 11500 kg
Engine	GH10 / 4-stroke / 6 cylinder
Gear box	4 gears automatic
Engine capacity	9603 cm³
Rated power	213 kW at 2200 rpm
Length / width / height	12000 / 2500 / 3270 mm
Emission class	EURO IV
Emissions in type approval (ETC) [g/kWh]:	NOx: 2.8 / PM: <0.01 / CO: 0.02 / NMHC: 0.00 / CH4: 1.1 2

Table 11 summarises the average cycle emissions measured for the Volvo 7000 CNG bus.

Table 11: Results from the measurements on the roller test bed for the Volvo 7000 CNG Bus, EURO IV

	Fuel consumption		CO_2	CO	HC	NO_x	PM	PM
	g/km	MJ/km	g/km	g/km	g/km	g/km	g/km	#/km
Idling [g/h]	2021.0	98.0	5531.9	5.30	0.761	3.68	-	1.9E+13
20km/h	325.2	15.8	891.0	0.25	0.201	12.59	0.019	3.4E+12
60km/h	220.9	10.7	605.4	0.24	0.017	1.71	0.050	5.8E+12
9040 cycle	473.1	22.9	1294.5	0.26	0.886	9.08	0.026	1.1E+12
Braunschweig	412.3	20.0	1128.6	0.22	0.598	6.62	0.017	1.7E+12

The measurement of the lambda value (λ) in the connection tube from tail pipe to the CVS tunnel showed a lean combustion with λ in the range of 1.5 in most of the relevant operation modes. In motoring phases, the λ value increases to the measurement range of the sensor due to the fact that no CNG is injected (Figure 16).

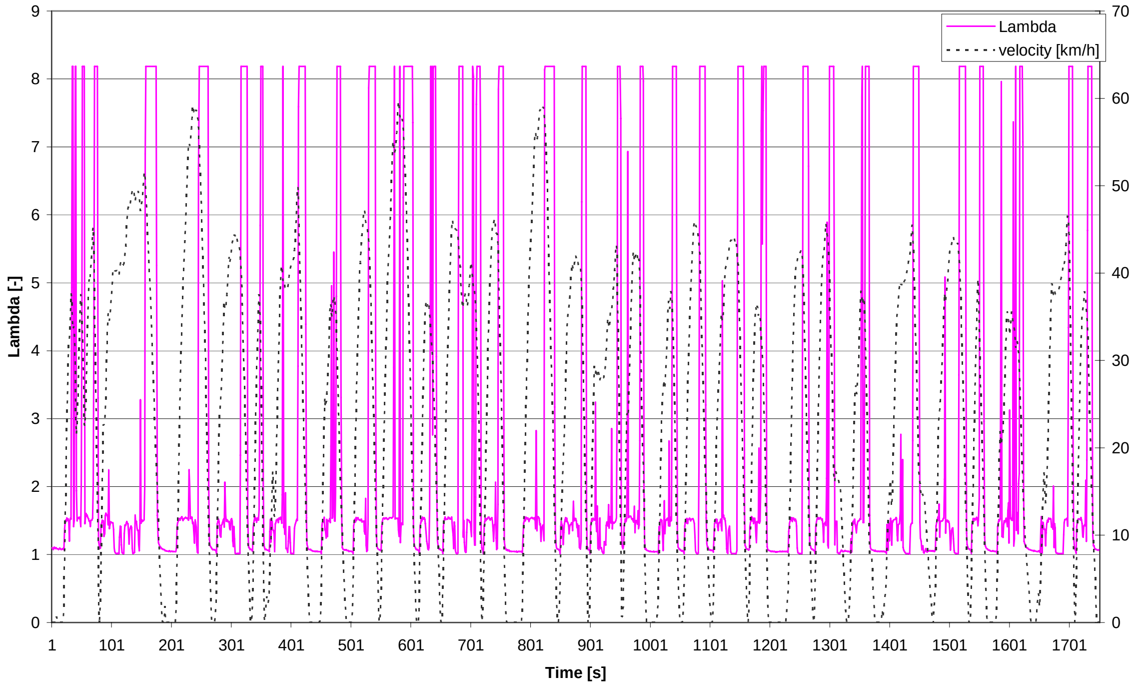

Figure 16: Measured Lambda value for the Volvo 7000 CNG bus in the "Braunschweig cycle"

In lower engine loads the lambda value varies more than in high loads. In the steady state cycles lambda was controlled for stoichiometric combustion up to 50 km/h. From 60 km/h on a lean combustion was detected. However, no significant link was detected between these variations and the emission behaviour.

