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Testing of unregulated emissions from heavy duty natural gas vehicles

(Provning av oreglerade emissioner i tunga metangasdrivna fordon)

Kristina Willner

"Catalyzing energygas development for sustainable solutions"

SGC Svenskt Gastekniskt Center AB

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Martin Ragnar
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Authors' foreword

The testing of unregulated emissions from heavy duty (HD) methane fuelled vehicles is an extension of a project within the framework of International Energy Agency and it´s Implementing Agreement Advanced Motor Fuels (IEA-AMF). Part one of the project (annex 39), a literature study, was finalized May 2010 and the result is presented in a Technical Report AVL MTC 9913. (http://www.iea-amf.vtt.fi/pdf/annex39_final.pdf). As conclusions and further recommendations a phase two of the project was initiated implying an emission testing program. The name of the project is "Enhanced Emission Performance and Fuel Efficiency for HD Methane Engines ".

The main objective of the IEA AMF project is to learn more about the current situation regarding emissions performance and energy efficiency for various types of engines fuelled by methane gas, which are used in heavy duty vehicles in different driving situations. In the near future, methane in various forms might play a significant role to combat CO_2 emissions from the transport sector. From a Swedish perspective this is essential especially for heavy duty vehicles.

Participating in the project is Canada, Denmark, Finland, Germany and Japan and with Sweden as the Operating Agent. Additionally, DG Energy participates in the program via IEA Bioenergy.

Phase two of the project was launched November 2010 with a planned time frame of about two years. However, due the difficulties to find suitable test vehicles the planned closing time for the project was prolonged to May 2013. At the latest AMF meeting (November 2012) it was further decided to extend the time scale to May 2014.

In order to learn more about, not only regulated emissions from methane operated heavy duty vehicles, but also unregulated emissions i.e. olefins, polycyclic aromatic hydrocarbons (PAH) and aldehydes, particle size distribution, level of mutagenicity of the exhaust, SGC (and partners) have financed the additional testing of the unregulated pollutants which are presented in this report.

The testing in this project has been carried out by AVL MTC Motortestcenter AB. The analysis of the aldehydes was performed by the Swedish Environmental Research Institute (IVL). PAH analysis was performed by the department of analytical chemistry, Arrhenius laboratory, University of Stockholm. The genotoxicity tests were performed by the Department of Molecular Biosciences, the Wenner-Gren Institute, Stockholm University. The vehicles have been provided by Volvo Lastvagnar AB, Scania CV AB, and Keolis Sverige AB.

This project started in 2012, and was finalized in December 2013.

Summary

On behalf of the SGC (and co-financiers) AVL MTC has measured emissions from three heavy duty vehicles running on a chassis dynamometer. The test cycle used for the dynamometer testing was the Worldwide Harmonized Transient Cycle for certification of Heavy Duty Engines (WHTC) modified to be used on chassis dynamometers, Worldwide Harmonized Vehicle Cycle (WHVC).

Vehicle number 1 was a CNG fuelled city bus approved according to emission standard EEV (Enhanced Environmental friendly Vehicle). The combustion principle of the engine was so called stoichiometric / "lean mix", i.e. alternating between stoichiometric and lean combustion. The vehicle was equipped with a three-way catalytic converter. The fuel used in the test was CNG from the tank of the vehicle which was filled up on a commercial fuelling station.

Vehicle number 2 was a (long-haul) truck converted to so-called Diesel Dual Fuel operation/methane-diesel, i.e. the engine was operating with a continuously varying mixture of diesel and methane gas. The truck was approved according to emission standards Euro V in its' original shape (diesel fuelled). Since a certification method for this type of engine currently is missing, the Swedish Transport Agency issues a waiver to the manufacturers which make it possible to register the vehicles. According to this waiver, the engine shall comply with the emission standard Euro V. The vehicle was equipped with a diesel oxidation catalyst and a SCR system. The fuel used in the testing of this vehicle was Mk1 (without HVO (Hydrotreated Vegetable Oil) additive) and LBG (Liquefied Bio Gas). Both Mk1 diesel and LBG was supplied by Volvo. Fuel specification for LBG can be found in the appendix.

Vehicle number 3 was a CNG fuelled city bus approved according to emission standard EEV. The combustion principle of the engine was so called "lean-burn", i.e. operating with air excess. The vehicle was equipped with a diesel oxidation catalyst. The fuel used in the test was CNG from the tank of the vehicle which was filled up on a commercial fuelling station.

Results from similar testing of a standard Diesel vehicle with a SCR after treatment system has been included in the report as reference [1].

The tests were performed with both cold and warm engine on all vehicles.

The emissions analyzed were the regulated exhaust components carbon monoxide (CO), total hydrocarbons (HC and CH_4), nitrogen oxides (NOx), carbon dioxide (CO_2) and particulate matter (PM). The fuel consumption has been calculated. The results of the regulated emissions will be reported in detail in the IEA AMF report, which is planned in May 2014

In addition, unregulated emissions were analyzed i.e. pollutants without limit values in applicable legal requirements, but which are known to have a negative impact on human health and the environment. The compounds analyzed were aldehydes, PAH and particle size distribution. In combination with the sample extracts from PAH analyzes were also Ames' salmonella tests performed. The results of the unregulated emissions are presented in this report.

For the Dual Fuel vehicle, measurements with FTIR were performed. The NO_2/NOx ratio for the Dual Fuel vehicle was, regardless of start temperature and drive cycle, slightly higher when driving in Diesel mode. No clear conclusion regarding emissions of N_2O could be drawn. No emissions of NH_3 were detected in

any test.

For all vehicles, formaldehyde and acetaldehyde dominated of the aldehydes measured. The sum of the other aldehydes varied between 3% and 17% of the total aldehydes. The amount of aldehydes appears to be reflected in the amount of THC/CH_4.

For the DDF vehicle operated in Dual Fuel mode, were the levels of formaldehyde considerable higher compared to the Diesel mode tests and the other vehicles.

The dedicated gas vehicles emitted significantly more formaldehyde during the cold start test compared to the warm start test. For the DDF vehicle was the situation opposite.

For the acetaldehyde levels, no clear trend depending on start temperature could be seen.

For all vehicles and for all particle sizes, it can be concluded that cold start tests generates slightly more particulates than warm start tests.

Particle size distribution and particle number did not vary significantly between the two driving modes of the DDF vehicle.

The dedicated gas vehicle with lean-burn technology generated the lowest amount of particles. Both the dedicated gas vehicles generate fewer particles than the DDF vehicle and the MK1 reference vehicle.

The higher PAH content of Diesel fuel compared to CNG was reflected in the exhaust emissions from the DDF vehicle (Diesel mode) and the MK1 vehicle. Particulate PAHs were significantly higher when Diesel was used as test fuel, whereas no such clear exemplification could be shown for the volatile PAH where the lean-mix vehicle showed the highest levels.

In Ames' test, the number of mutants increased in comparison to the blank sample for all analyzed samples, but in some not significantly. The highest level of mutagenicity response was in the cold start test of the dedicated gas vehicle with stoichiometric technology. The vehicle showed an increase of mutagens both with and without S9-mix. Also the DDF vehicle in DDF mode shows an increase of mutations, compared to the blank test, both with and without S9-mix, but less and with a lower significance level. For the DDF vehicle in diesel mode and for the MK1 reference vehicle, the results indicate that the exhaust components need to metabolically activated in order to induce mutations.

The higher levels of volatile PAH and genotoxicity for the lean-mix gas vehicle may have been caused by engine oil consumption which generally is higher for gas vehicles and the quality of the oil may also have influenced the result. In addition, the mileage of this vehicle was considerable higher for this vehicle compared to the other vehicles and the aftertreatment system was of a different kind.

Sammanfattning

På uppdrag av SGC (samt medfinansiärer) har AVL MTC mätt emissioner från tre tunga fordon då de körts på chassidynamometer. För provningen användes en för chassidynamometerprov modifierad version av provcykeln ”Worldwide Harmonized Transient Cycle” (WHTC) vilken används vid certifiering av motorer till tunga fordon. Benämningen på den modifierade provcykeln är Worldwide Harmonized Vehicle Cycle (WHVC).

Fordon nummer 1var en CNG driven citybuss godkänd enligt emissionsstandarden EEV(Enhanced Environmental friendly Vehicle). Förbränningsprincipen för motorn var sk stökiometrisk/”lean mix", dvs den växlade mellan stökiometrisk och mager förbränning. Fordonet var utrustat med en trevägskatalysator. Bränslet som användes vid provningen var CNG från fordonets egen tank, tankad på vanlig tankstation.

Fordon nummer 2 var en lastbil (för fjärrtransport) ombyggd till sk Dual Fuel drift/metandiesel, dvs motorn drevs med en varierande blandning mellan diesel och metangas. Lastbilen var godkänd enligt emissionsstandard Euro V i sin ursprungliga form (diesel bränsle). Då certifieringsmetod för denna typ av fordon i dagsläget saknas, utfärdar Transportstyrelsen dispenser till tillverkaren vilket möjliggör registrering av fordonen. Enligt denna dispens ska fordonet uppfylla emissionsstandard Euro V. Fordonet var utrustat med en oxidationskatalysator och ett SCR-system. Bränslet som användes vid provningen av detta fordon var Mk1 (utan HVO-tillsats) samt LBG (Liquefied Bio Gas). Både Mk1 diesel och LBG tankades av Volvo. Bränslespecifikationer för LBG finns bifogade i appendix.

Fordon nr 3 var en CNG driven buss av emissionsstandard EEV. Förbränningsprincipen för motorn var sk ”lean-burn”, dvs drevs med luftöverskott. Fordonet var utrustat med en oxidationskatalysator. Bränslet som användes vid provningen var CNG från fordonets egen tank, tankad på vanlig tankstation.

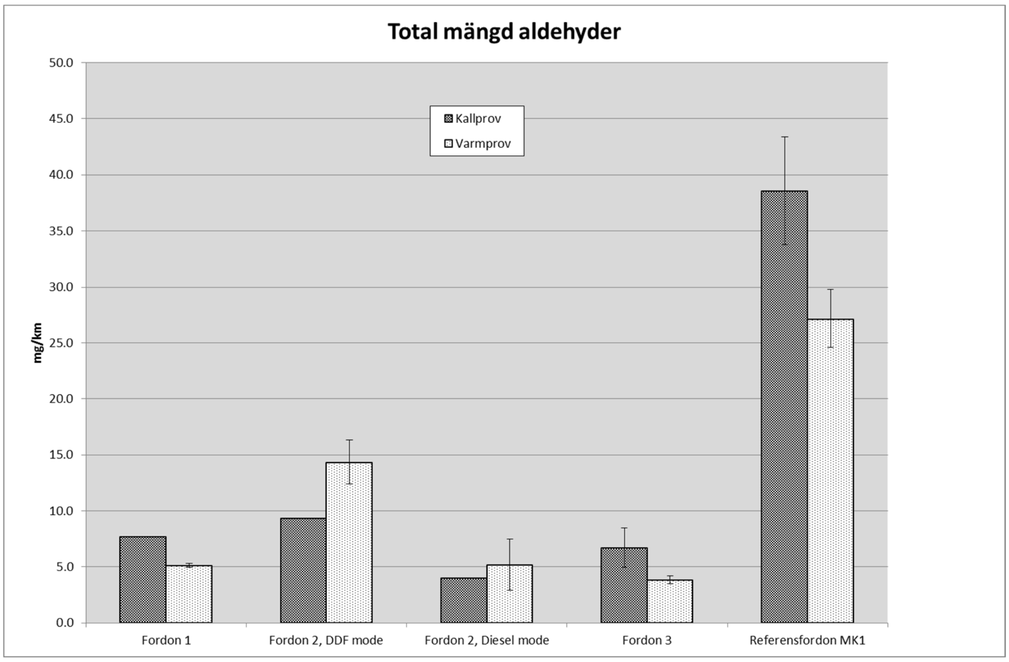
I rapporten har även resultat från liknande provning av ett Dieselfordon med SCR-efterbehandling tagits med som referens [1].

Prov genomfördes med både kall och varm motor på samtliga fordon.

De emissioner som analyserades var de reglerade avgaskomponenterna kolmonoxid (CO), kolväten (HC och CH_4) kväveoxider (NOx), koldioxid (CO_2) samt partiklar (PM). Bränsleförbrukningen har beräknats. Dessa resultat kommer att redovisas i den slutgiltiga IEA AMF-rapporten som beräknas vara klar i maj 2014.

Utöver detta analyserades oreglerade emissioner, dvs föreningar som saknar gränsvärden enligt gällande lagkrav men som är kända för att ha en negativ påverkan på hälsa och miljö. De föreningar som analyserades var aldehyder, polycykliska aromatiska kolväten (PAH) samt partikelstorleksfördelning. I kombination med provextrakten från PAH-analyserna genomfördes även Ames salmonella test. Resultat av oreglerade emissioner finns redovisade i denna rapport.

Av de mätta aldehyderna dominerade formaldehyd och acetaldehyd hos alla fordon. Summan av övriga aldehyder varierade mellan 3% och 17% av de totala aldehyderna. Mängden aldehyder verkar också avspeglas i mängden THC/CH_4.



Figur A. Total mängd aldehyder för samtliga fordon

Då DDF fordonet kördes i Dual Fuel mode, var nivåerna av formaldehyd avsevärt högre jämfört med då det kördes i Diesel mode och även jämfört med övriga fordon.

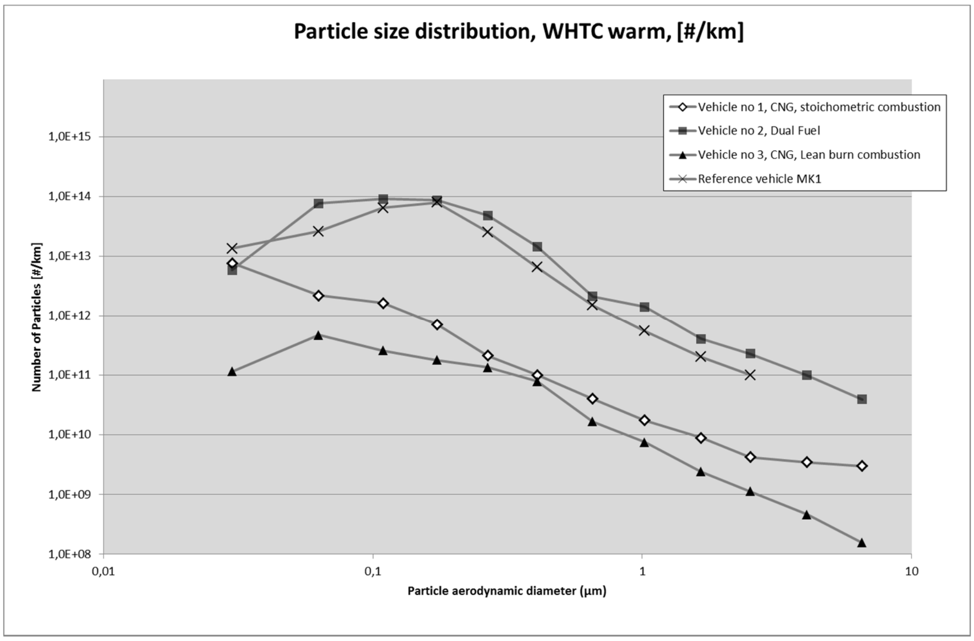
De dedikerade gasfordonen emitterade avsevärt mycket mer formaldehyd under kallstartprovet jämfört med varmstartproven. För DDF fordonet var situationen motsatt.

För acetaldehydnivåer kunde ingen tydlig trend beroende på starttemperatur ses.

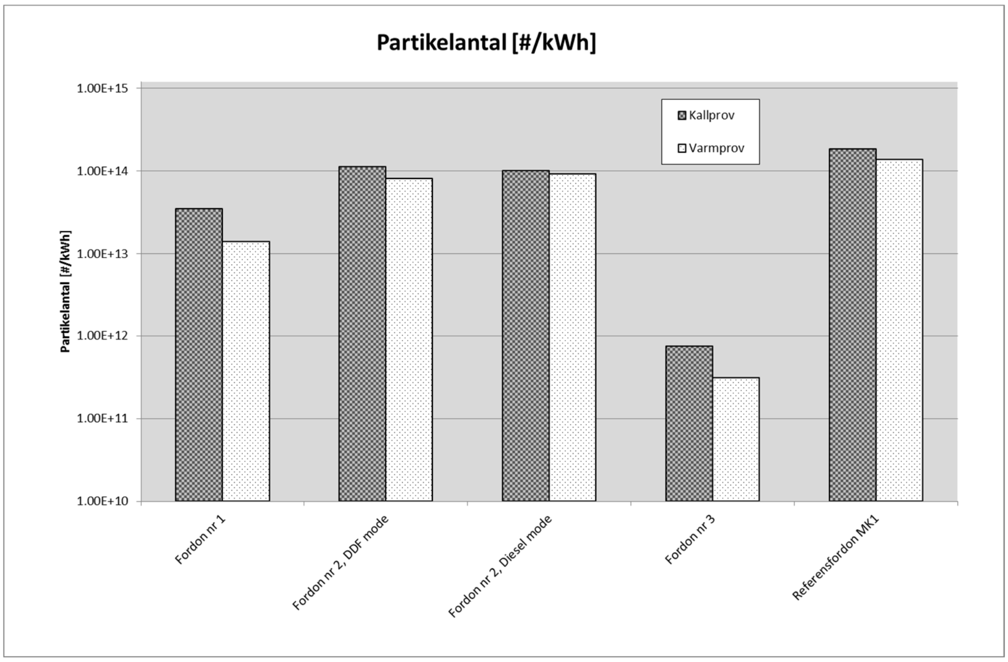
För alla fordon och för alla partikelstorlekar kan konstateras att kallstartprover genererar något fler partiklar än varmstartprover.

Det dedikerade gasfordonet som tillämpade lean burn-teknik genererade den lägsta mängden partiklar. Båda de dedikerade gasfordonen genererade färre partiklar än DDF fordonet och MK1 referensfordonet.

Det var ingen betydande skillnad på partikelstorleksfördelning och antal partiklar då DDF-fordonet kördes i Dual Fuel mode jämfört med Diesel mode.