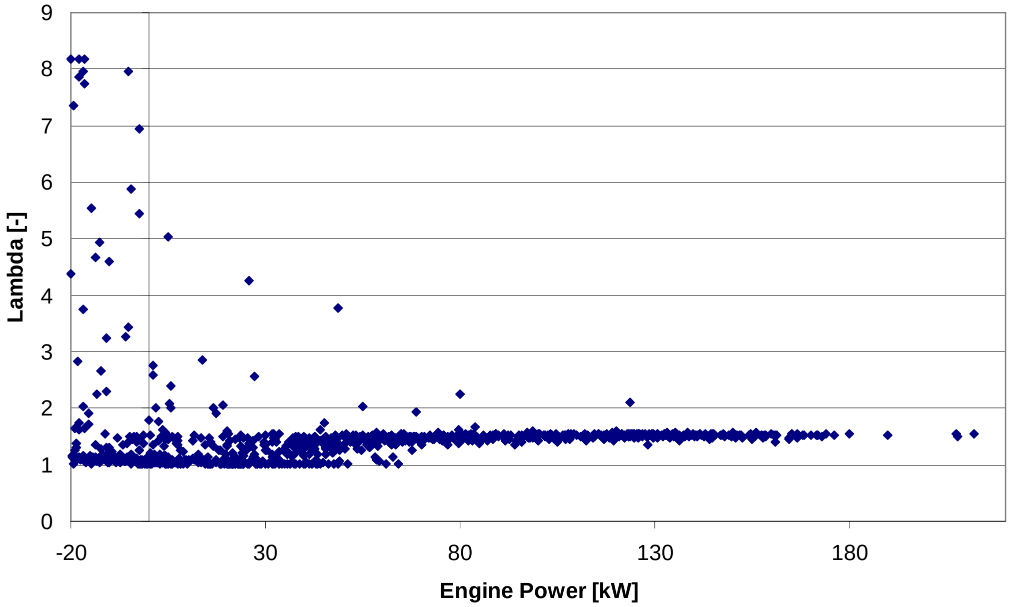

Figure 17: Measured Lambda value for the Volvo 7000 CNG bus in the "Braunschweig cycle" plotted over the engine power in the cycle

The Volvo showed peaks in the NO_x emission level at the beginning of several high load phases in the same order of magnitude as the Mercedes EEV CNG bus (Figure 18).

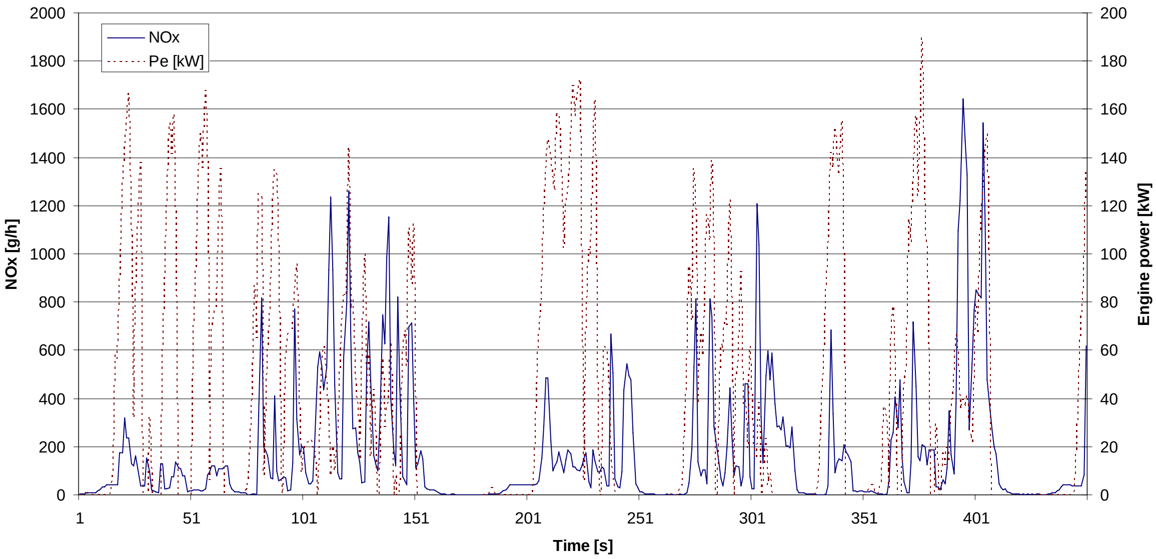

Figure 18: Measured NOx emission levels for the Volvo 7000 CNG bus in the first 450 seconds of the "Braunschweig cycle"

The frequency of NO_x peaks over the Braunschweig cycle is similar for the Volvo bus and for the Mercedes EEV CNG (compare Figure 15 and Figure 19).