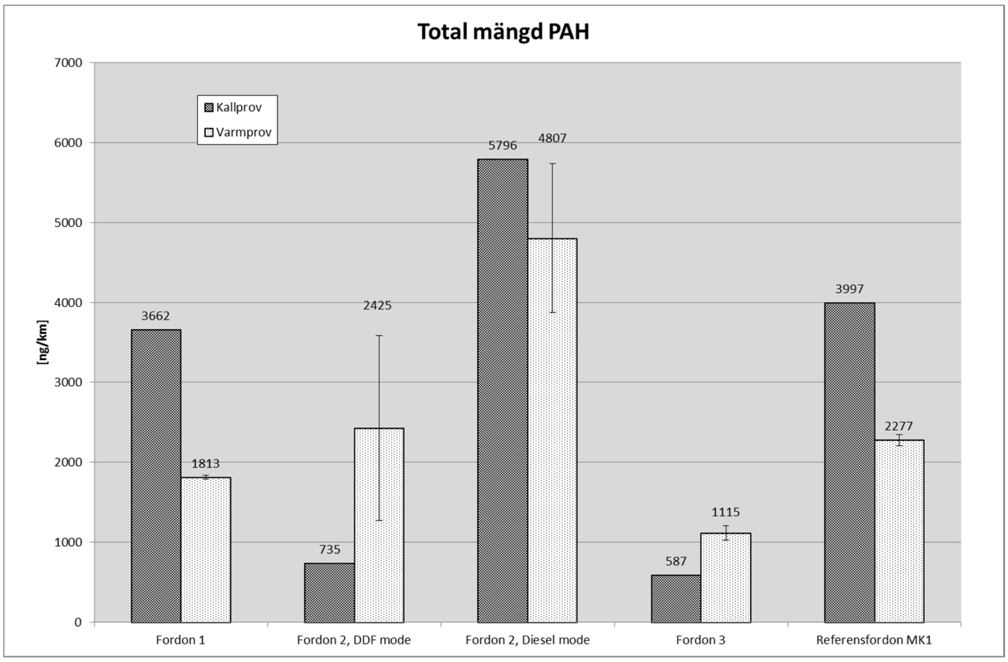


Figur B. Partikelstorleksfördelning för alla fordon vid varmprov



Figur C. Partikelantal för alla provade fordon

Dieselns högre PAH-innehåll jämfört med CNG avspeglas i emissionerna från DDF-fordonet (diesel mode) och i MK1 fordonet. Partikulärt PAH var signifikant högre när Diesel användes som testbränsle. För flyktiga PAH:er kunde inte samma tydliga samband visas då lean-mix/dedikerade gasfordonet visade de högsta nivåerna. Genotoxiciteten var också avvikande hög. Källan till detta kan vara motorolja. Motoroljekonsumtionen är generellt högre i gasfordon, och dessutom var körsträckan för detta fordon väsentligen högre än de andra fordonens, och efterbehandlingssystemet var av ett annat slag.



Figur D. Total mängd PAH, alla fordon, varma och kalla prov

I Ames test ökade antalet mutanter jämfört med blankprovet i alla analyserade prov men i några var ökningen inte signifikant. Den högsta nivån av mutagen respons kom i ett prov med det dedikerade gasfordonet med stökiometrisk teknologi. Fordonet påvisade mutagen effekt både med och utan tillsats av S9-mix. Även DDF fordonet i DDF mode uppvisar en ökning av multigeniet, jämfört med blankprovet, både när och utan S9-mix, dock på en lägre nivå och med en lägre signifikans. För DDF-fordonet i diesel mode och för MK1 referensfordonet indikerar resultatet att avgaskomponenterna behöver aktiveras metaboliskt för att ge upphov till mutationer.

Tabell A. Resultat från Ames test

Test	Revertants/m -S9	Revertants/m +S9
Vehicle 1, cold test	4,98 ± 1,07 ***	4,51 ± 1,42 ***
Vehicle 2, cold test, DDF mode	*(1,07 ± 0,86 ns)*	2,35 ± 0,71 **
Vehicle 2, warm test, DDF mode	3,12 ± 0,76 **	1,98 ± 0,65 *
Vehicle 2, warm test, DDF mode	2,29 ± 0,66 **	2,82 ± 0,56 ***
Vehicle 2, warm test, DDF mode	2,29 ± 0,84 *	2,06 ± 0,49 **
Vehicle 2, cold test, Diesel mode	2,05 ± 0,84 *	2,36 ± 0,59 **
Vehicle 2, warm test, Diesel mode	*(1,06 ± 0,64 ns)*	*(1,14 ± 0,60 ns)*
Vehicle 2, warm test, Diesel mode	*(3,01 ± 1,39 ns)*	2,39 ± 0,60 **
Vehicle 2, warm test, Diesel mode	3,02 ± 0,64 ***	4,37 ± 0,59 ***
Mk1 reference, cold test	*(1,61 ± 1,08 ns)*	4,55 ± 1,10 **
Mk1 reference, warm test	*(2,28 ± 1,35 ns)*	3,55 ± 1,14 *
Mk1 reference, warm test	*(1,35 ± 0,952 ns)*	4,74 ± 0,891 ***

Signifikansnivåer: * 0,005 < p <0,01; ** 0,001 < p < 0,005;
*** p < 0,001, i skillnad från kontrollvärden. Kursiva siffror är icke signifikanta värden.

Table of contents

1. Background

Methane gas is used as engine fuel worldwide and has the potential to complement Diesel oil and thereby help decreasing the consumption of the declining oil reserves. Furthermore, use of methane can be favourable in order to decrease emissions of CO_2, especially when the methane origins from biomass.

Both natural gas (NG) and gas originated from upgraded biomass contains mostly methane and can from an engine point of view normally be considered as equal fuels. Methane is considered to be a clean engine fuel. Exhaust emissions – especially particulates are very low and oxides of nitrogen can also be kept low by applying proper technology. Specific CO_2 emission (g CO_2/MJ) is lower for methane than for petrol or diesel due to high H/C ratio. However, both engine efficiency and specific CO_2 emissions affect tailpipe CO_2 emissions.

Other advantages are high octane number (>120) and noise levels are low compared to diesel engines. Drawbacks are that the operation range is shorter that with diesel vehicles and energy efficiency is not as good as that of diesel vehicles. However, using liquefied methane can to some extend improve this situation. Methane is also a very potent greenhouse gas and unburned methane passing through the engine can reduce or even nullify any environmental benefit compared to diesel. Still advantages of gaseous fuel are clear, and therefore e.g. CNG (Compressed Natural Gas) buses are quite common in many cities. Natural gas has been clearly cheaper than diesel in many countries, and this is one prerequisite for the fleet owners to invest to gas vehicles.

Today most heavy duty gas engines are spark ignited engines using the Otto cycle, and the advantage in fuel chemistry compared to diesel is lost due to lower energy efficiency of spark ignited engines. Dual fuel engines using gas as the main fuel are one step for better energy efficiency, but transient drive cycles with low average load are challenging applications for dual-fuel engines. [2]

Many substances found in the emissions of heavy duty engines are not included among the regulated emissions, which are limited to carbon monoxide (CO), nitrogen oxides (NOx), total hydrocarbons (HC), methane (CH_4) and particulates (PM). Some unregulated substances however, are proven to have a negative effect on human health and the environmental. The availability of data for those pollutants is limited, but there are indications that there may be differences between diesel and natural gas / bio methane.

Unregulated emissions are often more specified elements of the regulated emissions. Total hydrocarbons for example contain carbonyl compounds (aldehydes, ketones) and aromatic hydrocarbons (BTX and PAHs), NOx includes NO_2, which is not regulated but is the portion of the NOx that has the greatest effect on human health and the environment. The declining levels for limit values of NOx emissions from diesel vehicles shown in later years, has not been reflected in the NO_2 levels. Maybe this is a result of increasing differences between real life emissions and emissions measured during regulatory testing.

The aim of the project is to increase the knowledge about heavy duty gas operated vehicle's impact on the environment and human health, as well as reduction of greenhouse gases. In the long term, this may result in improved competitiveness and serve as an argument for investment in heavy duty gas operated vehicles, which often replaces diesel operated vehicles.

2. Experimental

2.1 Test Vehicles

Test vehicle data is presented in table 1. The European emission standards for gas engines are presented in table 2. Emission levels of the regulated emission components for each vehicle are presented in table 3-6.

Table 1. Test vehicle data

	Vehicle nr 1	Vehicle nr 2	Vehicle nr 3	Ref Diesel Vehicle
Year model:	2010	2011	2010	2011
Mileage [km]:	85 793		15 488	10 000
Combustion principle:	Stoichio-metric/"lean mix" (Eg alternates between stoichi-ometric and lean-burn)	Clean Air Pow-er DDF system, Pilot diesel in-jection (diesel cycle/lean burn)	Lean-burn	
Fuel:	CNG	LBG/MK1	CNG	Diesel
After treatment system	TWC	DOC, SCR	DOC	SCR
Engine power [kW]:	228	345	199	375
Emission stan-dard	EEV	Euro V	EEV	Euro V

Table 2. European emission legislation for gas engines (engine test)

	CO	NMHC	CH_4	NOx	NH_3	PM	PN#	Test Cycle
	g/kWh	*g/kWh*	*g/kWh*	*g/kWh*	*ppm*	*g/kWh*	*10^{12}/kWh*	
Euro III	5.45	0.78	1.6	5.0		0.16		ETC
Euro IV	4.0	0.55	1.1	3.5		0.03		ETC
Euro V	4.0	0.55	1.1	2.0	-	0.03		ETC
EEV	3.0	0.40	0.65	2.0	-	0.02		ETC
Euro VI	4.0	0.16	0.5	0.46	10	0.01	0.6	WHTC

Table 3. Regulated emission results, vehicle no 1

Vehicle no 1, Regulated emission results	CO	THC	CH4	NOX	CO2	PM	CO	THC	CH4	NOX	CO2	PM
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/km	g/km	g/km	g/km	g/km	g/km
Average WHVC cold	6.67	0.88	0.82	1.03	1145	0.008	5.96	0.79	0.73	0.92	1024	0.007
Average WHVC warm	1.28	0.20	0.21	0.73	1087	0.005	1.14	0.18	0.18	0.65	974	0.004
Average FIGE	0.86	0.48	0.47	0.93	1103	0.006	0.75	0.42	0.40	0.80	953	0.005

Table 4. Regulated emission results, vehicle no 2

Vehicle no 2, Regulated emission results	CO	THC	CH4	NOX	CO2	PM	CO	THC	CH4	NOX	CO2	PM
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/km	g/km	g/km	g/km	g/km	g/km
Average WHVC cold DDF	0.29	6.29	6.57	5.79	783	0.063	0.27	5.90	6.15	5.42	733	0.059
Average WHVC cold Diesel	0.34	0.00	0.00	5.76	829	0.069	0.32	0.00	0.00	5.36	771	0.064
Average WHVC warm DDF	0.07	8.54	9.14	4.47	666	0.046	0.06	7.86	8.41	4.11	612	0.042
Average WHVC warm Diesel	0.20	0.01	0.00	5.88	792	0.057	0.18	0.01	0.00	5.33	718	0.051
Average FIGE DDF	0.08	6.78	8.70	3.95	612	0.031	0.06	5.49	7.05	3.20	497	0.025
Average FIGE Diesel	0.05	0.00	0.00	5.15	699	0.044	0.04	0.00	0.00	4.25	578	0.037

Table 5. Regulated emission results, vehicle no 3

Vehicle no 3, Regulated emission results	CO	THC	CH4	NOX	CO2	PM	CO	THC	CH4	NOX	CO2	PM
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/km	g/km	g/km	g/km	g/km	g/km
Average WHVC cold	0.50	1.81	1.85	2.04	939	0.003	0.45	1.63	1.66	1.84	844	0.003
Average WHVC warm	0.07	0.42	0.42	1.62	881	0.003	0.06	0.38	0.38	1.46	795	0.002
Average FIGE	0.03	0.56	0.57	1.17	779	0.004	0.03	0.48	0.48	0.99	660	0.004

Table 6. Regulated emission results, reference MK1 vehicle

MK1 Vehicle, Regulated emission results	CO	HC	CH4	NOX	CO2	PM	CO	HC	CH4	NOX	CO2	PM
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/km	g/km	g/km	g/km	g/km	g/km
Average WHVC cold	1.62	n.d	n.d	4.84	906	0.063	1.90	n.d	n.d	5.69	1065	0.074
Average WHVC warm	0.73	0.01	n.d	3.97	809	0.046	0.88	0.02	n.d	4.75	968	0.055

2.2 Engine technology information

Comparing lean burn and stoichiometric technologies

Two different technologies can be used for operating methane fuelled SI engines, either stoichiometric ($\lambda=1$) or lean burn ($\lambda>1$). It is also possible to combine the technologies i.e. lean-stoichiometric/mix, which uses stoichiometric combustion on low load and lean-burn combustion on high load.

When operating in stoichiometric conditions, a three-way catalyst (TWC) can be used as an effective and cost efficient aftertreatment system to reduce HC, CO and NO_x. The downsides with stoichiometric engines are lower part load efficiency, higher combustion temperature and higher knock sensitivity compared to lean burn engines.

The reason for increased combustion temperature and knock sensitivity is less dilution (with air) compared to lean burn engines. This also leads to a demand for lower compression ratio in a stoichiometric engine compared to a lean burn engine to avoid knocking. For stoichiometric engines, adding an emission reduction system comprising cooled Exhaust Gas Recirculation (EGR) at full load, is an effective way to increase the knock tolerance and decrease combustion temperature. The EGR system could also be used at part load to decrease engine efficiency and thereby making the stoichiometric engine more efficient. In addition, many of the original Diesel engine components (such as cylinder head, exhaust manifold, turbine etc) can be used.

Lean burn engines emits higher tail pipe NOx emissions compared to stoichiometric engines which benefits from the high NOx reduction in the TWC that does not exist in oxidation catalysts. Lean burn engines on the other hand emit less engine out emissions of NOx. This will limit the use of lean burn technology to meet maximum Euro V emission levels if no aftertreatment for reduction of NOx such as SCR (Selective Catalytic Reduction) is used. The cost and complexity of the SCR aftertreatment system in combination with the oxidation catalyst, loaded with high amount of precious metal, makes the aftertreatment system for a lean burn gas engine meeting Euro VI emission requirement more expensive and complex compared to the stoichiometric engine meeting the same emission requirements.

Another important drawback with lean burn Euro V and Euro VI engines are the high discharge voltage leading to high risk of problems with the ignition system. (Examples such as flash-over, misfire, short lifetime for spark plugs etc.).

Diesel Dual Fuel (DDF)

In DDF engines, a small amount of Diesel fuel is injected and used to ignite the air/methane mixture like a “liquid” spark plug. This “micro pilot” Diesel injection introduces far more energy than a spark from the spark plug which increases the lean burn capability compared to SI concept.

There are generally two different types of DDF combustion systems, one uses a port injected “premixed” air/methane mixture which is ignited by the Diesel injection and burns with a flame propagation (like the Otto combustion). The second type uses direct injected (DI) methane which burns with diffusion controlled combustion (like the Diesel combustion). The most common DDF system is the premixed concept which is relatively cost effective, simple to install and enable the Diesel engine to operate on “Diesel fuel only” mode with full performance (when the gas tank is empty). The major drawbacks with the premixed system are high levels of unburned methane (methane slip) and knock limited gas substitution over the full operating range of the engine. The direct injected (DI) DDF system has the potential for less methane slip and higher gas substitution but has limited performance in Diesel (only “limp home” mode) when the gas tank is empty. Further, the system is generally more expensive than the premixed DDF system because it demands a complete new fuel system for methane and Diesel, including engine controller, high pressure fuel pumps (methane and Diesel) and specially designed fuel injectors.

The main reasons for methane slip are believed to be poor combustion of methane at part load due to very lean methane/air mixture, unfavourable piston design for flame propagation, blow by of unburned methane during valve overlap and large crevice volumes where the flame cannot propagate. This is due to the fact that conventional Diesel combustion system is not designed for premixed flame propagation. Most of the DDF systems cannot take full control of the Diesel injections to overcome these problems. One way of minimizing this problem could be to introduce an effective methane catalyst. Another way could be to optimize the combustion control by using the potential of modern common rail Diesel injection systems. Direct injection of methane can however, to some extent overcome these drawbacks but such concepts may instead suffer from high engine out NO_x emissions. [3, 4, 5, 6]

2.3 Test Program

All vehicles have been tested during the WHVC test cycle. Both cold tests and warm tests have been performed. Regulated emissions and fuel consumption have been measured/calculated as well as unregulated emissions. Regulated emissions will be presented in the IEA-AMF report which is planned in May 2014.

The following have been measured for all vehicles:

- Regulated emissions, CO_2 and fuel consumption
- Particle number and size distribution (ELPI)
- Carbonyl compounds (Formaldehyde, Acetaldehyde, Acetone, Acrolein, Propionaldehyde, Crotonaldehyde, Methyletylketon, Butyraldehyde, Benzaldehyde)
- PAH analysis (chemical characterization, 20 different components);
- Genotoxicity tests (AMES test) (Unfortunately no results were obtained for vehicle nr 3 since the amount of PAH extract was not sufficient for analysis)

For vehicle no 1 have

- Olefins: C_2H_4 (ethane), C_3H_6 (Propene), C_4H_6 (Butadiene), C_6H_6 (Benzene), have been measured with Mass Spectrometer (MS)

For vehicle no 2 have

- NH_3, N_2O, NO and NO_2 been measured with FTIR.
- Measurements of olefins with MS were performed but no reliable results were obtained.

For vehicle no 3 have

- Measurements of olefins with MS were performed but no reliable results were obtained.

2.4 Test cycle

The WHVC/WHTC test cycle

The WHTC (World Harmonized Transient Cycle) test cycle will become the future test cycle for certification of engines. The WHVC (World Harmonized Vehicle Cycle) test cycle, which can be used for testing entire vehicles on a chassis dynamometer, is the test cycle from which the WHTC was developed. The WHVC is not identical to the WHTC since it was only an intermediate step from data collection to engine test bench cycle, but it is the closest there is today.

The test procedures for chassis dynamometer testing are not identical to the procedures used for engine dynamometer testing, but the results using the WHVC test cycle can be used in order to compare the emission levels from a vehicle with the emissions levels of an engine tested with the WHTC test cycle. The emission results are presented in g/km but also converted from g/km to g/kWh using estimations of executed work during the transient test cycle.

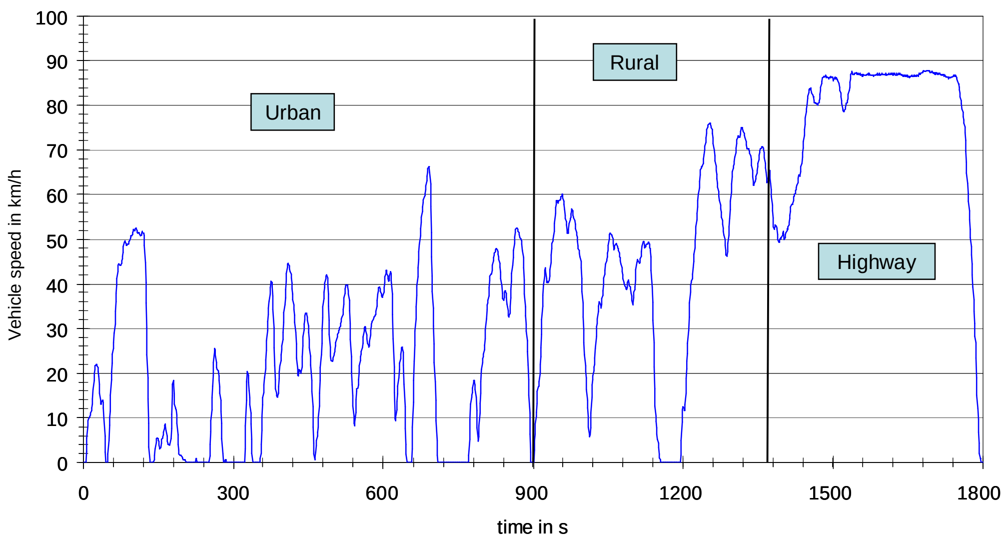


Figure 1. The WHVC/WHTC test cycle

The transient cycle used in the test was the “WHVC” test cycle (unofficial).