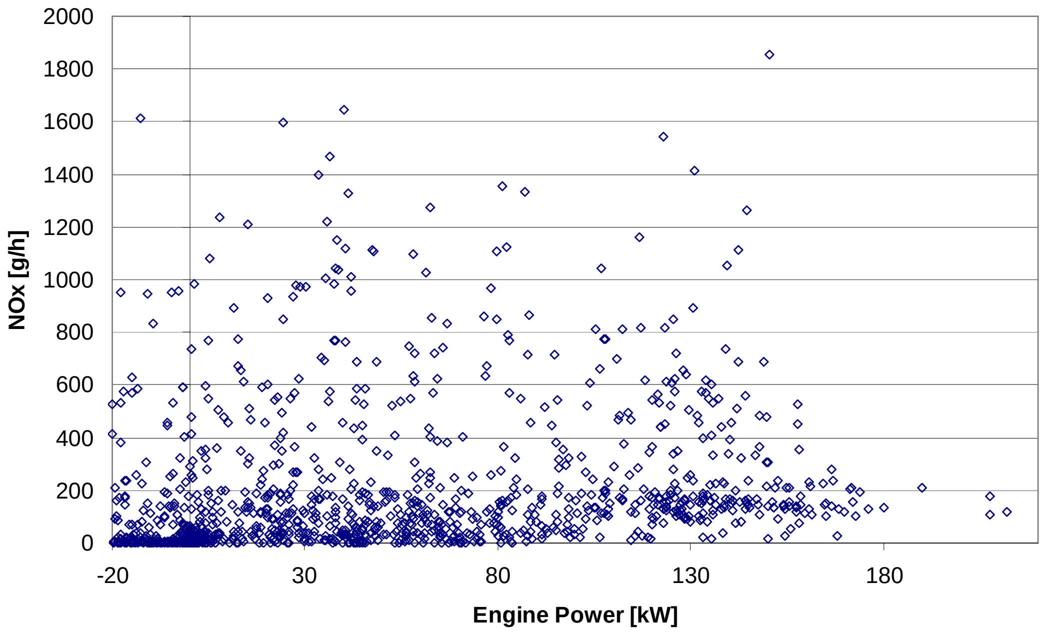

Figure 19: Measured NO_x emissions for the Volvo 7000 CNG bus in the "Braunschweig cycle" in 1 Hz as a function of the actual engine power

Figure 20 shows the particle size distribution measured in the steady state cycles for the Volvo 7000 CNG bus. As for the other CNG buses, the particle number emissions increase with increasing vehicle speed. However, the absolute numbers are kept at a low level. The size distribution shows the maxima at less than 30nm. Diesel buses have comparably larger particles with maxima in the range of approx. 60 to 80 nm (e.g. Ntziachristos, 2006). This suggests that the particles counted for the CNG have different morphology than particles from diesel exhaust. Perhaps the particles counted at the CNG buses originate from lube oil droplets in the exhaust.

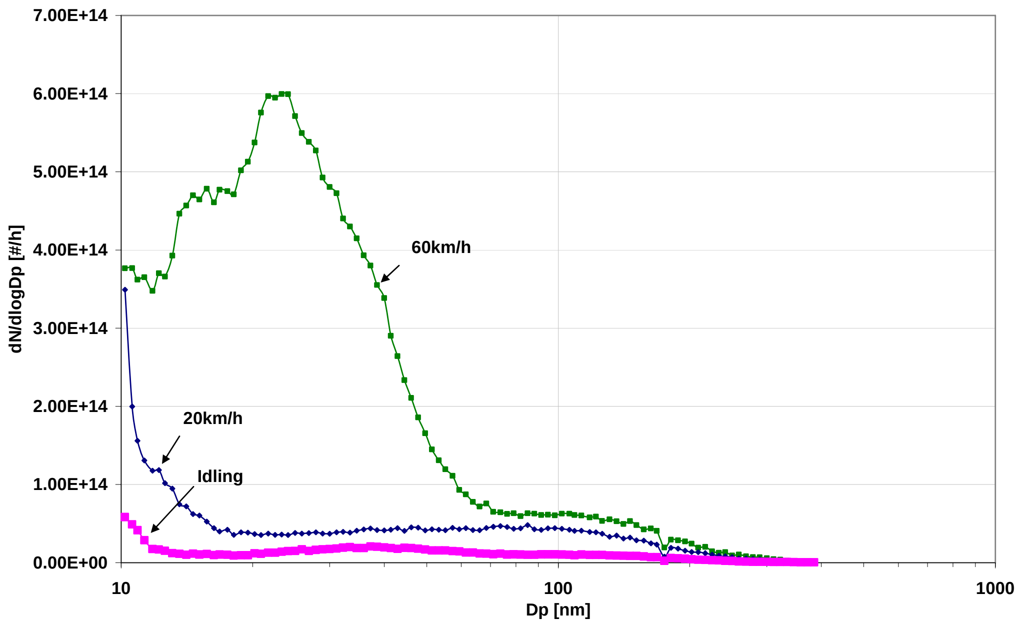

Figure 20: Particle size distribution measured in the steady state cycles for the Volvo 7000 CNG bus

4.2.4 Irisbus CITELIS S CNG, EEV

The Irisbus is certified according to EEV standard. The engine is driven by stoichometric combustion (Lambda controlled to oscillate narrowly around 1.0). Thus, a 3-way catalyst can be used to minimise NO_x, HC and CO. The technical data for the bus is given in Table 12.

Table 12: Vehicle data Irisbus CITELIS S CNG, EEV

Vehicle category	2-axle / low-floor bus
Manufacturer / Model	Irisbus CITELIS S
Year of first registration	2003
Km-driven at test start	19300
Propulsion system	CNG EEV /turbo charging with charge air cooling/ central CNG injection / stoichometric combustion /3-way catalyst
Vehicle empty weight	12500 kg
Total vehicle weight for testing	15500 kg
Maximum allowed gross weight	18000 kg
Seats	26
Standing room (persons)	86
Highest axle load front/rear	7245 / 12600 kg
Engine	C78 ENT G / 4-stroke / 6 cylinder
Gear box	4 gear automatic
Engine capacity	7800 cm³
Rated power	200 kW at 2000 rpm
Length / width / height	11900 / 2500 / 2979 mm
Emission class	EEV (Enhanced Environmentally Friendly Vehicle)

Table 13 summarises the average cycle emissions measured for the Irisbus CITELIS S CNG.

Table 13: Results from the measurements on the roller test bed for the Irisbus CITELIS S CNG, EEV

	Fuel Consumption		CO2	CO	HC	NOx	PM	PM
	g/km	MJ/km	g/km	g/km	g/km	g/km	g/km	#/km
9040_	472.1	21.9	1225.4	0.562	0.108	1.510	0.010	3.67E+12
Braunschweig	409.8	19.0	1062.5	0.447	0.153	1.448	0.008	4.51E+12
60kmh	218.5	10.2	567.4	0.109	0.023	0.414	0.006	1.00E+12
20kmh	283.8	13.2	888.4	0.123	0.120	0.468	0.007	1.16E+12

As for the other CNG concepts, NO_x peaks occur during high load phases. For the Irisbus CNG these peaks have been the lowest detected so far. Figure 21 shows the first 450 seconds in the Braunschweig cycle.

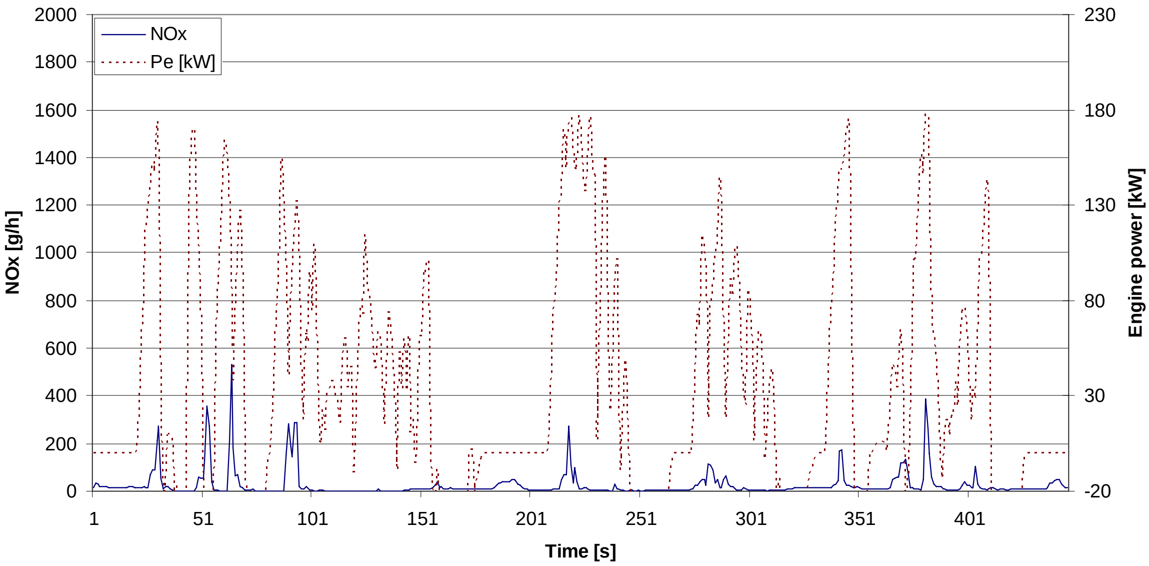

Figure 21: Measured NOx emissions for the Irisbus CITELIS S CNG, EEV bus in the first 450 seconds of the “Braunschweig cycle”

The frequencies of NO_x peaks over the Braunschweig cycle are lower than for the Volvo bus and for the Mercedes EEV CNG bus (compare e.g. Figure 22 with Figure 15 and Figure 19).

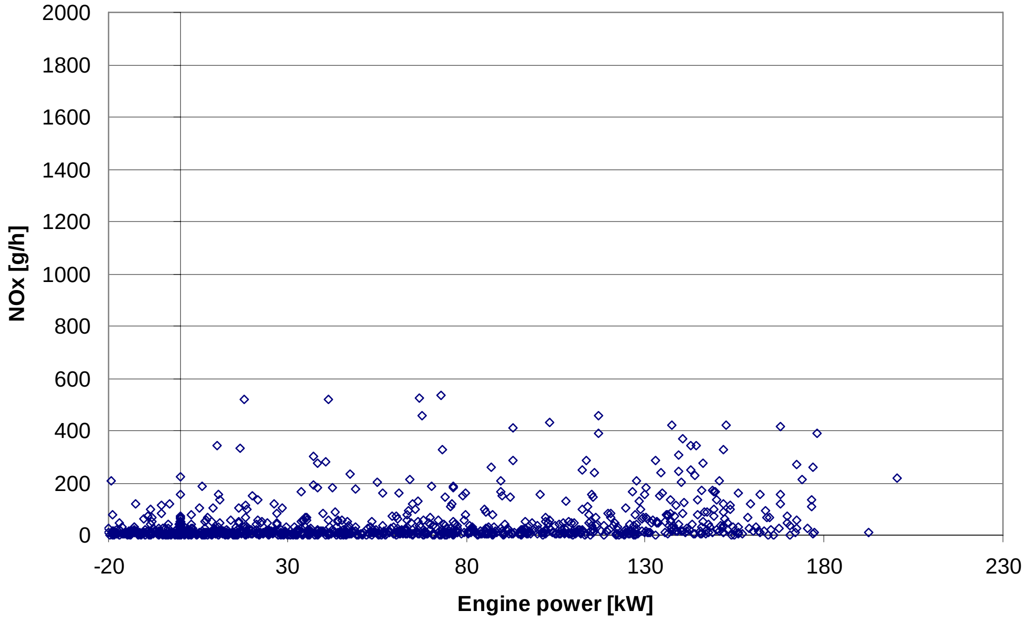

Figure 22: Measured NOx emission levels for the Irisbus CITELIS S CNG, EEV bus in the "Braunschweig cycle" in 1 Hz as a function of the actual engine power