The WHVC is a transient test of 1800 s duration, with several motoring segments.

Different driving conditions are represented by three parts of the WHVC cycle, including urban, rural and highway driving.

The duration of the entire cycle is 1800s.

- The first 900 seconds represents urban driving with an average speed of 21 km/h, maximum speed of 66 km/h. This part includes frequent starts, stops and idling.
- The following 468 seconds represents rural driving with an average speed of 43 km/h and maximum speed of 76 km/h.
- The last 432 seconds are defined as highway driving with average speed of about 76 km/h.

2.5 Test equipment AVL

Chassis dynamometer test cell

The chassis dynamometer is a cradle dynamometer with 515 mm roller diameters. The maximum permitted axle load is 13 000 kg. Vehicle inertia is simulated by flywheels in steps of 226 kg from 2 500 kg to 20 354 kg. The maximum speed is 120 km/h without flywheels and 100 km/h with flywheels.

Two DC motors, each 200 kW maximum load, and separate control system serves as power absorption units. The DC motors and their computer-controlled software enable an excellent road load simulation capability. The software sets the desired road load curve through an iterative coast down procedure with test vehicle on the dynamometer.

An AVL PUMA computer system is used as a superior test cell computer for engine monitoring and also for the measurement and collection of all data emanating from the vehicle, emission measurement system and test cell.

2.6 Measuring method – engine power

The engine power was estimated by adding the integrated signals from measured acceleration force of the inertia used and the road-load. There has been no fan correction used in this calculation.

2.7 Measuring methods – Unregulated emissions

FTIR – CH_4, NO, NO2, N_2O, NH_3

CH_4, NO_2, N_2O, and ammonia slip (NH_3) was measured using FTIR (Fourier Transform InfraRed)

The FTIR measurement was performed on raw exhaust emissions and provided second-by-second data. The FTIR instrument has the capability to measure many substances at the same time, with a fast response.

Mass Spectrometer (MS)

The Mass Spectrometer was used for determination of olefins and aromatics. It separates molecules in a gas stream by using the quote between the mass and the charge of the molecules (when ionised).

Measurement with the Mass Spectrometer is not a regulated procedure and is mostly used for research purposes for determination of unregulated emissions.

The MS consists of four parts and the incoming molecules are treated in the different stages; the ionisation, the accelerator, the separator and the detector stage. In the MS the atoms/molecules are first ionised, by force, into positive ions. The ions are then accelerated and thereafter immediately deflected in a curved magnetic field according to their masses. The lighter molecules are deflected more than the heavier ones. The level of deflection is also dependent of the positive charge of the molecule – if more than one electron has been knocked off, the molecule has a stronger charge – and is more deflected. It is only the ions with the correct mass/charge relationship that passes through to the detector stage. By varying the magnetic field ions with different mass/charge relationship can be analysed.

The MS is a fast response instrument; it is possible to get modal measurement at a speed of up to 50 Hz which makes it possible to measure at transient conditions. It can be used for raw exhausts as well as for diluted exhausts. It is possible to detect many different molecules with the MS, Different molecules will be distinguished through their different molecule weight. If however the concentration of specific substance is an issue, the instrument needs to be calibrated with a known concentration of the specific substances.

Particulate size distribution

An Electrical Low Pressure Impactor (ELPI) was used for particle size distribution. The instrument was manufactured by Dekati Ltd. in Finland. The principle of the ELPI instrument is described below.

Before entering the ELPI instrument, the exhaust gases are diluted in order to reduce their concentration. In this case, sampling was carried out from the full flow primary dilution tunnel. The diluted exhaust is drawn through the instrument using a vacuum pump. In an impactor, the particles are classified according to their aerodynamic diameter. The ELPI impactor is equipped with a filter stage, and measures particle size distribution in 12 stages in the size range of 7nm to 10um. Before entering the first impactor stage the particles are charged using a unipolar charger. The particles are collected on a specific impactor stage and produce an electrical current that is recorded in real time using a multichannel electrometer.

Measurement of aldehydes

The analysis of the aldehydes was performed by the Swedish Environmental Research Institute (IVL).

Analysis of aldehydes was carried out using 2.4-di nitro phenyl hydrazine (DNPH) coated filter cartridges which, after sampling, where extracted with distilled acetonitrile and analyzed on a C-18 silica column with a methanol/water gradient and HPLC/UV detection. Quantification was carried out with corresponding hydrazone as external standard.

PAH analysis

The extraction and analysis of the samples was carried out at the department of analytical chemistry, Arrhenius laboratory, University of Stockholm.

A standard mixture of the PAHs determined in the present study and the deuterated PAHs phenanthrene-D_{10}, pyrene-D_{10}, benzo[a]anthracene-D_{12}, benzo[a]pyrene-D_{12}, benzo[ghi]perylene-D_{12} and dibenzo[a,i]pyrene-D_{14} was used for identification and quantification purposes.

A solution containing the deuterated PAHs phenanthrene-D_{10}, pyrene-D_{10}, benzo[a]anthracene-D_{12}, benzo[a]pyrene-D_{12} and benzo[ghi]perylene-D_{12} was used along with a solution of dibenzo[a,i]pyrene-D_{14} in toluene as internal standards. The PUF and filter samples were extracted with pressurized fluid extraction using an ASE 200 accelerated solvent extraction system.

The filter samples were extracted in 5 ml extraction cells with an ASE method recently developed and validated for analysis of PAHs in diesel particulate matter using standard reference materials from the US National Institute of Standards and Technology (NIST). Extractions were performed with a mixture of toluene and methanol (9:1; v/v) at elevated temperature and pressure (200 °C and 3000 psi). The extraction consisted of five 30 min extraction cycles.

The PUF samples were extracted in 33 ml extraction cells with acetone at 110 °C and 500 psi using two extraction cycles of 5 min. A 20 % flush was used and the purge time was set to 60 seconds.

Before sampling the PUFs were cleaned in a washing machine at 90°C and hand squeezed in ethanol. They further cleaned-up in 33 ml extraction cells using the ASE with two consecutive 5 min extractions of toluene and acetone, respectively, at 110 °C and 500 psi. The flush was set to 60 % and the purge time was 60 seconds.

The extracts were concentrated to about 5 mL using a under a gentle stream of nitrogen gas. The extracts were then transferred to glass vials with screw caps and stored in a freezer at -20 °C.
For AMES test aliquots of the PUF extracts were transferred to glass vials and evaporated to dryness using nitrogen gas. Aliquots of the corresponding filter extracts were then added to the glass vials. The solutions were evaporated to dryness and the samples were re-dissolved in approximately 500 µl dimethyl sulfoxide.

For analysis of PAH content in the filter and PUF extracts aliquots were transferred from the glass vials containing the extracts to disposable test tubes. Internal standards were added and the filter extracts were evaporated to approximately 0.5 ml while 0.5 ml toluene was added to the PUF extracts before reducing the volume to about 0.5 ml. The samples were then cleaned-up using a solid phase extraction (SPE) protocol.

The analysis of PAHs was performed using a hyphenated High Performance Liquid Chromatography- Gas Chromatography/Mass Spectrometry (HPLC-GC/MS) system. The HPLC system consisted of an, an inert solvent delivery, a UV and a nitrophenylpropylsilica column (4.0 mm i.d. x 125 mm, 5 µm particle size) Isocratic separation was performed using hexane with 0.1% dodecane (v/v) as the mobile phase. The HPLC part was connected to a GC through a fused silica capillary inserted into the Programmed Temperature Vaporizer injector, which was operated in the solvent vent mode. The GC separation was carried out on a DB-17MS capillary column (60 m × 0.25 mm i.d. with 0.15 µm film thickness) equipped with a retention gap (5 m x 250 µm i.d.). Mass selective detection was performed using a quadrupole mass spectrometer operated in the electron ionization (EI) mode. Data acquisition was performed operating the quadrupole mass analyzer in selected ion monitoring (SIM) mode.

Genotoxicity tests

The genotoxicity tests were performed by the Department of Molecular Biosciences, the Wenner-Gren Institute at Stockholm University.

Mutagenicity tests were carried out using Salmonella typhimurium strain TA98 according to Maron and Ames [6] with a slight modification in which histidine and biotin were added to the minimal medium instead of to the soft agar [8]. The bacteria strain was tested with and without a liver preparation (S9) from Aroclor-1254 pretreated male Sprague-Dawley rats (lyophilized samples from Moltox, USA. The metabolizing system, the S9-mix, contained necessary cofactors and 10 % of the rat liver fraction was used in an amount of 50 µL per plate.

Both filter extracts (particulates) and PUF extracts (semivolatile phase) were subjected to chemical analyses. For the mutagenicity tests the extracts from the particulate and the corresponding semivolatile phase were combined before testing. All extracts were evaporated to nearly dryness under nitrogen and then diluted with dimethyl sulfoxide (DMSO) to known volumes and tested for mutagenicity. The extracts were tested in three concentrations per plate, in triplicates, corresponding to driving distances of 1.5, 3 and 6 m. The volumes of each sample added to the soft agar were 25, 50, and 100 µL, respectively, and DMSO served as a negative control. Another negative control was also used “Blank” corresponding to a combined particulate and semivolatile extract of exhaust free air.

3. Results and discussion

3.1 FTIR test results

The results from the FTIR measurements of the Dual Fuel vehicle are presented in figure 2-3 and table 7. The numerical results are presented in Appendices.

Diesel mode driving generated slightly higher proportions of NO_2 of total NO compared to DDF mode. This may be a result of that high NO_2/NO_X ratios are favoured at low exhaust temperatures and the temperature of diesel combustion exhaust is lower than of NG combustion exhaust [9].

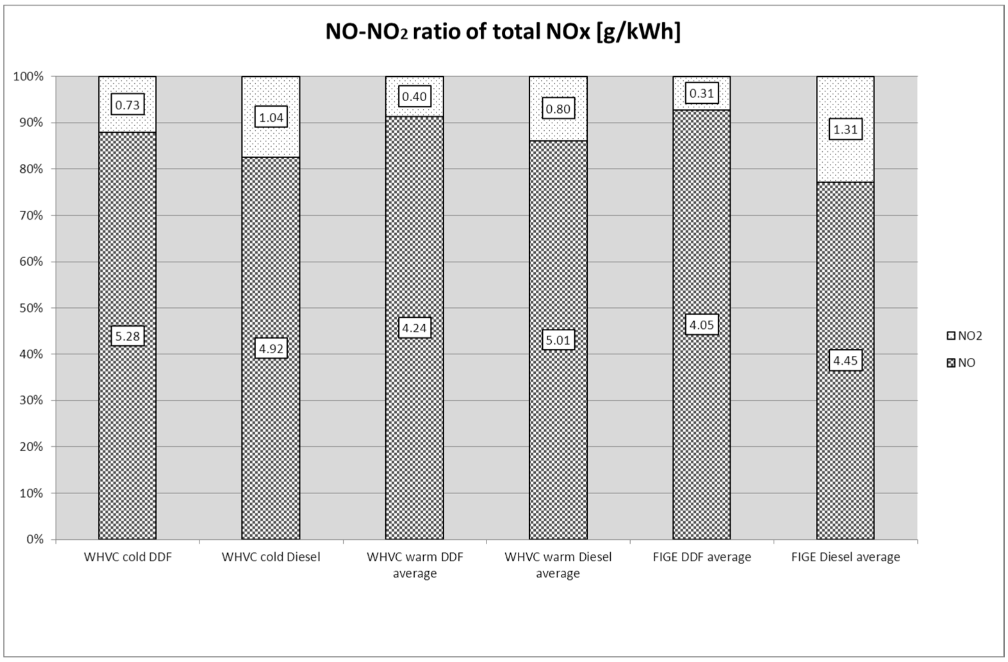


Figure 2. NO/NO$_2$ ratio of total NOx from vehicle no 2

The emissions of N_2O differed approximately 35% between the highest and the lowest result. Depending on start temperature and drive cycle, Diesel mode seems to give slightly lower results than Dual Fuel mode

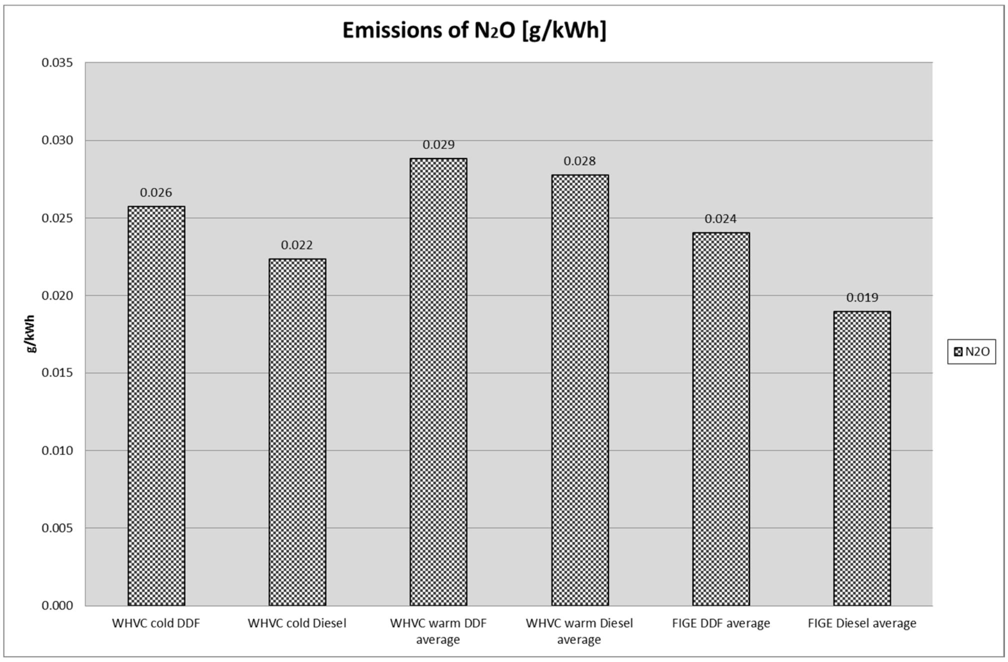


Figure 3. Emissions of N_2O from vehicle no 2

No emissions of NH_3 were detected in any test.

Table 7 Emissions of NH_3 from vehicle no 2

	NH_3
	ppm (average)
WHVC cold DDF	n.d
WHVC cold Diesel	n.d
WHVC warm DDF average	n.d
WHVC warm Diesel average	n.d
FIGE DDF average	n.d
FIGE Diesel average	n.d

3.2 Mass Spectrometer (MS) test results

The results from the MS measurements are presented in figure 4. Both the lubricant oil and the fuel may be the origin of the olefins.

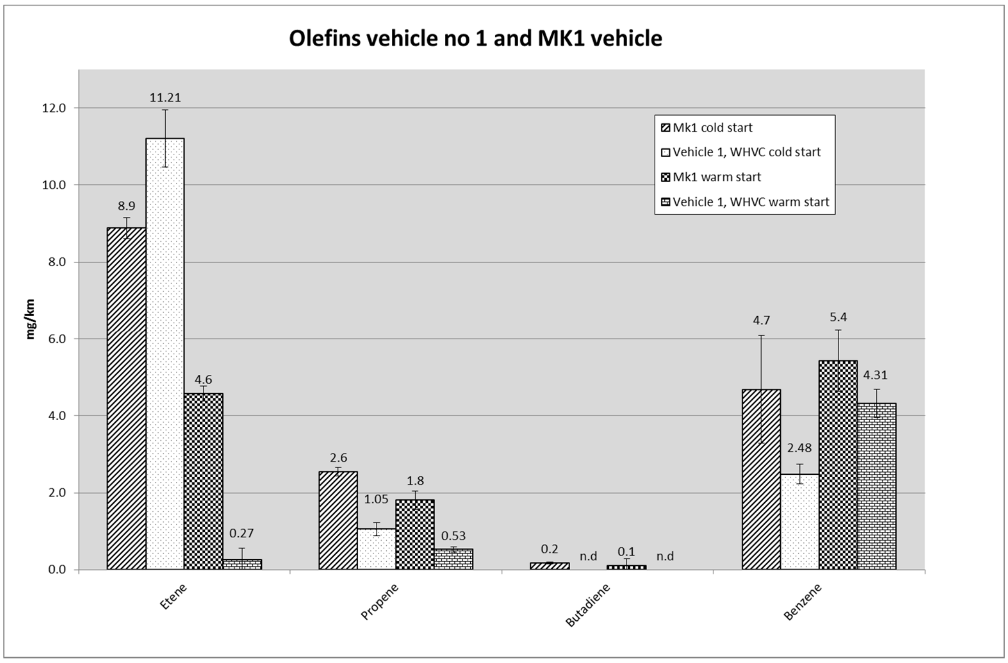


Figure 4. Olefines from vehicle no 1, cold start and warm start

3.3 Particulate size distribution test results

The results are presented as diagrams in Figure 5-12 and numerical results are presented in Appendices. For all vehicles and for all particle sizes, it can be concluded that cold start tests generated slightly more particulates than warm start tests.