Figure 23 shows the particle size distribution measured in the steady state cycles for the Irisbus CITELIS S CNG, EEV. As for the other CNG buses, the particle number emissions increase with increasing vehicle speed. However, the absolute numbers are kept at a very low level. The size distribution shows the maxima at less than 40nm. As previously discussed for the Volvo CNG bus, diesel buses have comparably larger particles with maxima in the range of approx. 60 to 80 nm.

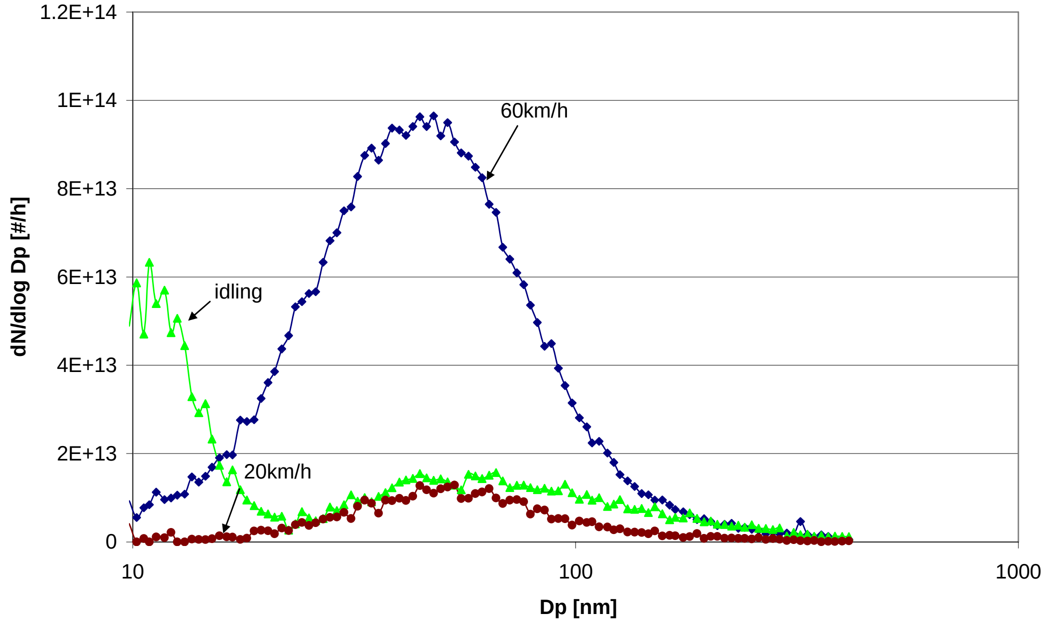

Figure 23: Particle size distribution measured in the steady state cycles for the Irisbus CITELIS S CNG, EEV

4.2.5 Irisbus CITELIS S Diesel, EEV

The Irisbus CITELIS S Diesel is equipped with a SCRT exhaust gas after treatment system which combines a SCR and a CRT. The SCR (Selective Catalytic Reduction) lowers the NO_x emissions by reaction with NH_3. The NH_3 is gained from urea which is stored on board as AdBlue (urea dissolved in water). The SCR is capable of reducing the NO_x raw emissions by more than 80% as long as the exhaust gas temperature is higher than approx. 200°C and the AdBlue dosing system is not frozen (at temperatures below approx. -11°C the AdBlue dosing system is heated before it becomes active). At low engine loads, where the exhaust gas temperature is lower than 200°C, the NO_x emissions have to be kept low by measures in the engine.

The CRT (Continuous Regenerating Trap) uses a closed PM trap and reduces the particulate matter. The filter in the Irisbus obviously was very effective and removed more than 99% of all particles (mass and number). The technical details of the Irisbus CITELIS S Diesel are listed in Table 14.

Table 14: Vehicle data Irisbus CITELIS S Diesel, EEV

Vehicle category	2-axle / low-floor bus
Manufacturer / Model	Irisbus CITELIS S
Year of first registration	2005
Km-driven at test start	19300
Propulsion system	Diesel engine, direct injection with SCRT
Vehicle empty weight	11400 kg
Total vehicle weight for testing	14400 kg
Maximum allowed gross weight	18000 kg
Seats	26
Standing room (persons)	86
Highest axle load front/rear	7245 / 12600 kg
Engine	C8 SCRT EEV/ 4-Stroke
Gear box	4 gear automatic
Engine capacity	7800 cm³
Rated power	213 kW at 2050 rpm
Length / width / height	11900 / 2500 / 2979 mm
Emission class	EEV (Enhanced Environmentally Friendly Vehicle)

Table 15 summarises the average cycle emissions measured for the Irisbus CITELIS S Diesel.

Table 15: Results from the measurements on the roller test bed for the Irisbus CITELIS S Diesel, EEV

	Fuel consumption		CO_2	CO	HC	NO_x	PM	PM
	g/km	MJ/km	g/km	g/km	g/km	g/km	g/km	#/km
Idling [g/h]	1136.4	48.9	3589.5	2.66	0.495	73.1	0.0018	8.0E+10
20km/h	176.1	7.6	557.0	0.35	0.081	6.4	0.00002	4.3E+11
60km/h	181.7	7.8	574.8	0.23	0.014	1.2	0.0005	2.5E+11
9040 cycle warm	343	14.8	1087	0,58	0,00	4,43	0,002	5,7E+12
9040 cycle cold	367	15,8	1161	0,69	0,04	13,50	0,002	7,4E+11
Braunschweig	340.0	14.6	1076.3	0.70	0.012	4.5	0.0051	2.7E+12

The CRT system collects the particles and burns them off at temperatures above approx. 300°C by reaction with NO_2. Cleaning of the system of remaining ash will be necessary over the lifetime of the bus. The exhaust gas after treatment system in the Irisbus is isolated to obtain the best thermal conditions for the SCRT.

The SCR system reached the standard working temperature in all cycles. Starting from cold, SCR reaches the operating temperature within 10 to 15 minutes after start. Figure 24 shows the course of the brake specific NOx emissions of the bus over the cycle time for 3 different test cycles. The RATP was measured by a cold start, the 9040 cycle was measured after a slight warm up and 10 minutes idling, and the Braunschweig cycle was measured after a warm up and 10 minutes idling. It can be seen that the NOx emission level in the hot Braunschweig cycle is low from the beginning on, while the cycles by cold and cool starts show NO_x peaks in the first minutes of the test cycle. These peaks occur when the exhaust gas temperature before the SCR is too low for the SCR to be active. Certainly the CRT is removing particles from the beginning of each cycle on so that a very low PM level is found over the total cycles.

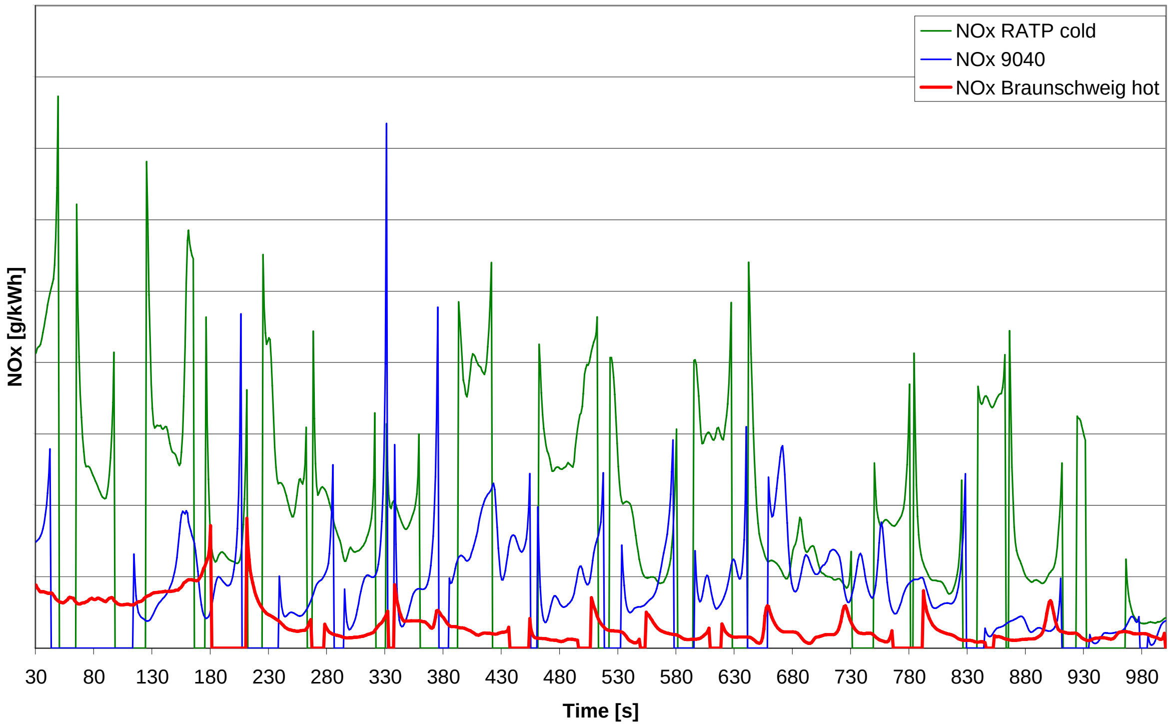

Figure 24: 30 Second averages for the NO_x emissions in [g/kWh] measured in 3 different cycles (RATP after cold start, 9040 after cool start, Braunschweig after warm start)

Figure 25 shows the course of the NO_x emissions measured in the first 450 seconds of the Braunschweig cycle as for the other buses, too. The NO_x peaks occur rather at the beginning of high loads after low load engine operation when the transient load change leads to rather low SCR temperature and a proper NH_3 dosing has to be managed in a short time period. The absolute level of the NO_x peaks is comparable to the Volvo CNG bus and to the Mercedes EEV CNG bus.