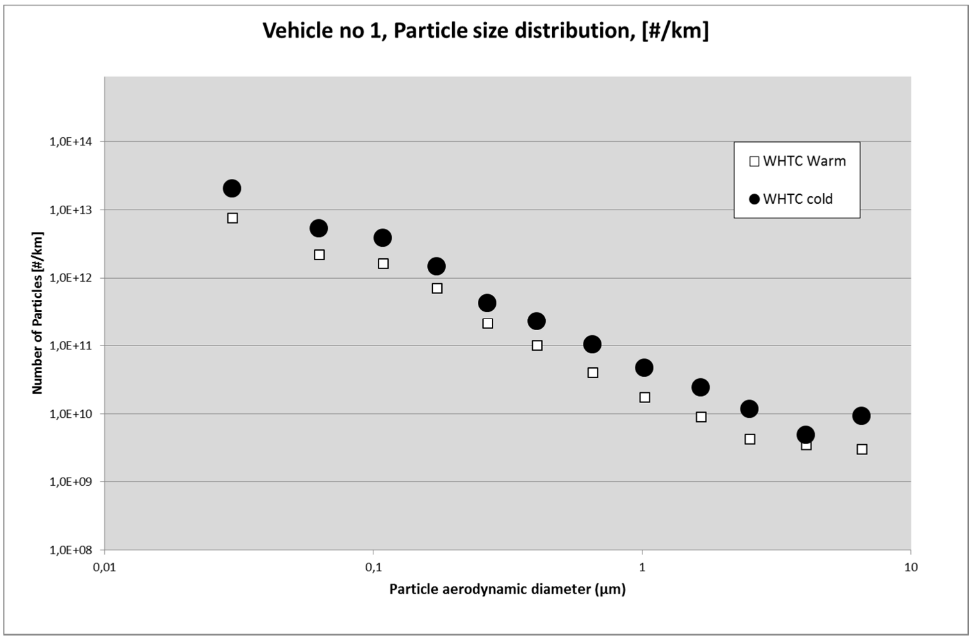


Figure 5. Particle size distribution of vehicle no 1, comparing the warm and the cold tests

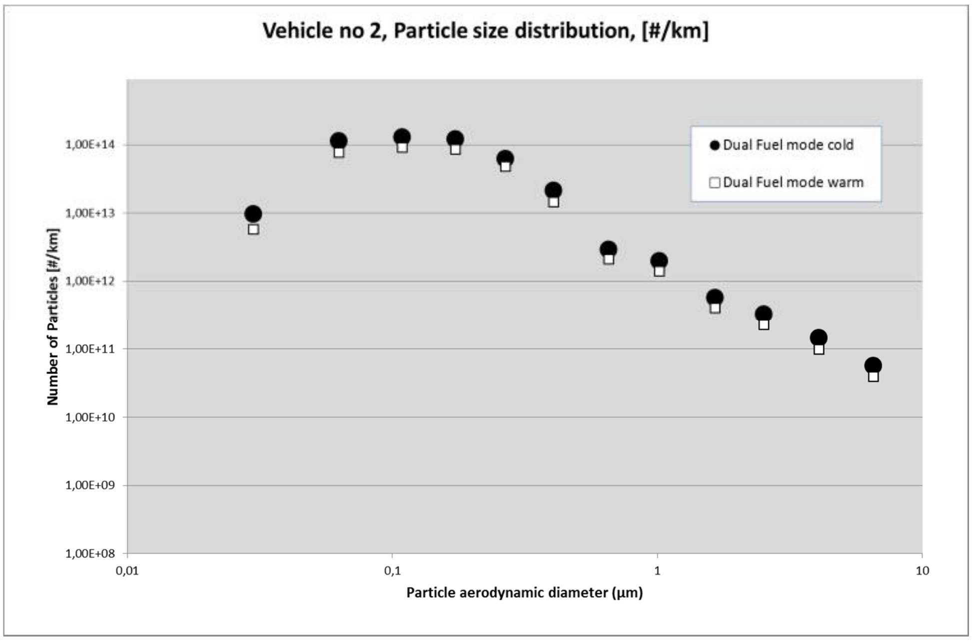


Figure 6. Particle size distribution of vehicle no 2, comparing the warm and the cold test when operating in DDF mode

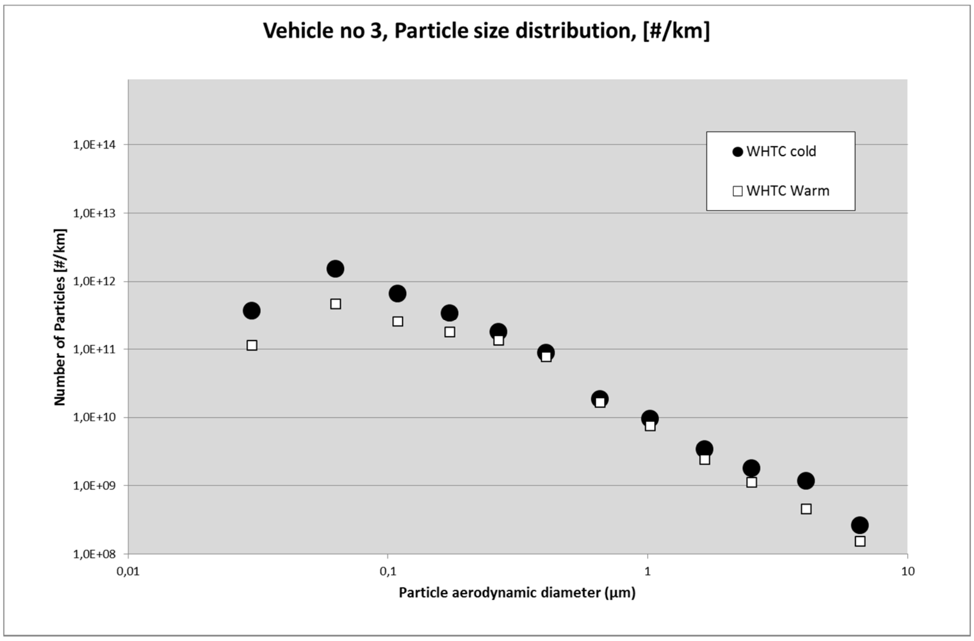


Figure 7. Particle size distribution of vehicle no 3, comparing the warm and the cold tests

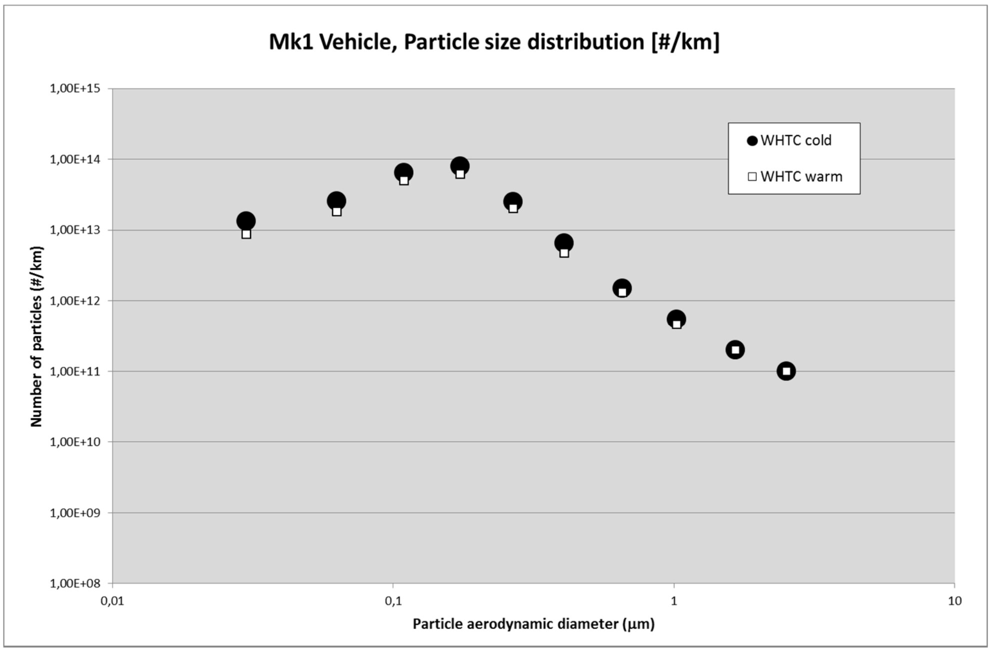


Figure 8. Particle size distribution of MK1 vehicle, comparing the warm and the cold tests

In figure 9-10 it can be seen that no significant difference could be observed when the Dual Fuel vehicle was operated in Diesel mode vs Dual Fuel mode.

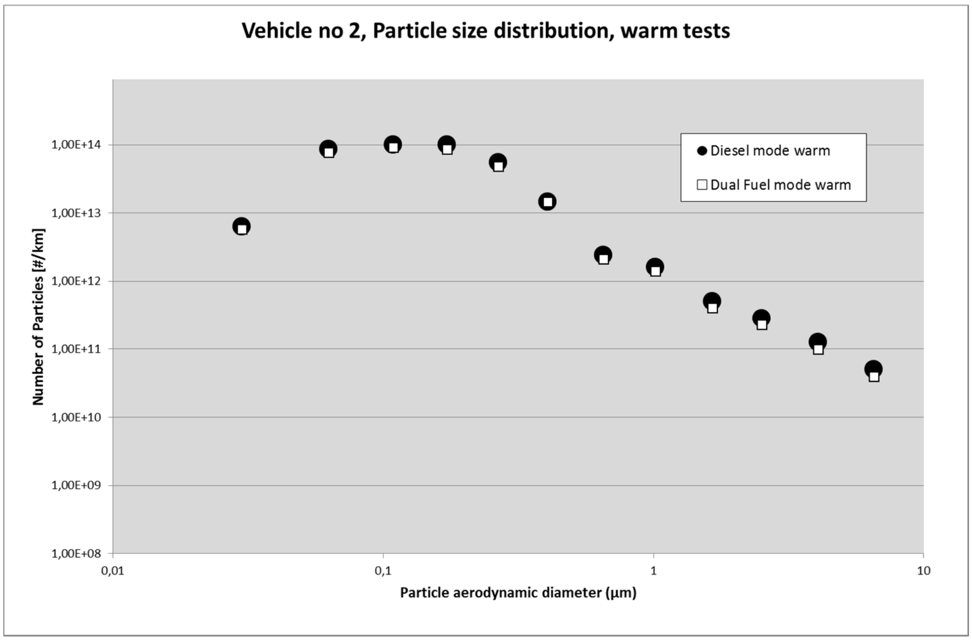


Figure 9. Particle size distribution of vehicle no 2, comparing warm tests when operating in DDF mode vs Diesel mode

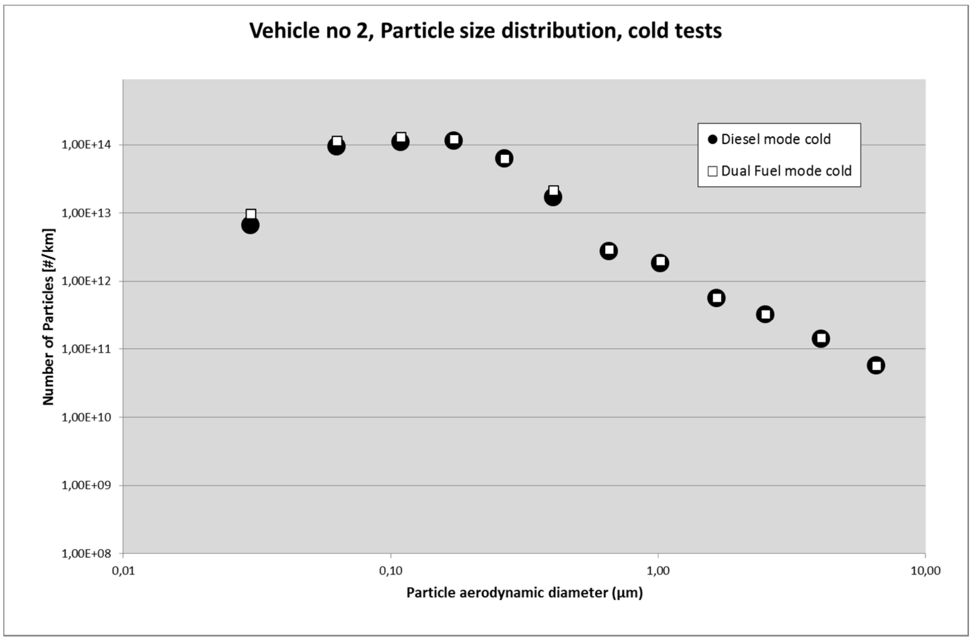


Figure 10. Particle size distribution of vehicle no 2, comparing cold tests when operating in DDF mode vs Diesel mode

Figure 11 shows that the dedicated gas vehicles generate significantly fewer particles than the DDF vehicle.

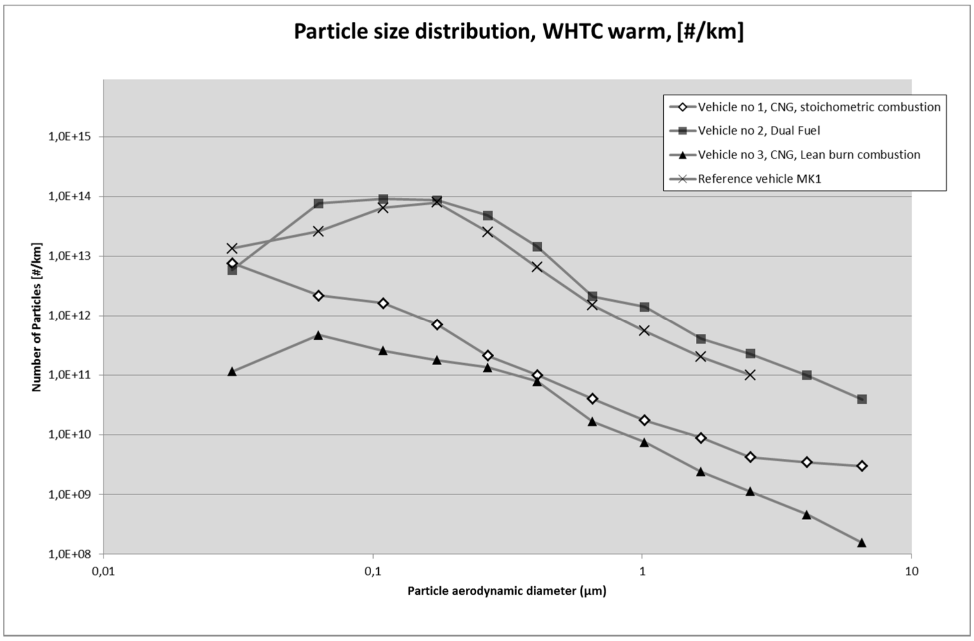


Figure 11. Particle size distribution of all tested vehicles during the warm tests

In Figure 12 it can be seen that vehicle no 3 (lean-burn) generates the least number of particles while the DDF vehicle generates the most, regardless of fuel mode.

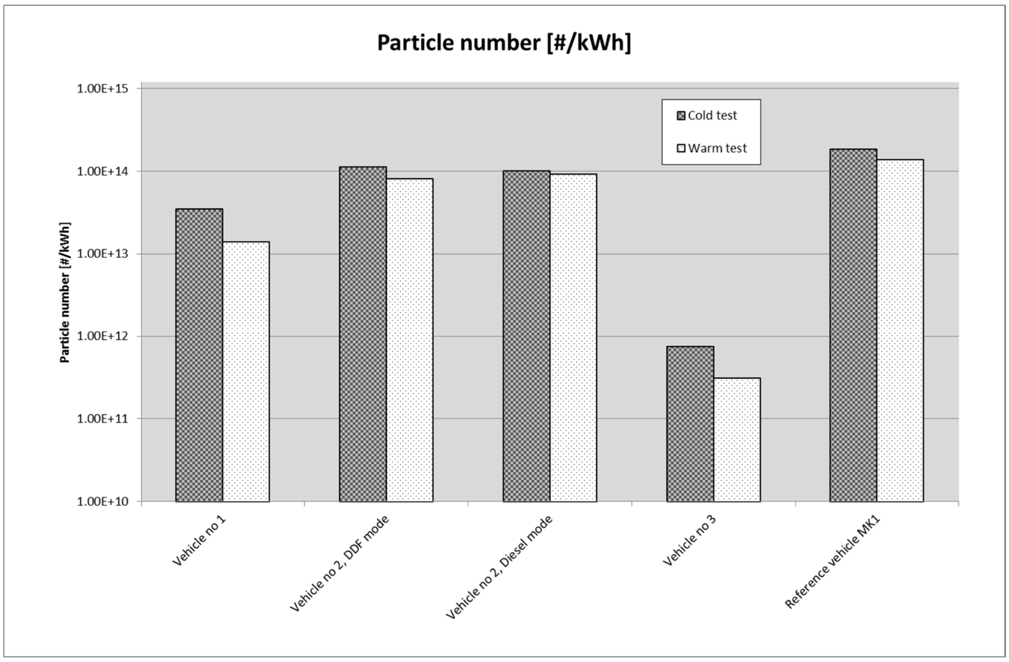


Figure 12. Particle number of all tested vehicles

3.4 Measurement of aldehydes

Aldehyde emission results from the test vehicles are shown in Figure 13-17 and in the detailed results in Appendices.

The aldehyde emission levels of dedicated gas vehicles were low. Formaldehyde and acetaldehyde were dominating compounds.

Vehicle no 1 showed significant higher levels of formaldehyde and acetaldehyde in the cold start tests compared to the warm start tests. This is explained by the fact that also the THC of this vehicle was higher in the cold start tests compared to the warm start tests. Formaldehyde was the dominating aldehyde during the cold start tests (55% formaldehyde, 41% acetaldehyde), whereas acetaldehyde was the dominating aldehyde during warm start tests (formaldehyde 18%, acetaldehyde 73%).

High levels of Acetone were detected. Since there is no explanation for this phenomenon, it can be suspected that the test samples have been contaminated.

Small portions of Butyraldehyde, Benzaldehyde, m+p-Tolualdehyde and Isovaleraldehyde were also detected (not more than 0.09 mg/km for any component in any test).

Vehicle no 3 showed significant higher levels of formaldehyde in the cold start tests compared to the warm start tests. Also for this vehicle was the THC higher in the cold start tests compared to the warm start tests. The levels of acetaldehyde during the cold start tests performed showed a large variance and therefore is the influence of the start temperature unclear. The formaldehyde covered 53 % and acetaldehyde 38 % of the sum of aldehydes during cold start. The corresponding values for the warm start were 18% and 67%.

Small portions of Propionaldehyde, Butyraldehyde, Benzaldehyde, Valeraldehyde, m+p-Tolualdehyde and Hexaldehyde were detected (not more than 0.24 mg/km for any component in any test).

The DDF vehicle (vehicle no 2) showed significant higher levels of formaldehyde when operated in Dual Fuel mode compared to the dedicated gas vehicles. Also the levels of THC were considerably higher for the DDF vehicle in DDF mode. During Diesel mode where the aldehyde levels comparable as well as the THC levels. The level of acetaldehyde also dominated as aldehyde but was on a lower level, comparable to the ones for the dedicated gas vehicles.

The warm start tests generated more formaldehyde compared to the cold start tests in DDF mode. A possible reason for this is that formaldehyde is generated by the catalyst when methane is oxidized, and that the catalyst, due to the higher temperature, starts to oxidize Methane earlier in the cycle, which then results in more formaldehyde. During DDF mode, the formaldehyde covered 75 % and acetaldehyde 19 % of the sum of aldehydes during cold start. The corresponding values for the warm start were 89% and 7%. During Diesel mode, the formaldehyde covered 45 % and acetaldehyde 38 % of the sum of aldehydes during cold start. The corresponding values for the warm start were 49% and 44%

For the DDF vehicle, small portions of Butyraldehyde, Propionaldehyde, Benzaldehyde, Hexaldehyde and Isovaleraldehyde were detected when the vehicle was operated in DDF mode as well as Diesel mode (2-4% of total aldehydes in Diesel mode).

The reference Mk1 vehicle shows higher levels of aldehydes than the DDF vehicle in both DDF mode and Diesel mode. It also shows slightly higher levels of THC than the DDF vehicle in Diesel mode which may be a part of the explanation why the aldehyde levels are higher than the DDF vehicle in Diesel mode. It may also indicate that the DDF vehicle is equipped with a catalyst with more PGM (Platinum Group Metal). It must however be emphasized that the DDF vehicle and the MK1 vehicle are two different vehicle individuals.