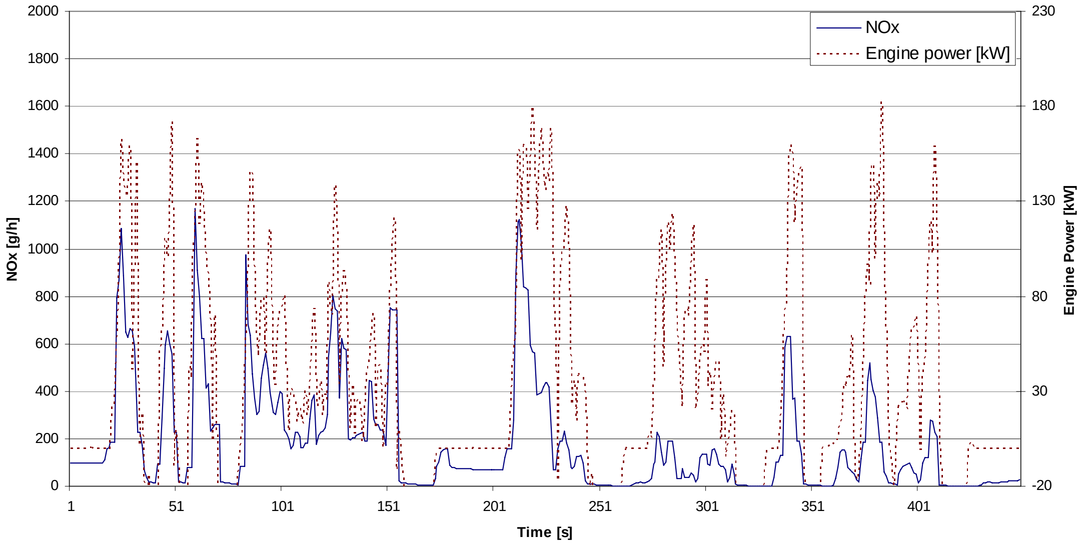

Figure 25: Measured NOx emission levels for the Irisbus CITELIS S Diesel, EEV bus in the first 450 seconds of the "Braunschweig cycle"

The frequencies of NO_x peaks over the Braunschweig cycle are similar to the Volvo CNG bus and to the Mercedes EEV CNG bus (compare e.g. Figure 26 with Figure 15 and Figure 19).

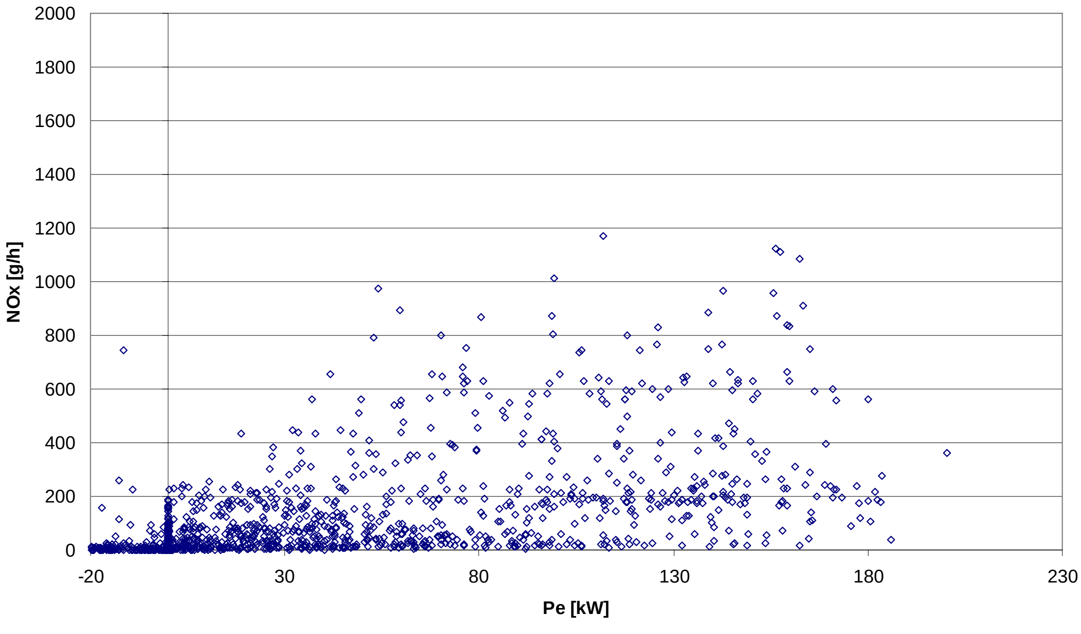

Figure 26: Measured NOx emission levels for the Irisbus CITELIS S Disel, EEV bus in the "Braunschweig cycle" in 1 Hz as a function of the actual engine power

Figure 27 shows the particle size distribution measured in the steady state cycles for the Irisbus CITELIS S Diesel, EEV. The SMPS in combination with the standard exhaust gas dilution was close to the detection limit in the measurements of the Irisbus, since the particle numbers counted were very low. This results in the scattering of the distribution curve.