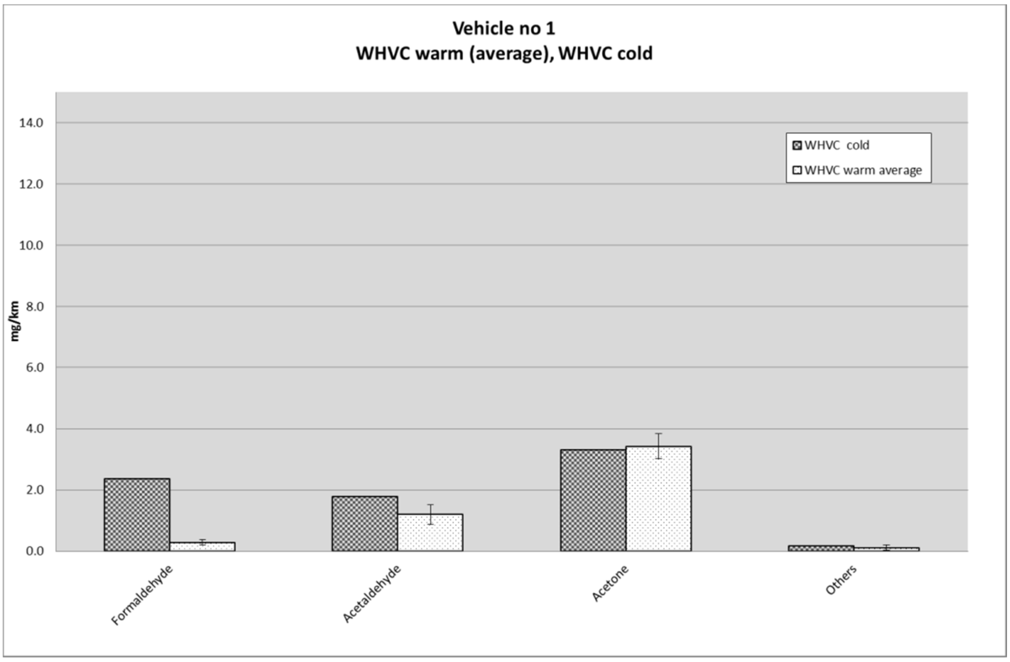


Figure 13. Aldehyde results, vehicle no 1

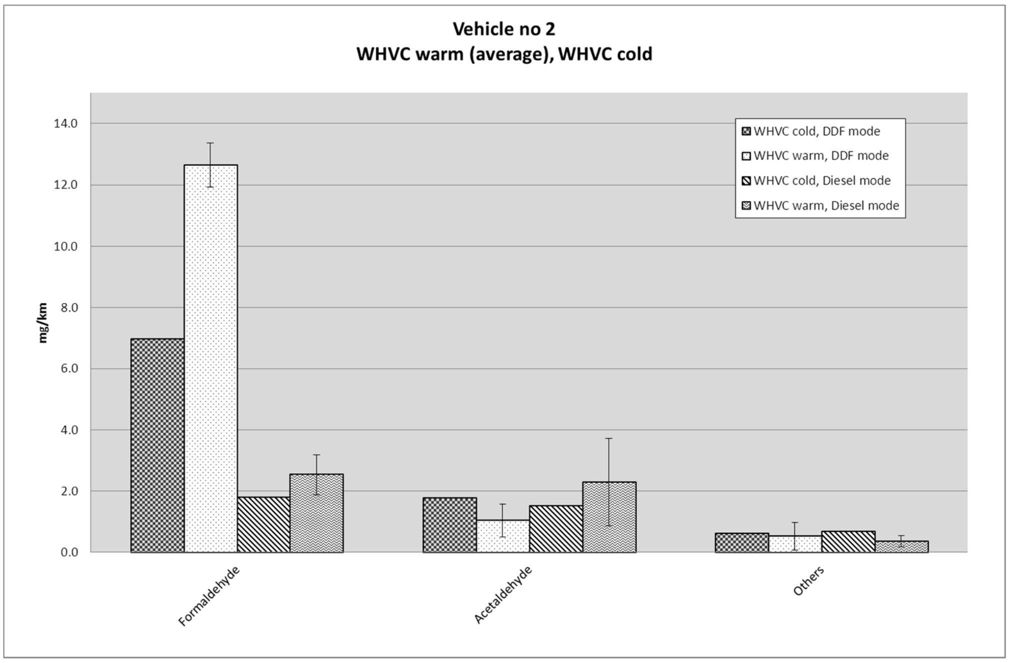


Figure 14. Aldehyde results, vehicle no 2

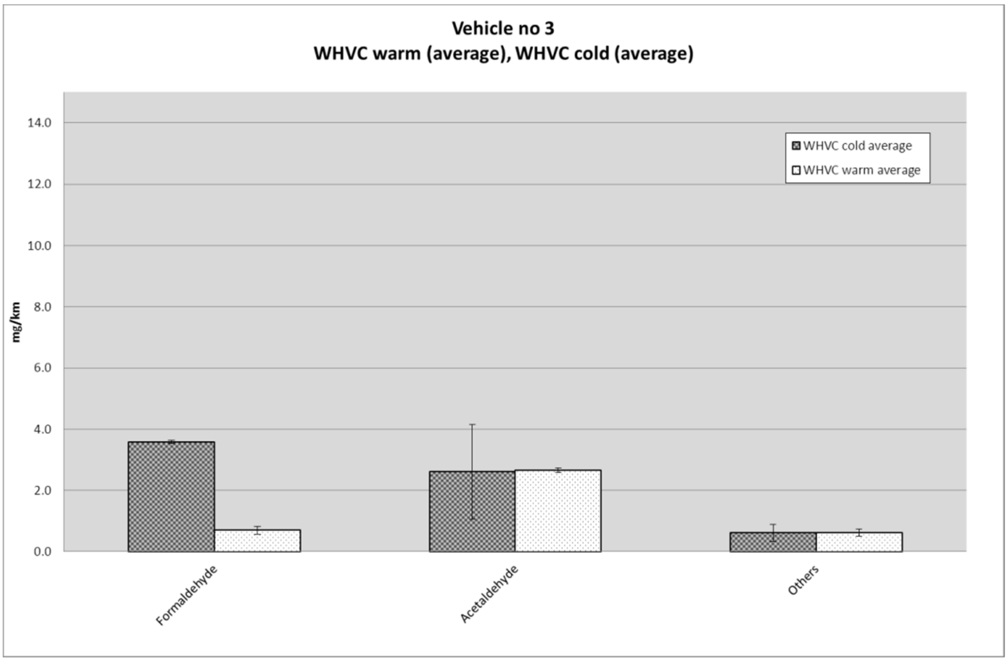


Figure 15. Aldehyde results, vehicle no 3

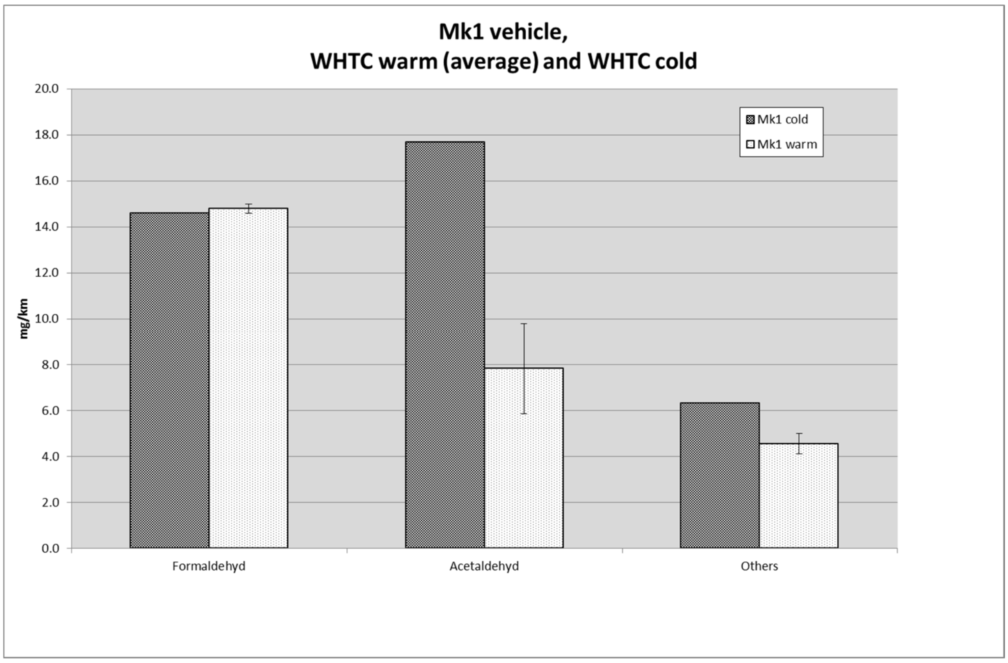


Figure 16. Aldehyde results, reference Mk1 vehicle

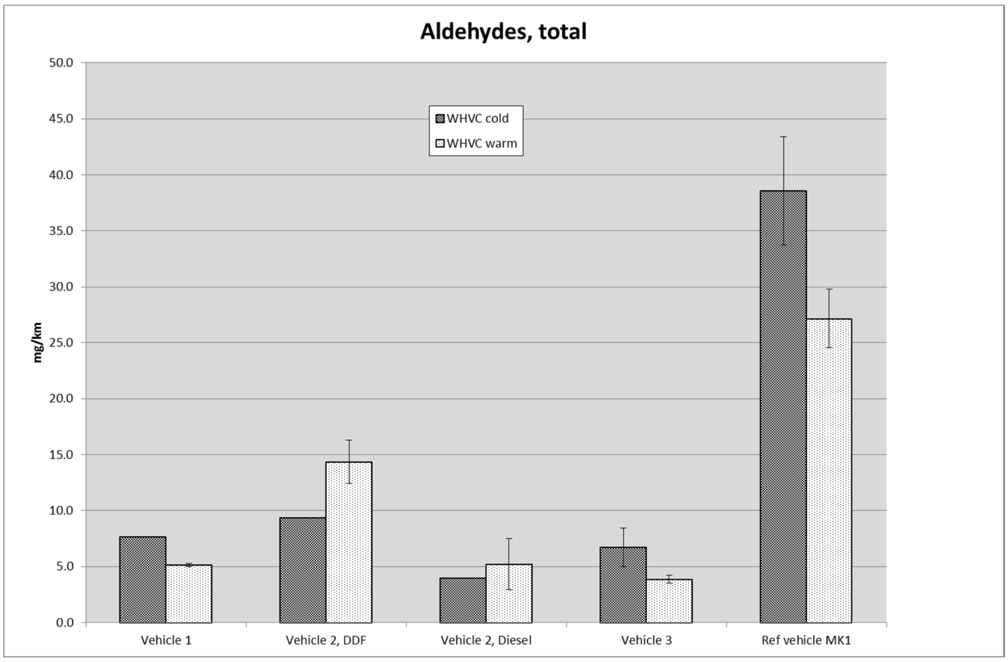


Figure 17. Total amount of aldehydes, all vehicles

3.5 PAH analysis

The interest in PAHs mainly emanates from the fact that a number of these compounds may cause tumours in humans. Many PAHs are considered to be complete carcinogens, i.e. compounds that are both tumour initiators and promoters. Animal experiments have also indicated that PAHs, besides being carcinogenic, may give rise to immunological and reproductive disorders, but the carcinogenicity is often regarded as the most critical effect.

The PAH in the emissions can be derived from unburned residues of fuel and as a byproduct from the combustion. PAHs are generally associated with both the particulate phase and the gaseous phase in exhaust emissions. Consequently, PAHs in exhaust emissions are generally determined as semi-volatile or particle-associated fractions [10]. For a vehicle that emits low amounts of particles (PM and PN), will the volatile fraction increase since there are less particle surface to condensate on.

Gas vehicles generally have higher oil consumption in comparison to diesel vehicles and both the amount and the quality of the oil may influence the levels of PAH. It has also been indicated that aftertreatment devices may have a large influence the level of PAHs [11].

PAH emission results are presented in figure 18-20 and detailed results are resented in appendices.

The cold test results are represented by only one test from each vehicle and the standard deviation in the warm tests are relatively large.

The Diesel fuel contains higher amounts of PAH then NG which is reflected in the exhaust emissions from the DDF vehicle (diesel mode) and the MK1 vehicle compared to when NG has been used as fuel. The relatively high levels of PAH from vehicle no 1 may be explained by the different aftertreatment system (three-way converter instead of oxidation catalyst).

Particulate PAHs are significantly higher in the diesel fuel tests whereas no such clear exemplification can be shown for the volatile PAHs where the lean-mix vehicle shows higher levels.

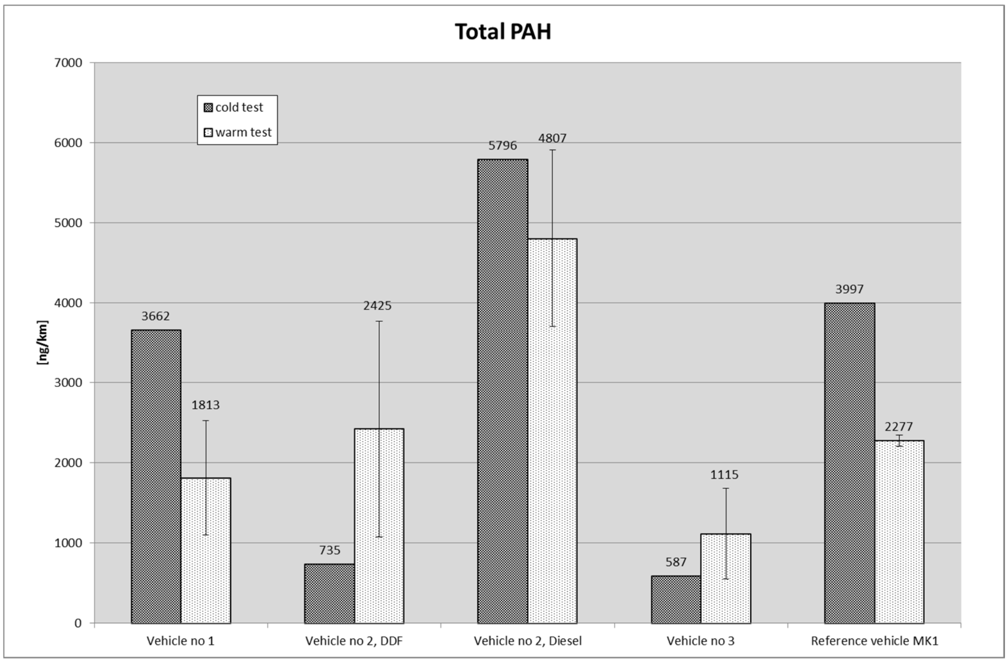


Figure 18. Total amount of PAH, all vehicles, warm and cold tests

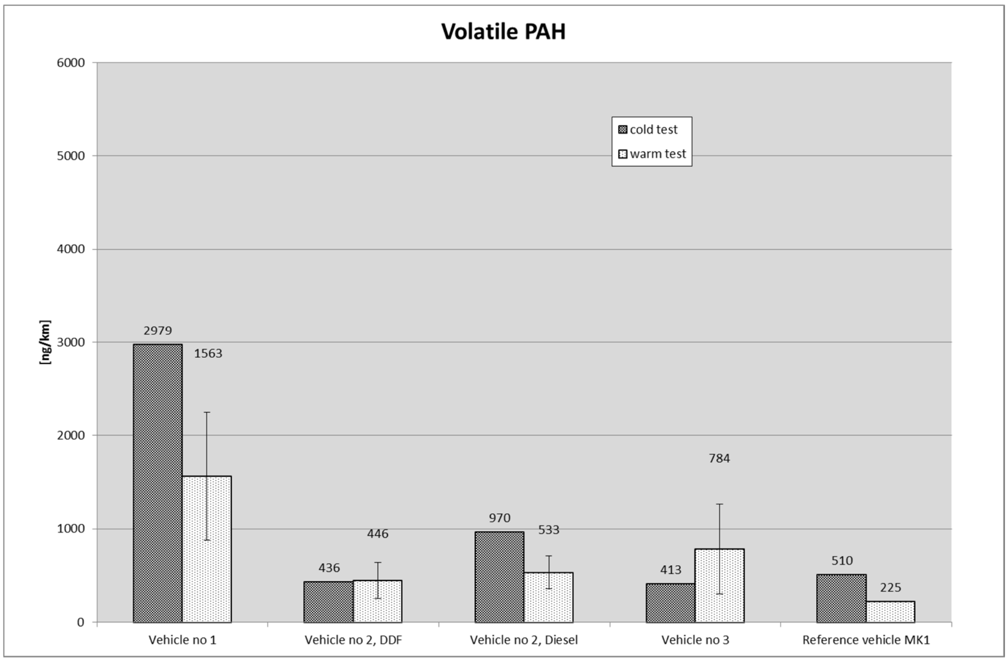


Figure 19. Volatile PAH, all vehicles, warm and cold tests

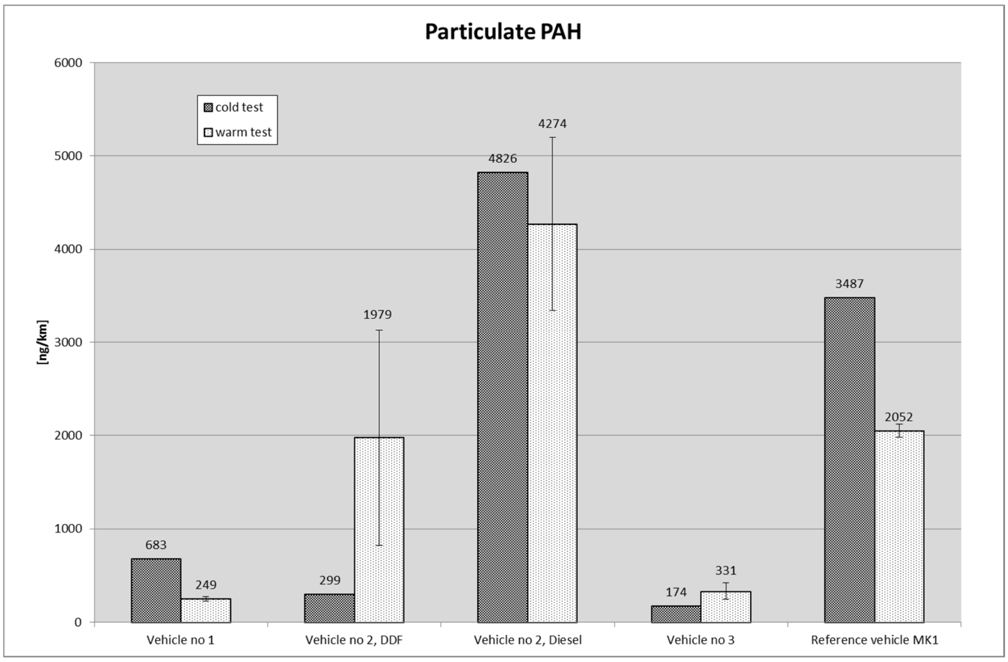


Figure 20. Particulate PAH, all vehicles, warm and cold tests

3.6 Genotoxicity tests

To investigate the mutagenicity of the PAH extracts, the Ames' bioassay test was used. In this test altered strains of *Salmonella* bacteria have been used. The strains are mutated and can no longer produce the essential amino acid histidine by themselves. To be able to grow, the bacteria require histidine, and in the Ames' bioassay test the reversion to become self-sufficient on histidine is investigated.