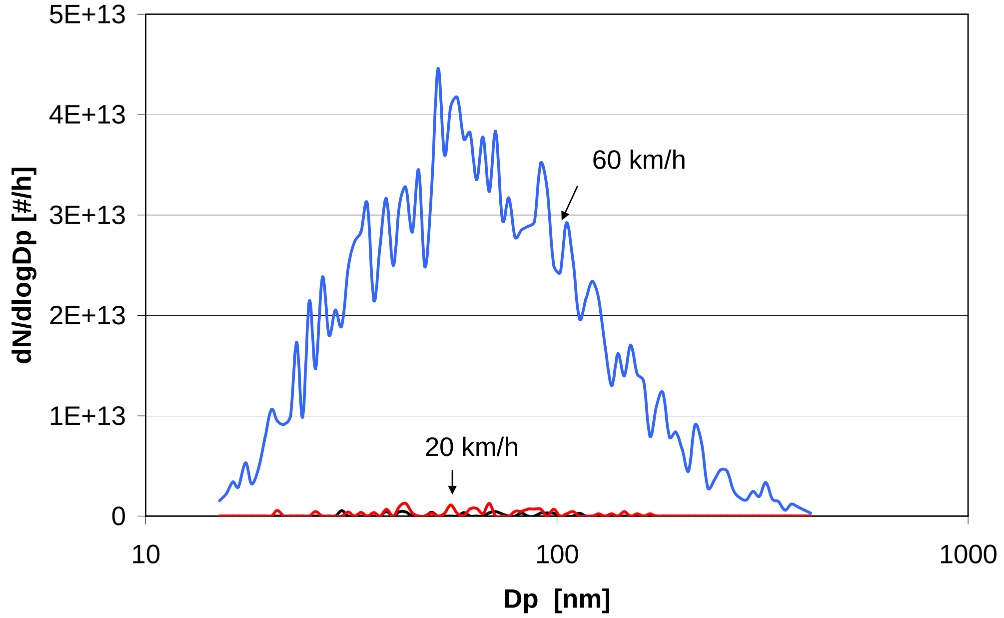

Figure 27: Particle size distribution measured in the steady state cycles for the Irisbus CITELIS S Diesel, EEV

5 Comparison with existing emission factors

The emissions measured for the clean city bus concepts show quite good agreement with the assumptions made in the most recent emission factor database (ARTEMIS, see Table 16). Only PM emissions are clearly lower for the buses measured since ARTEMIS and HBEFA did not assume diesel particle filters for the average EURO V city bus. This assumption may need to be revised in the future. The assumptions on CO and HC emissions from the HBEFA are too pessimistic compared to the measurements. Obviously the effect of the catalytic exhaust gas after treatment systems was underestimated in HBEFA.

Table 16: Comparison of emissions measured in the 9040 cycle and forecasts for EURO V from HBEFA and ARTEMIS

	FC	**CO_2**	**CO**	**HC**	**NO_x**	**PM**
	[g/km]					
Irisbus CITELIS S Diesel EEV	343	1087	0.58	0.00	4.43	0.002
CNG EEV average measured	513	1305	0.71	1.59	3.93	0.015
EURO V from HBEFA (1)	*383*	*1204*	*2.04*	*0.80*	*4.25*	*0.073*
EURO V from ARTEMIS (1)	*420*	*1319*	*0.32*	*0.04*	*5.10*	*0.070*

(1) Forecast on emission factors for EURO V diesel city buses in the “Handbook on Emission Factors”, (Hausberger, 2002)

(2) Forecast on emission factors for EURO V diesel city buses in the “ARTEMIS” emission database, (Rexeis, 2005)

6 Conclusions

The type approval test cycles ESC and ETC do not sufficiently cover the engine loads occurring in city operation. As a result, the emissions measured in type approval do not necessarily represent the emissions in real world city bus cycles for modern engines. This is especially relevant for the NO_x emissions since a trade off exists between the targets fuel efficiency and low NO_x emission levels for Diesel engines and lean burn Otto engines. The EEV city buses measured showed NO_x emission levels in the city bus cycles in the range of 0.8 to 3.6 g/kWh under hot operating conditions. The limit value in the ETC cycle for EEV is 2.0 g/kWh for NO_x.

Vehicles with exhaust gas after treatment systems (especially SCR) were found to be sensitive to the exhaust gas temperature. At low engine loads with low exhaust gas temperatures the catalysts are not working and the emission levels can increase significantly compared to hot operation conditions. A properly insulated catalyst close to the engine can reduce the impact of low load cycles. However, the current type approval method does not monitor these effects at all. Thus, future HDV exhaust gas legislation should also cover cold starts and consequently would have to monitor the complete vehicle. Such an extended test procedure would also demand low emissions in congested urban driving cycles.

In the meantime, it is recommended to continue the city bus tests in the D.A.CH.-NL-S group to provide information on new and clean city bus concepts for the stakeholders as well as for the assessment of the effects of different measures in the field of public transport on urban air quality. Since at present several new models of EEV buses have entered the market, a regular test procedure of this kind could also stimulate manufacturers to further optimize towards low exhaust gas emissions in typical city cycles.

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