In a human cell, compounds entering the cell are metabolized by enzymes. Some compounds are changed in the metabolic process, and some compounds are not mutagenic until metabolized. The *Salmonella* bacteria does not have the same enzymes as mammals, and in order to simulate this metabolism, enzymes (denoted S9-mix, from rat liver) are added to the bacteria when they are being exposed to the extracted PAH. Benzo(a)pyrene is an example of a metabolically activated compound, where the metabolites are mutagenic and highly carcinogenic (Benzo(a)pyrene is listed as a Group 1 carcinogen by the IARC (International Agency for Research on Cancer).

Carcinogenesis is a multistep process divided in three main steps – initiation, promotion and progression. Many PAHs are considered to be complete carcinogens (can act on all of these steps) whereas some compounds only act on parts of the process. In the Ames' bioassay test the initiation step is studied.

The mutagenic effects are given as number of mutants/plate per meter driving distance ± standard deviation, taken from the linear regression analyses. The results are presented in Table 8.

Table 8. Results from Ames' bioassay test.

Test	Revertants/m -S9	Revertants/m +S9
Vehicle 1, cold test	4,98 ± 1,07 ***	4,51 ± 1,42 ***
Vehicle 2, cold test, DDF mode	*(1,07 ± 0,86 ns)*	2,35 ± 0,71 **
Vehicle 2, warm test, DDF mode	3,12 ± 0,76 **	1,98 ± 0,65 *
Vehicle 2, warm test, DDF mode	2,29 ± 0,66 **	2,82 ± 0,56 ***
Vehicle 2, warm test, DDF mode	2,29 ± 0,84 *	2,06 ± 0,49 **
Vehicle 2, cold test, Diesel mode	2,05 ± 0,84 *	2,36 ± 0,59 **
Vehicle 2, warm test, Diesel mode	*(1,06 ± 0,64 ns)*	*(1,14 ± 0,60 ns)*
Vehicle 2, warm test, Diesel mode	*(3,01 ± 1,39 ns)*	2,39 ± 0,60 **
Vehicle 2, warm test, Diesel mode	3,02 ± 0,64 ***	4,37 ± 0,59 ***
Mk1 reference, cold test	*(1,61 ± 1,08 ns)*	4,55 ± 1,10 **
Mk1 reference, warm test	*(2,28 ± 1,35 ns)*	3,55 ± 1,14 *
Mk1 reference, warm test	*(1,35 ± 0,952 ns)*	4,74 ± 0,891 ***

Significance levels: * 0,005 < p <0,01; ** 0,001 < p < 0,005; *** p < 0,001, in difference from control values. Numbers in (Italic) are not significant.

The result from the cold start test with vehicle 1 showed the highest significance level. The results are based on one test run. The same significance level was found both with and without the metabolically activating S9-mix, indicating that the exhausts are directly mutagenic.

The results from the cold start test with vehicle 2 showed a slight increase of mutagens for diesel mode when S9-mix was not added to the bacteria. With the addition of S9-mix the significance level increased both for diesel and DDF mode. The results indicate that the components in the exhausts need to be metabolically activated in order to induce mutations. The results are based on one test from each fuel mode.

The warm start test with vehicle 2 was repeated three times for each fuel mode. The results from the diesel mode indicated a slight increase of mutations and significance level with the addition of S9-mix. As for the cold start test, these results indicate that metabolic activation increases the risk of mutations.

The warm start test from the DDF mode showed that the exhausts induce mutations, but the variation in the significance levels show that the results are not consistent.

Both the cold start test and the warm start tests from the MK1 reference vehicle showed an increase of mutagens and significance levels when S9-mix was added which indicate that the components in the exhaust needs to be metabolically activated in order to induce mutations.

The health effects of different fuels are often related to the factors affecting the exhaust emissions, i.e. engine technology, exhaust aftertreatment, fuel properties, driving cycles etc. Other factors that will influence the result are the methodology, exposure levels and the endpoints for the investigation (i.e. mutations, cell death etc).

Despite the rapid growth of biofuel production and usage worldwide, its impact on human health has not been thoroughly investigated and the methods used are not standardized. In addition, the research activities often have different objectives and approaches and the results can therefore rarely be directly compared to each other.

Acknowledged approaches for scientific research are in-vitro (i.e. cell cultures, Ames' bioassay etc) and in-vivo (animal exposure) methods. There are also more theoretical methods, where factors for different compounds are used to calculate the potential effects, i.e. the US EPA use Toxic Equivalence factors (TEF) for different compounds. This method assumes that compounds have additive effect, and that the effect is linear. The IARC Monographs Program identifies environmental factors that can increase the risk of human cancer. The Monograph is a comprehensive and critical review and evaluation of the published scientific evidence on the carcinogenicity of human exposures. [12]

In the test methods used for PAH analysis, measurement of aldehydes, mass spectrometer tests and the FTIR tests, only the pre-test predicted and selected components will be measured. The test result for each measured compound is presented separately whereas the possibility of synergetic, additive or antagonistic effects of all the different compounds in the exhaust gas mixture leaving tailpipe is not taken into account. In Ames test however, the salmonella bacteria are exposed to the entire, and partly unknown, component mixture. It can be used in order to detect the presence of mutagenic compounds rather than to determine the specific type of mutagen(s).

4. Conclusions

The FTIR test results on the DDF vehicle showed slightly higher levels of NO_2 when the vehicle was operated in Diesel mode compared to DDF mode. A possible reason for this may be that high NO_2/NO_X ratios are favoured at low exhaust temperatures and the temperature of diesel combustion exhaust is lower than of NG combustion exhaust [9].

Diesel mode gave slightly lower levels N_2O compared to DDF mode. No emissions of NH_3 were detected.

For all vehicles and for all particle sizes, it can be concluded that cold start tests generates slightly more particulates than warm start tests.

Particle size distribution and particle number did not significantly vary between the two driving modes of the DDF vehicle.

The dedicated gas vehicle with lean-burn technology generated the lowest amount of particles. Both the dedicated gas vehicles generated fewer particles than the DDF vehicle.

For all vehicles, formaldehyde and acetaldehyde dominated of the aldehydes measured. The sum of the other aldehydes varied between 3% and 17% of the total aldehydes. The total amount of aldehydes appears to be related to the amount of THC emitted in the test.

For the DDF vehicle operated in Dual Fuel mode, the levels of formaldehyde where considerable higher compared to the Diesel mode tests and also more as of the dedicated gas vehicles.

The dedicated gas vehicles emitted significant more formaldehyde during the cold start test compared to the warm start test. For the DDF vehicle was the situation opposite.

For acetaldehyde levels, no clear trend depending on start temperature could be seen.

The higher level of PAH in Diesel fuel compared to Natural gas was reflected in the amount of particulate PAH contained in the Diesel exhaust which was significantly higher than the NG exhaust. However, the highest amount of volatile PAH was found in the exhaust from the lean-mix, dedicated gas vehicle, which also showed the highest increase of mutagens and highest significance levels in the Ames' test.

The higher levels of volatile PAH and genotoxicity for the lean-mix gas vehicle may have been caused by engine oil consumption which generally is higher for gas vehicles and the quality of the oil may also have influenced the result. In addition, the mileage of this vehicle was considerable higher for this vehicle compared to the other vehicles and the aftertreatment system was of a different kind.

5. Literature

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6. List of abbreviations

A/F Ratio	Air / Fuel Ratio
BSFC	Brake Specific Fuel Consumption
BTX	“Benzene, Toluene, Xylene”
CH_4	Methane
CI	Compression Ignited
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DDF	Diesel Dual Fuel
DI	Direct Injection
ECU	Electronic Control Unit
EEV	Enhanced Environmental friendly Vehicle
EGR	Exhaust Gas Recirculation
ELPI	Electrical Low Pressure Impactor
FAME	Fatty Acid Methyl Ester
FTIR	Fourier Transform InfraRed
GFV	Gas Fuelled Vehicles
GHG	Green House Gases
H/C	Hydrogen to Carbon ratio
HC, THC	Hydrocarbons, Total Hydrocarbons
HD	Heavy Duty
HPLC	High-performance liquid chromatography
HVO	Hydrotreated Vegetable Oil
IEA – AMF	International Energy Agency – Advanced Motor Fuels
IVL	Swedish Environmental Research Institute
LBG	Liquefied Bio Gas
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
MK1	Environmental Class 1 (Miljöklass 1)
MS	Mass Spectrometer
NG	Natural Gas
NGV	Natural Gas Vehicle
NMHC	Non-Methane Hydrocarbons
NOx	Oxides of Nitrogen
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
OIGI	Oil Ignition Gas Injection
PAH	Polycyclic Aromatic Hydrocarbons
PGM	Platinum Group Metal
PM	Particulate Matter
RON	Research Octane Number
SCR	Selective Catalytic Reduction

SGC	Swedish Gas Technology Centre
SI	Spark Ignited
TCDD	2,3,7,8-tetraklordibenso-p-dioxin
TWC	Three Way Catalyst
UV	Ultra Violet
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle

Appendix 1, Particle size distribution results

Table 9. Vehicle no 1

Vehicle no 1, cold test													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	1.5E+14	4.3E+13	3.2E+13	1.4E+13	4.1E+12	2.0E+12	7.8E+11	3.4E+11	1.8E+11	8.3E+10	6.8E+10	5.9E+10	2.5E+14
Urban	1.8E+12	3.1E+12	6.1E+12	4.4E+12	1.4E+12	4.1E+11	8.7E+10	3.4E+10	1.8E+10	8.7E+09	5.7E+09	5.8E+09	1.7E+13
Rural	8.4E+12	2.5E+12	1.7E+12	6.5E+11	2.3E+11	1.3E+11	5.7E+10	2.3E+10	1.2E+10	5.3E+09	1.2E+09	7.3E+09	1.4E+13
Highway	1.4E+14	3.7E+13	2.4E+13	8.9E+12	2.5E+12	1.4E+12	6.4E+11	2.8E+11	1.5E+11	6.9E+10	6.1E+10	4.5E+10	2.2E+14
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	7.6E+12	2.2E+12	1.6E+12	7.1E+11	2.1E+11	1.0E+11	4.0E+10	1.7E+10	8.9E+09	4.2E+09	3.5E+09	3.0E+09	1.3E+13
Urban	8.9E+10	1.6E+11	3.1E+11	2.2E+11	7.1E+10	2.1E+10	4.4E+09	1.7E+09	8.9E+08	4.4E+08	2.9E+08	3.0E+08	8.8E+11
Rural	4.3E+11	1.3E+11	8.6E+10	3.3E+10	1.2E+10	6.5E+09	2.9E+09	1.2E+09	5.9E+08	2.7E+08	6.1E+07	3.7E+08	7.0E+11
Highway	7.1E+12	1.9E+12	1.2E+12	4.5E+11	1.3E+11	7.2E+10	3.2E+10	1.4E+10	7.4E+09	3.5E+09	3.1E+09	2.3E+09	1.1E+13
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	8.6E+12	2.4E+12	1.8E+12	7.9E+11	2.4E+11	1.1E+11	4.5E+10	2.0E+10	1.0E+10	4.7E+09	3.9E+09	3.4E+09	1.4E+13
Urban	9.9E+10	1.7E+11	3.5E+11	2.5E+11	7.9E+10	2.3E+10	4.9E+09	1.9E+09	1.0E+09	4.9E+08	3.2E+08	3.3E+08	9.8E+11
Rural	4.8E+11	1.4E+11	9.7E+10	3.7E+10	1.3E+10	7.3E+09	3.3E+09	1.3E+09	6.6E+08	3.0E+08	6.9E+07	4.2E+08	7.9E+11
Highway	8.0E+12	2.1E+12	1.4E+12	5.1E+11	1.4E+11	8.1E+10	3.6E+10	1.6E+10	8.4E+09	3.9E+09	3.5E+09	2.6E+09	1.2E+13

Table 10. Vehicle no 1

Vehicle no 1, warm tests, average													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	4.0E+14	1.0E+14	7.5E+13	2.9E+13	8.2E+12	4.5E+12	2.0E+12	9.1E+11	4.7E+11	2.3E+11	9.5E+10	1.8E+11	6.2E+14
Urban	2.0E+13	1.4E+13	1.4E+13	6.4E+12	1.6E+12	5.5E+11	1.5E+11	6.1E+10	3.1E+10	1.5E+10	8.1E+09	8.1E+10	5.7E+13
Rural	1.2E+13	2.5E+12	1.9E+12	7.7E+11	2.8E+11	1.7E+11	8.1E+10	3.6E+10	1.9E+10	9.1E+09	2.8E+09	4.4E+10	1.7E+13
Highway	3.6E+14	8.7E+13	5.8E+13	2.2E+13	6.4E+12	3.8E+12	1.8E+12	8.2E+11	4.2E+11	2.0E+11	8.4E+10	5.3E+10	5.4E+14
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	2.0E+13	5.3E+12	3.8E+12	1.5E+12	4.2E+11	2.3E+11	1.0E+11	4.7E+10	2.4E+10	1.2E+10	4.8E+09	9.1E+09	3.2E+13
Urban	1.0E+12	7.2E+11	7.3E+11	3.3E+11	8.1E+10	2.8E+10	7.8E+09	3.1E+09	1.6E+09	7.4E+08	4.1E+08	4.1E+09	2.9E+12
Rural	5.9E+11	1.3E+11	9.8E+10	3.9E+10	1.4E+10	8.6E+09	4.1E+09	1.8E+09	9.6E+08	4.7E+08	1.4E+08	2.3E+09	8.9E+11
Highway	1.9E+13	4.4E+12	3.0E+12	1.1E+12	3.2E+11	1.9E+11	9.1E+10	4.2E+10	2.2E+10	1.0E+10	4.3E+09	2.7E+09	2.8E+13
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	2.3E+13	5.9E+12	4.3E+12	1.6E+12	4.7E+11	2.6E+11	1.2E+11	5.2E+10	2.7E+10	1.3E+10	5.4E+09	1.0E+10	3.5E+13
Urban	1.1E+12	8.0E+11	8.2E+11	3.7E+11	9.1E+10	3.1E+10	8.8E+09	3.5E+09	1.8E+09	8.3E+08	4.6E+08	4.7E+09	3.3E+12
Rural	6.6E+11	1.4E+11	1.1E+11	4.4E+10	1.6E+10	9.6E+09	4.6E+09	2.1E+09	1.1E+09	5.2E+08	1.6E+08	2.5E+09	9.9E+11
Highway	2.1E+13	5.0E+12	3.3E+12	1.2E+12	3.6E+11	2.2E+11	1.0E+11	4.7E+10	2.4E+10	1.2E+10	4.8E+09	3.0E+09	3.1E+13

Table 11. Vehicle no 2

Vehicle no 2, Dual Fuel mode, cold test													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	1.9E+14	2.3E+15	2.6E+15	2.4E+15	1.3E+15	4.3E+14	5.9E+13	4.0E+13	1.2E+13	6.7E+12	3.0E+12	1.2E+12	2.1E+15
Urban	1.4E+14	1.6E+15	1.7E+15	1.5E+15	7.3E+14	2.5E+14	3.3E+13	2.3E+13	6.7E+12	4.0E+12	1.8E+12	6.9E+11	1.3E+15
Rural	3.0E+13	4.4E+14	5.4E+14	5.4E+14	3.1E+14	1.1E+14	1.5E+13	1.0E+13	2.7E+12	1.5E+12	6.8E+11	2.7E+11	4.7E+14
Highway	2.3E+13	3.1E+14	3.8E+14	4.0E+14	2.4E+14	8.0E+13	1.1E+13	7.4E+12	2.1E+12	1.2E+12	5.2E+11	2.1E+11	3.4E+14
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	9.5E+12	1.1E+14	1.3E+14	1.2E+14	6.3E+13	2.1E+13	2.9E+12	2.0E+12	5.7E+11	3.3E+11	1.5E+11	5.7E+10	1.1E+14
Urban	6.9E+12	7.7E+13	8.3E+13	7.3E+13	3.6E+13	1.2E+13	1.6E+12	1.1E+12	3.3E+11	2.0E+11	8.7E+10	3.4E+10	6.6E+13
Rural	1.5E+12	2.1E+13	2.7E+13	2.7E+13	1.5E+13	5.2E+12	7.3E+11	4.9E+11	1.3E+11	7.5E+10	3.4E+10	1.3E+10	2.3E+13
Highway	1.1E+12	1.5E+13	1.9E+13	2.0E+13	1.2E+13	3.9E+12	5.5E+11	3.7E+11	1.0E+11	5.9E+10	2.6E+10	1.0E+10	1.7E+13
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	1.0E+13	1.2E+14	1.4E+14	1.3E+14	6.7E+13	2.3E+13	3.1E+12	2.1E+12	6.1E+11	3.5E+11	1.6E+11	6.1E+10	1.1E+14
Urban	7.4E+12	8.2E+13	8.9E+13	7.8E+13	3.8E+13	1.3E+13	1.7E+12	1.2E+12	3.5E+11	2.1E+11	9.3E+10	3.6E+10	7.0E+13
Rural	1.6E+12	2.3E+13	2.8E+13	2.9E+13	1.6E+13	5.6E+12	7.8E+11	5.2E+11	1.4E+11	8.0E+10	3.6E+10	1.4E+10	2.5E+13
Highway	1.2E+12	1.6E+13	2.0E+13	2.1E+13	1.2E+13	4.2E+12	5.9E+11	3.9E+11	1.1E+11	6.3E+10	2.7E+10	1.1E+10	1.8E+13

Table 12. Vehicle no 2

Vehicle no 2, Diesel mode, cold test													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	1.3E+14	1.9E+15	2.2E+15	2.3E+15	1.3E+15	3.5E+14	5.6E+13	3.8E+13	1.2E+13	6.6E+12	2.9E+12	1.2E+12	2.0E+15
Urban	8.2E+13	1.1E+15	1.3E+15	1.3E+15	7.2E+14	1.9E+14	3.1E+13	2.1E+13	6.6E+12	3.8E+12	1.7E+12	6.8E+11	1.1E+15
Rural	3.1E+13	4.7E+14	5.5E+14	5.9E+14	3.3E+14	9.0E+13	1.5E+13	9.7E+12	3.1E+12	1.7E+12	7.8E+11	3.3E+11	4.9E+14
Highway	2.2E+13	3.1E+14	3.7E+14	4.0E+14	2.3E+14	6.4E+13	1.1E+13	6.7E+12	2.0E+12	1.0E+12	4.1E+11	1.6E+11	3.3E+14
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	6.5E+12	9.2E+13	1.1E+14	1.1E+14	6.2E+13	1.7E+13	2.7E+12	1.8E+12	5.6E+11	3.2E+11	1.4E+11	5.6E+10	9.4E+13
Urban	3.9E+12	5.5E+13	6.4E+13	6.4E+13	3.5E+13	9.3E+12	1.5E+12	1.0E+12	3.2E+11	1.8E+11	8.3E+10	3.3E+10	5.4E+13
Rural	1.5E+12	2.2E+13	2.6E+13	2.8E+13	1.6E+13	4.3E+12	7.1E+11	4.7E+11	1.5E+11	8.4E+10	3.8E+10	1.6E+10	2.4E+13
Highway	1.0E+12	1.5E+13	1.8E+13	1.9E+13	1.1E+13	3.1E+12	5.1E+11	3.2E+11	9.6E+10	5.0E+10	2.0E+10	7.7E+09	1.6E+13
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	7.0E+12	9.9E+13	1.2E+14	1.2E+14	6.7E+13	1.8E+13	2.9E+12	1.9E+12	6.1E+11	3.4E+11	1.5E+11	6.1E+10	1.0E+14
Urban	4.2E+12	5.9E+13	6.8E+13	6.9E+13	3.7E+13	1.0E+13	1.6E+12	1.1E+12	3.4E+11	2.0E+11	8.9E+10	3.5E+10	5.8E+13
Rural	1.6E+12	2.4E+13	2.8E+13	3.0E+13	1.7E+13	4.7E+12	7.6E+11	5.0E+11	1.6E+11	9.0E+10	4.0E+10	1.7E+10	2.5E+13
Highway	1.1E+12	1.6E+13	1.9E+13	2.1E+13	1.2E+13	3.3E+12	5.5E+11	3.5E+11	1.0E+11	5.4E+10	2.1E+10	8.3E+09	1.7E+13

Table 13. Vehicle no 2

Vehicle no 2, Dual Fuel mode, warm test, average													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	1.2E+14	1.5E+15	1.8E+15	1.7E+15	9.7E+14	2.9E+14	4.3E+13	2.9E+13	8.2E+12	4.6E+12	2.0E+12	7.9E+11	1.5E+15
Urban	6.2E+13	8.6E+14	1.0E+15	9.3E+14	4.9E+14	1.4E+14	2.1E+13	1.4E+13	4.2E+12	2.4E+12	1.1E+12	4.2E+11	8.1E+14
Rural	3.3E+13	4.2E+14	5.0E+14	5.0E+14	2.9E+14	8.9E+13	1.3E+13	8.7E+12	2.4E+12	1.3E+12	5.5E+11	2.2E+11	4.3E+14
Highway	2.2E+13	2.7E+14	3.1E+14	3.2E+14	1.9E+14	5.9E+13	8.8E+12	5.7E+12	1.7E+12	9.5E+11	4.0E+11	1.6E+11	2.8E+14
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	5.8E+12	7.6E+13	9.1E+13	8.6E+13	4.8E+13	1.4E+13	2.1E+12	1.4E+12	4.1E+11	2.3E+11	9.9E+10	3.9E+10	7.5E+13
Urban	3.1E+12	4.2E+13	5.0E+13	4.6E+13	2.4E+13	7.1E+12	1.0E+12	7.1E+11	2.1E+11	1.2E+11	5.2E+10	2.1E+10	4.0E+13
Rural	1.6E+12	2.1E+13	2.5E+13	2.4E+13	1.4E+13	4.4E+12	6.5E+11	4.3E+11	1.2E+11	6.3E+10	2.7E+10	1.1E+10	2.1E+13
Highway	1.1E+12	1.3E+13	1.5E+13	1.6E+13	9.3E+12	2.9E+12	4.4E+11	2.8E+11	8.4E+10	4.7E+10	2.0E+10	7.6E+09	1.4E+13
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	6.3E+12	8.3E+13	9.9E+13	9.3E+13	5.2E+13	1.6E+13	2.3E+12	1.5E+12	4.4E+11	2.5E+11	1.1E+11	4.2E+10	8.2E+13
Urban	3.3E+12	4.6E+13	5.5E+13	5.0E+13	2.6E+13	7.7E+12	1.1E+12	7.7E+11	2.2E+11	1.3E+11	5.6E+10	2.3E+10	4.4E+13
Rural	1.8E+12	2.3E+13	2.7E+13	2.7E+13	1.5E+13	4.8E+12	7.1E+11	4.6E+11	1.3E+11	6.8E+10	2.9E+10	1.2E+10	2.3E+13
Highway	1.2E+12	1.4E+13	1.7E+13	1.7E+13	1.0E+13	3.2E+12	4.7E+11	3.1E+11	9.1E+10	5.1E+10	2.1E+10	8.3E+09	1.5E+13

Table 14. Vehicle no 2

Vehicle no 2, Diesel mode, warm test, average													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	1.3E+14	1.8E+15	2.0E+15	2.1E+15	1.1E+15	3.0E+14	4.9E+13	3.3E+13	1.0E+13	5.8E+12	2.6E+12	1.0E+12	1.7E+15
Urban	6.3E+13	9.1E+14	1.1E+15	1.1E+15	5.6E+14	1.5E+14	2.4E+13	1.6E+13	5.2E+12	3.0E+12	1.3E+12	5.3E+11	8.9E+14
Rural	3.8E+13	5.0E+14	5.5E+14	5.6E+14	3.1E+14	8.2E+13	1.4E+13	9.2E+12	2.9E+12	1.7E+12	7.5E+11	3.0E+11	4.8E+14
Highway	2.7E+13	3.6E+14	4.1E+14	4.3E+14	2.5E+14	6.7E+13	1.2E+13	7.2E+12	2.2E+12	1.1E+12	4.7E+11	1.9E+11	3.7E+14
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	6.3E+12	8.6E+13	9.8E+13	1.0E+14	5.4E+13	1.4E+13	2.4E+12	1.6E+12	5.0E+11	2.8E+11	1.2E+11	5.0E+10	8.5E+13
Urban	3.1E+12	4.4E+13	5.2E+13	5.2E+13	2.7E+13	7.1E+12	1.2E+12	8.0E+11	2.5E+11	1.4E+11	6.5E+10	2.6E+10	4.4E+13
Rural	1.9E+12	2.4E+13	2.7E+13	2.7E+13	1.5E+13	4.0E+12	6.8E+11	4.5E+11	1.4E+11	8.0E+10	3.7E+10	1.5E+10	2.3E+13
Highway	1.3E+12	1.7E+13	2.0E+13	2.1E+13	1.2E+13	3.3E+12	5.6E+11	3.5E+11	1.1E+11	5.6E+10	2.3E+10	9.1E+09	1.8E+13
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	6.9E+12	9.5E+13	1.1E+14	1.1E+14	6.0E+13	1.6E+13	2.7E+12	1.8E+12	5.5E+11	3.1E+11	1.4E+11	5.5E+10	9.3E+13
Urban	3.4E+12	4.9E+13	5.7E+13	5.7E+13	3.0E+13	7.8E+12	1.3E+12	8.8E+11	2.8E+11	1.6E+11	7.1E+10	2.8E+10	4.8E+13
Rural	2.0E+12	2.7E+13	3.0E+13	3.0E+13	1.6E+13	4.4E+12	7.5E+11	4.9E+11	1.6E+11	8.9E+10	4.0E+10	1.6E+10	2.6E+13
Highway	1.5E+12	1.9E+13	2.2E+13	2.3E+13	1.3E+13	3.6E+12	6.2E+11	3.9E+11	1.2E+11	6.1E+10	2.5E+10	1.0E+10	2.0E+13

Table 15. Vehicle no 3

Vehicle no 3, cold test, average													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	7.3E+12	3.0E+13	1.3E+13	6.6E+12	3.5E+12	1.7E+12	3.6E+11	1.9E+11	6.6E+10	3.5E+10	2.3E+10	5.1E+09	1.3E+13
Urban	6.0E+12	2.3E+13	9.6E+12	4.5E+12	2.1E+12	1.0E+12	2.2E+11	1.2E+11	4.2E+10	2.3E+10	1.8E+10	3.6E+09	9.9E+12
Rural	1.0E+12	5.7E+12	2.6E+12	1.5E+12	8.9E+11	4.1E+11	8.6E+10	4.5E+10	1.7E+10	8.9E+09	4.0E+09	1.4E+09	2.5E+12
Highway	2.2E+11	8.0E+11	6.3E+11	5.5E+11	5.0E+11	2.7E+11	5.5E+10	2.3E+10	6.8E+09	2.5E+09	8.9E+08	1.5E+08	7.3E+11
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	3.7E+11	1.5E+12	6.6E+11	3.4E+11	1.8E+11	8.8E+10	1.9E+10	9.5E+09	3.4E+09	1.8E+09	1.2E+09	2.6E+08	6.8E+11
Urban	3.1E+11	1.2E+12	4.9E+11	2.3E+11	1.1E+11	5.3E+10	1.1E+10	6.1E+09	2.2E+09	1.2E+09	9.2E+08	1.8E+08	5.1E+11
Rural	5.4E+10	2.9E+11	1.3E+11	7.9E+10	4.6E+10	2.1E+10	4.4E+09	2.3E+09	8.5E+08	4.6E+08	2.0E+08	7.2E+07	1.3E+11
Highway	1.1E+10	4.1E+10	3.2E+10	2.8E+10	2.6E+10	1.4E+10	2.9E+09	1.2E+09	3.5E+08	1.3E+08	4.6E+07	7.7E+06	3.8E+10
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	4.2E+11	1.7E+12	7.3E+11	3.8E+11	2.0E+11	9.8E+10	2.1E+10	1.1E+10	3.8E+09	2.0E+09	1.3E+09	2.9E+08	7.5E+11
Urban	3.4E+11	1.3E+12	5.5E+11	2.6E+11	1.2E+11	5.9E+10	1.3E+10	6.7E+09	2.4E+09	1.3E+09	1.0E+09	2.0E+08	5.6E+11
Rural	6.0E+10	3.3E+11	1.5E+11	8.8E+10	5.1E+10	2.4E+10	4.9E+09	2.6E+09	9.5E+08	5.1E+08	2.3E+08	8.0E+07	1.5E+11
Highway	1.3E+10	4.6E+10	3.6E+10	3.2E+10	2.9E+10	1.6E+10	3.2E+09	1.3E+09	3.9E+08	1.4E+08	5.1E+07	8.5E+06	4.2E+10

Table 16. Vehicle no 3

Vehicle no 3, warm test, average													
Particle aerodynamic diameter [µm]	0.03	0.063	0.109	0.173	0.267	0.407	0.655	1.021	1.655	2.52	4.085	6.56	ELPI_tot
	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test	#/test
Total	2.2E+12	9.1E+12	5.0E+12	3.5E+12	2.6E+12	1.5E+12	3.2E+11	1.5E+11	4.7E+10	2.2E+10	8.9E+09	3.0E+09	5.5E+12
Urban	1.6E+12	6.7E+12	3.3E+12	2.1E+12	1.4E+12	8.2E+11	1.7E+11	8.1E+10	2.7E+10	1.3E+10	5.6E+09	2.0E+09	3.5E+12
Rural	5.0E+11	2.1E+12	1.2E+12	9.5E+11	7.3E+11	4.1E+11	8.6E+10	4.0E+10	1.3E+10	6.0E+09	2.5E+09	8.4E+08	1.4E+12
Highway	1.6E+11	3.3E+11	4.6E+11	4.7E+11	4.9E+11	3.0E+11	6.2E+10	2.5E+10	7.1E+09	2.5E+09	7.7E+08	1.4E+08	5.9E+11
	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km	#/km
Total	1.1E+11	4.7E+11	2.6E+11	1.8E+11	1.3E+11	7.8E+10	1.6E+10	7.5E+09	2.4E+09	1.1E+09	4.6E+08	1.5E+08	2.8E+11
Urban	8.1E+10	3.4E+11	1.7E+11	1.1E+11	7.3E+10	4.2E+10	8.9E+09	4.2E+09	1.4E+09	6.8E+08	2.9E+08	1.0E+08	1.8E+11
Rural	2.6E+10	1.1E+11	6.4E+10	4.9E+10	3.7E+10	2.1E+10	4.4E+09	2.0E+09	6.6E+08	3.1E+08	1.3E+08	4.3E+07	7.0E+10
Highway	8.1E+09	1.7E+10	2.4E+10	2.4E+10	2.5E+10	1.5E+10	3.2E+09	1.3E+09	3.7E+08	1.3E+08	4.0E+07	7.4E+06	3.1E+10
	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh	#/kWh
Total	1.3E+11	5.2E+11	2.8E+11	2.0E+11	1.5E+11	8.7E+10	1.8E+10	8.3E+09	2.7E+09	1.2E+09	5.1E+08	1.7E+08	3.1E+11
Urban	9.0E+10	3.8E+11	1.9E+11	1.2E+11	8.1E+10	4.7E+10	9.9E+09	4.6E+09	1.5E+09	7.6E+08	3.2E+08	1.2E+08	2.0E+11
Rural	2.8E+10	1.2E+11	7.1E+10	5.4E+10	4.1E+10	2.4E+10	4.9E+09	2.3E+09	7.3E+08	3.4E+08	1.4E+08	4.8E+07	7.8E+10
Highway	8.9E+09	method	2.6E+10	2.7E+10	2.8E+10	1.7E+10	3.5E+09	1.4E+09	4.1E+08	1.4E+08	4.4E+07	8.2E+06	3.4E+10

Appendix 2, Aldehyde emission results

Table 17. Vehicle no 1, distance specific aldehyde results

	WHVC cold	WHVC warm Test 1	WHVC warm Test 2	WHVC warm Test 3	WHVC warm average	Standard deviation
	(mg/km)	(mg/km)	(mg/km)	(mg/km)	(mg/km)	(mg/km)
Substance						
Formaldehyde	2.379	0.197	0.326	0.360	0.294	0.086
Acetaldehyde	1.793	1.356	0.839	1.432	1.209	0.323
Acrolein	n.d.	n.d.	n.d.	n.d.		
Acetone	3.322	3.106	3.286	3.887	3.426	0.409
Propionaldehyde	0.018	n.d	n.d	n.d		
Crotonaldehyde	n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.076	0.056	0.016	0.039	0.037	0.020
Benzaldehyde	0.018	n.d.	n.d.	0.028		
Isovaleraldehyde	n.d.	n.d.	n.d.	0.089		
Valeraldehyde	n.d	n.d	n.d.	n.d		
o-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	0.075	0.036	0.047	0.058	0.047	0.011
Hexaldehyde	n.d.	n.d.	n.d.	n.d.		
Dimethylbenzaldehyde	n.d.	n.d.	n.d.	n.d.		

Table 18. Vehicle no 1, break specific aldehyde results

	WHVC cold	WHVC warm Test 1	WHVC warm Test 2	WHVC warm Test 3	WHVC warm average	Standard deviation
	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)
Substance						
Formaldehyde	2.670	0.219	0.362	0.405	0.329	0.098
Acetaldehyde	2.012	1.506	0.931	1.611	1.349	0.366
Acrolein	n.d.	n.d.	n.d.	n.d.		
Acetone	3.727	3.450	3.648	4.373	3.824	0.486
Propionaldehyde	0.020	n.d	n.d	n.d		
Crotonaldehyde	n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.085	0.062	0.018	0.044	0.041	0.022
Benzaldehyde	0.020	n.d.	n.d.	0.032		
Isovaleraldehyde	n.d.	n.d.	n.d.	0.100		
Valeraldehyde	n.d.	n.d.	n.d.	n.d.		
o-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	0.084	0.040	0.052	0.065	0.052	0.012
Hexaldehyde	n.d.	n.d.	n.d.	n.d.		
Dimethylbenzaldehyde	n.d.	n.d.	n.d.	n.d.		

Table 19. Vehicle no 2, distance specific aldehyde results, Dual Fuel mode

Dual Fuel mode Tests						
	WHVC cold	**WHVC warm Test 1**	**WHVC warm Test 2**	**WHVC warm Test 3**	**WHVC warm average**	**Standard deviation**
	(mg/km)	**(mg/km)**	**(mg/km)**	**(mg/km)**	**(mg/km)**	**(mg/km)**
Substance						
Formaldehyde	6.958	13.429	12.001	12.516	12.649	0.723
Acetaldehyde	1.774	0.804	0.671	1.663	1.046	0.539
Acrolein	n.d.	n.d.	n.d.	n.d.		
Acetone	n.d.	n.d.	n.d.	n.d.		
Propionaldehyde	0.170	0.069	0.056	0.279	0.134	0.125
Crotonaldehyde	n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.157	n.d.	n.d.	0.154		
Benzaldehyde	0.083	0.107	0.082	0.187	0.125	0.055
Isovaleraldehyde	0.029	0.164	0.012	n.d.		
Valeraldehyde	0.082	n.d.	n.d.	0.167		
o-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
Hexaldehyde	0.087	0.054	n.d.	0.234		
Dimethylbenzaldehyde	n.d.	n.d.	n.d.	n.d.		

Table 20. Vehicle no 2, break specific aldehyde results, Dual Fuel mode

Dual Fuel mode Tests						
	WHVC cold	WHVC warm Test 1	WHVC warm Test 2	WHVC warm Test 3	WHVC warm average	Standard deviation
	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)
Substance						
Formaldehyde	7.428	14.834	13.101	13.338	13.758	0.940
Acetaldehyde	1.893	0.888	0.732	1.772	1.131	0.561
Acrolein	n.d.	n.d.	n.d.	n.d.		
Acetone	n.d.	n.d.	n.d.	n.d.		
Propionaldehyde	0.181	0.076	0.061	0.297	0.145	0.132
Crotonaldehyde	n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.168	n.d.	n.d.	0.164		
Benzaldehyde	0.089	0.118	0.089	0.199	0.135	0.057
Isovaleraldehyde	0.031	0.181	0.013	n.d.		
Valeraldehyde	0.087	n.d.	n.d.	0.178		
o-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
Hexaldehyde	0.093	0.059	n.d.	0.250		
Dimethylbenzaldehyde	n.d.	n.d.	n.d.	n.d.		

Table 21. Vehicle no 2, distance specific aldehyde results, Diesel mode

Diesel mode tests						
	WHVC cold	**WHVC warm Test 1**	**WHVC warm Test 2**	**WHVC warm Test 3**	**WHVC warm average**	**Standard deviation**
	(mg/km)	**(mg/km)**	**(mg/km)**	**(mg/km)**	**(mg/km)**	**(mg/km)**
Substance						
Formaldehyde	1.797	3.251	2.393	1.962	2.536	0.656
Acetaldehyde	1.510	3.883	1.909	1.102	2.298	1.431
Acrolein	n.d.	n.d.	n.d.	n.d.		
Acetone	n.d.	n.d.	n.d.	n.d.		
Propionaldehyde	0.126	0.061	0.096	0.093	0.083	0.020
Crotonaldehyde	n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.137	0.094	0.141	0.064	0.099	0.039
Benzaldehyde	0.110	0.100	0.095	0.072	0.089	0.015
Isovaleraldehyde	0.153	0.032	0.236	0.000	0.089	0.128
Valeraldehyde	0.058	n.d.	n.d.	n.d.		
o-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
Hexaldehyde	0.101	n.d.	n.d.	n.d.		
Dimethylbenzaldehyde	n.d.	n.d.	n.d.	n.d.		

Table 22. Vehicle no 2, brake specific aldehyde results, Diesel mode

Diesel mode tests						
	WHVC cold	WHVC warm Test 1	WHVC warm Test 2	WHVC warm Test 3	WHVC warm average	Standard deviation
	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)
Substance						
Formaldehyde	1.931	3.518	2.694	2.161	2.791	0.684
Acetaldehyde	1.623	4.202	2.149	1.214	2.522	1.529
Acrolein	n.d.	n.d.	n.d.	n.d.		
Acetone	n.d.	n.d.	n.d.	n.d.		
Propionaldehyde	0.135	0.066	0.108	0.103	0.092	0.023
Crotonaldehyde	n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.147	0.101	0.158	0.071	0.110	0.044
Benzaldehyde	0.118	0.108	0.107	0.080	0.098	0.016
Isovaleraldehyde	0.165	0.034	0.266	0.000	0.100	0.145
Valeraldehyde	0.062	n.d.	n.d.	n.d.		
o-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	n.d.	n.d.	n.d.	n.d.		
Hexaldehyde	0.108	n.d.	n.d.	n.d.		
Dimethylbenzaldehyde	n.d.	n.d.	n.d.	n.d.		

Table 23. Vehicle no 3, distance specific aldehyde results

	WHVC cold Test 1	WHVC cold Test 2	WHVC cold average	Standard deviation		WHVC warm Test 1	WHVC warm Test 2	WHVC warm Test 3	WHVC warm Test 4	WHVC warm average	Standard deviation
	(mg/km)	(mg/km)	(mg/km)	(mg/km)		(mg/km)	(mg/km)	(mg/km)	(mg/km)	(mg/km)	(mg/km)
Substance											
Formaldehyde	3.548	3.611	3.579	0.045		0.710	0.601	0.872	0.615	0.700	0.125
Acetaldehyde	1.515	3.692	2.603	1.539		2.772	2.636	2.583	2.629	2.655	0.081
Acrolein	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Acetone	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Propionaldehyde	0.064	0.119	0.092	0.039		0.110	0.126	0.168	0.131	0.134	0.025
Crotonaldehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.048	0.094	0.071	0.032		n.d.	0.084	0.110	0.086		
Benzaldehyde	0.054	0.072	0.063	0.012		0.049	0.049	0.072	0.160	0.082	0.053
Isovaleraldehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Valeraldehyde	n.d.	0.163				0.124	0.135	0.138	0.074	0.118	0.030
o-Tolualdehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	0.099	0.128	0.113	0.020		n.d.	0.061	0.067	n.d.		
Hexaldehyde	0.142	0.231	0.186	0.063		0.155	0.194	0.123	0.231	0.176	0.047
Dimethylbenzaldehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		

Table 24. Vehicle no 3, break specific aldehyde results

	WHVC cold Test 1	WHVC cold Test 2	WHVC cold average	Standard deviation		WHVC warm Test 1	WHVC warm Test 2	WHVC warm Test 3	WHVC warm Test 4	WHVC warm average	Standard deviation
	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)		(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)	(mg/kWh)
Substance											
Formaldehyde	3.933	4.040	3.986	0.076		0.795	0.672	0.960	0.681	0.777	0.134
Acetaldehyde	1.680	4.130	2.905	1.733		3.101	2.946	2.842	2.912	2.950	0.109
Acrolein	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Acetone	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Propionaldehyde	0.071	0.134	0.102	0.044		0.123	0.141	0.185	0.145	0.149	0.026
Crotonaldehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Butyraldehyde	0.053	0.105	0.079	0.036		n.d.	0.094	0.121	0.095		
Benzaldehyde	0.060	0.080	0.070	0.014		0.054	0.055	0.079	0.177	0.091	0.058
Isovaleraldehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
Valeraldehyde	n.d.	0.182				0.138	0.151	0.152	0.082	0.131	0.033
o-Tolualdehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		
m+p-Tolualdehyde	0.110	0.143	0.126	0.024		n.d.	0.068	0.074	n.d.		
Hexaldehyde	0.157	0.258	0.208	0.072		0.174	0.216	0.135	0.256	0.195	0.052
Dimethylbenzaldehyde	n.d.	n.d.				n.d.	n.d.	n.d.	n.d.		

Appendix 3, PAH emission results

Table 25Particulate PAH emissions, vehicle no 1

Particulate PAH	Vehicle no 1, warm 1	Vehicle no 1, warm 2	Vehicle no 1, warm 3	Average	STD	Vehicle no 1, cold
Phenanthrene	29.08	29.20	33.50	30.59	2.06	71.88
Anthracene	4.26	8.35	6.23	6.28	1.67	24.84
3-Methylphenanthrene	7.63	8.98	7.86	8.16	0.59	14.10
2-Methylphenanthrene	11.47	12.17	10.97	11.54	0.49	20.51
2-Methylanthracene	1.53	1.61	1.26	1.47	0.15	4.06
9-Methylphenanthrene	7.99	9.29	8.19	8.49	0.57	14.91
1-Methylphenanthrene	7.04	7.72	6.71	7.16	0.42	14.48
4H-cyclopenta(def)phenanth	1.15	1.25	1.08	1.16	0.07	3.07
9-Methylanthracene	0.00	0.00	0.00	0.00	0.00	0.00
2-Phenylnaphthalene	3.35	4.11	4.64	4.03	0.53	7.69
3,6-Dimethylphenanthrene	1.07	1.55	1.46	1.36	0.21	2.13
3,9-Dimethylphenanthrene	8.03	9.43	8.71	8.73	0.57	18.65
Fluoranthene	23.91	27.02	24.17	25.03	1.41	55.47
Pyrene	26.33	27.44	22.70	25.49	2.03	67.80
9,10-Dimethylanthracene	0.00	0.00	0.00	0.00	0.00	0.00
1-Methylfluoranthene	4.17	3.99	3.34	3.83	0.36	10.50
Benz(a)fluorene	1.21	1.19	1.06	1.15	0.06	3.03
Benz(b)fluorene	0.40	0.39	0.43	0.40	0.02	1.18
2-Methylpyrene	3.16	2.91	2.23	2.77	0.40	8.23
4-Methylpyrene	5.06	4.69	3.16	4.30	0.82	12.37
1-Methylpyrene	2.11	1.99	1.72	1.94	0.16	5.66
Benzo(ghi)fluoranthene	18.96	17.39	12.97	16.44	2.54	53.26
Benzo(c)phenanthrene	3.83	3.66	2.89	3.46	0.41	9.58
Benzo(b)naphto(1,2-d)thiop	0.66	0.56	0.46	0.56	0.08	1.28
Cyclopenta(cd)pyrene	9.28	8.55	6.48	8.10	1.19	23.26
Benz(a)anthracene	9.61	9.43	7.62	8.89	0.90	26.32
Chrysene	18.85	20.32	15.47	18.21	2.03	49.49
3-Methylchrysene	0.71	0.78	0.55	0.68	0.10	1.34
2-Methylchrysene	1.17	0.95	0.97	1.03	0.10	3.46
6-Methylchrysene	0.67	0.00	0.49	0.39	0.28	1.68
1-Methylchrysene	0.86	0.84	0.74	0.81	0.05	2.25
Benzo(b)fluoranthene	10.59	11.89	7.67	10.05	1.76	38.40
Benzo(k)fluoranthene	2.12	2.37	1.54	2.01	0.35	7.47
Benzo(e)pyrene	7.90	8.43	5.08	7.13	1.47	32.59
Benzo(a)pyrene	2.84	2.30	2.37	2.51	0.24	8.66
Perylene	0.74	0.51	0.70	0.65	0.10	1.86
Indeno(1,2,3-cd)fluoranthe	0.54	0.44	0.32	0.44	0.09	1.42
Indeno(1,2,3-cd)pyrene	3.32	3.05	2.71	3.03	0.25	11.90
Dibenz(a,h)anthracene	0.55	0.46	0.40	0.47	0.06	1.66
Picene	0.37	0.26	0.21	0.28	0.07	0.93
Benzo(ghi)perylene	6.85	6.44	5.38	6.22	0.62	28.37
Dibenzo(a,l)pyrene	0.00	0.36	0.00	0.12	0.17	0.00
Dibenzo(a,e)pyrene	0.04	0.31	0.12	0.16	0.11	0.72
Coronene	4.30	3.87	2.66	3.61	0.69	16.41
Dibenzo(a,i)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,h)pyrene	0.00	0.00	0.00	0.00	0.00	0.00

Table 26 Volatile PAH emissions, vehicle no1

Volatile PAH	Vehicle no 1, warm 1	Vehicle no 1, warm 2	Vehicle no 1, warm 3	Medel	STD	Vehicle no 1, cold
Phenanthrene	454.80	235.69	610.42	433.64	153.71	656.77
Anthracene	54.21	83.74	52.24	63.40	14.40	69.61
3-Methylphenanthrene	72.65	28.39	153.23	84.76	51.68	196.31
2-Methylphenanthrene	88.97	45.27	126.40	86.88	33.15	152.26
2-Methylanthracene	11.06	15.61	12.68	13.12	1.88	42.75
9-Methylphenanthrene	68.84	17.01	104.72	63.52	36.00	155.83
1-Methylphenanthrene	56.91	62.64	85.08	68.21	12.16	128.50
4H-cyclopenta(def)phenanth	14.86	16.37	17.51	16.24	1.09	28.37
9-Methylanthracene	0.00	0.00	208.19	69.40	98.14	181.28
2-Phenylnaphthalene	49.70	45.91	31.56	42.39	7.81	66.64
3,6-Dimethylphenanthrene	14.91	4.14	10.94	10.00	4.45	37.71
3,9-Dimethylphenanthrene	95.86	34.45	68.40	66.24	25.12	259.38
Fluoranthene	236.65	79.62	137.17	151.14	64.86	337.77
Pyrene	255.84	143.44	159.88	186.38	49.57	399.53
9,10-Dimethylanthracene	0.00	0.00	0.00	0.00	0.00	0.00
1-Methylfluoranthene	30.90	4.65	22.32	19.29	10.93	51.67
Benz(a)fluorene	7.88	7.81	2.90	6.20	2.33	10.34
Benz(b)fluorene	1.49	2.07	0.99	1.51	0.44	2.22
2-Methylpyrene	19.21	6.67	19.87	15.25	6.08	29.05
4-Methylpyrene	32.18	4.88	34.09	23.72	13.34	41.75
1-Methylpyrene	13.90	9.94	17.24	13.69	2.98	16.62
Benzo(ghi)fluoranthene	57.36	61.85	20.37	46.53	18.59	43.57
Benzo(c)phenanthrene	19.34	0.00	5.29	8.21	8.16	14.60
Benzo(b)naphto(1,2-d)thiop	1.82	0.00	2.24	1.36	0.97	2.65
Cyclopenta(cd)pyrene	5.82	0.00	5.61	3.81	2.70	11.66
Benz(a)anthracene	4.35	0.00	4.61	2.99	2.11	3.81
Chrysene	15.00	58.64	13.79	29.15	20.86	10.25
3-Methylchrysene	0.37	0.00	2.72	1.03	1.21	0.00
2-Methylchrysene	0.51	4.62	5.72	3.62	2.24	0.81
6-Methylchrysene	0.00	57.84	0.00	19.28	27.27	0.00
1-Methylchrysene	0.00	1.34	2.94	1.42	1.20	0.30
Benzo(b)fluoranthene	2.78	0.68	4.27	2.58	1.47	0.10
Benzo(k)fluoranthene	0.81	0.34	3.52	1.55	1.40	19.99
Benzo(e)pyrene	1.19	3.00	9.69	4.63	3.66	5.97
Benzo(a)pyrene	0.00	0.00	1.86	0.62	0.88	0.00
Perylene	0.00	0.00	1.35	0.45	0.64	0.88
Indeno(1,2,3-cd)fluoranthe	0.00	0.00	0.00	0.00	0.00	0.00
Indeno(1,2,3-cd)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenz(a,h)anthracene	0.00	0.00	0.00	0.00	0.00	0.00
Picene	0.03	0.04	0.03	0.03	0.01	0.05
Benzo(ghi)perylene	0.00	0.00	3.27	1.09	1.54	0.00
Dibenzo(a,l)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,e)pyrene	0.07	0.18	0.14	0.13	0.05	0.11
Coronene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,i)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,h)pyrene	0.00	0.00	0.00	0.00	0.00	0.00

Table 27. Particulate PAH emissions, vehicle no 2

Particulate PAH	Vehicle no 2, DDF, warm 1	Vehicle no 2, DDF, warm 2	Vehicle no 2, DDF, warm 3	Average	STD	Vehicle no 2, Diesel, warm 1	Vehicle no 2, Diesel, warm 2	Vehicle no 2, Diesel, warm 3	Average	STD	Vehicle no 2, DDF, cold	Vehicle no 2, Diesel, cold
	ng/km	ng/km	ng/km	ng/km		ng/km	ng/km	ng/km	ng/km		ng/km	ng/km
Phenanthrene	369.45	52.46	386.58	**269.50**	153.63	530.68	339.38	656.11	**508.72**	130.23	59.97	652.68
Anthracene	117.56	14.47	83.71	**71.92**	42.90	94.68	65.75	143.31	**101.25**	32.00	11.70	136.26
3-Methylphenanthrene	107.73	16.84	115.20	**79.92**	44.71	177.98	124.92	292.73	**198.55**	70.03	12.36	143.98
2-Methylphenanthrene	154.65	24.12	170.69	**116.49**	65.64	269.53	185.01	429.66	**294.73**	101.46	14.08	208.39
2-Methylanthracene	27.15	4.37	24.20	**18.57**	10.12	35.61	24.82	55.82	**38.75**	12.85	4.98	22.66
9-Methylphenanthrene	65.38	10.14	64.54	**46.69**	25.85	105.63	72.35	173.17	**117.05**	41.94	8.50	91.17
1-Methylphenanthrene	75.39	11.02	74.85	**53.75**	30.22	123.75	87.84	199.21	**136.93**	46.41	9.65	103.04
4H-cyclopenta(def)phenanth	14.71	1.99	16.11	**10.94**	6.35	27.24	19.33	40.15	**28.91**	8.58	2.83	41.62
9-Methylanthracene	0.00	0.00	0.00	**0.00**	0.00	16.00	12.88	18.24	**15.71**	2.20	3.87	0.00
2-Phenylnaphthalene	38.20	6.32	47.25	**30.59**	17.55	68.23	51.28	81.85	**67.12**	12.50	5.33	93.89
3,6-Dimethylphenanthrene	13.57	2.12	14.00	**9.89**	5.50	22.71	15.67	27.85	**22.08**	4.99	1.09	18.88
3,9-Dimethylphenanthrene	33.98	8.63	55.28	**32.63**	19.07	95.09	62.77	112.61	**90.16**	20.64	4.85	78.93
Fluoranthene	170.03	23.47	166.69	**120.06**	68.31	270.29	210.59	336.88	**272.59**	51.58	20.49	393.94
Pyrene	300.86	38.98	277.90	**205.91**	118.41	458.28	333.86	565.82	**452.66**	94.78	29.28	557.38
9,10-Dimethylanthracene	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00
1-Methylfluoranthene	20.31	3.16	24.92	**16.13**	9.36	36.51	33.48	52.69	**40.89**	8.43	2.75	49.40
Benz(a)fluorene	9.46	1.36	11.50	**7.44**	4.38	19.56	18.81	26.09	**21.48**	3.27	1.39	26.11
Benz(b)fluorene	6.87	1.01	8.15	**5.34**	3.11	12.93	11.58	17.42	**13.98**	2.50	0.80	16.10
2-Methylpyrene	48.28	6.89	54.96	**36.71**	21.26	87.81	65.16	110.45	**87.81**	18.49	4.36	81.96
4-Methylpyrene	38.63	5.13	40.97	**28.25**	16.37	69.11	51.69	86.42	**69.07**	14.18	4.02	70.23
1-Methylpyrene	29.30	3.60	31.49	**21.46**	12.67	51.57	38.82	60.84	**50.41**	9.03	3.41	57.64
Benzo(ghi)fluoranthene	126.63	14.79	102.79	**81.41**	48.10	202.72	121.32	223.10	**182.38**	43.97	9.26	256.22
Benzo(c)phenanthrene	20.36	2.83	18.98	**14.06**	7.96	36.89	31.21	50.82	**39.64**	8.24	2.09	45.93
Benzo(b)naphto(1,2-d)thiop	0.61	0.00	0.62	**0.41**	0.29	0.76	0.89	1.00	**0.88**	0.10	0.07	16.26
Cyclopenta(cd)pyrene	136.35	13.76	102.99	**84.37**	51.75	156.37	153.11	194.32	**167.93**	18.70	10.62	245.04
Benz(a)anthracene	119.97	16.98	120.16	**85.70**	48.60	181.86	160.05	233.29	**191.73**	30.70	11.16	229.60
Chrysene	109.87	14.67	94.63	**73.06**	41.75	148.99	138.46	202.09	**163.18**	27.85	9.99	209.76
3-Methylchrysene	8.05	0.75	6.76	**5.19**	3.18	10.76	5.66	15.42	**10.62**	3.99	0.23	17.81
2-Methylchrysene	8.16	1.26	7.42	**5.62**	3.09	12.13	11.05	16.11	**13.10**	2.17	0.86	16.13
6-Methylchrysene	4.35	0.62	4.39	**3.12**	1.77	7.08	7.29	9.04	**7.80**	0.88	0.47	3.61
1-Methylchrysene	3.97	0.59	3.83	**2.79**	1.56	6.21	6.59	8.69	**7.16**	1.09	0.00	8.75
Benzo(b)fluoranthene	131.65	15.67	116.07	**87.80**	51.40	186.68	200.75	255.92	**214.45**	29.88	11.54	247.95
Benzo(k)fluoranthene	53.12	6.50	44.52	**34.71**	20.26	61.75	78.53	93.69	**77.99**	13.04	4.89	78.26
Benzo(e)pyrene	119.60	13.33	91.70	**74.88**	44.99	153.28	151.28	193.72	**166.09**	19.55	10.80	208.26
Benzo(a)pyrene	148.69	15.56	119.04	**94.43**	57.07	178.65	179.33	214.12	**190.70**	16.56	11.32	217.26
Perylene	23.76	2.36	18.10	**14.74**	9.05	26.84	26.36	35.65	**29.61**	4.27	2.00	35.26
Indeno(1,2,3-cd)fluoranthe	4.87	0.45	4.23	**3.19**	1.95	4.15	4.63	5.26	**4.68**	0.46	0.00	0.00
Indeno(1,2,3-cd)pyrene	58.41	5.43	46.40	**36.75**	22.68	46.68	60.51	55.27	**54.15**	5.70	2.69	50.05
Dibenz(a,h)anthracene	5.14	0.88	9.41	**5.14**	3.48	9.62	12.38	12.34	**11.45**	1.29	0.00	9.25
Picene	0.03	0.01	3.78	**1.27**	1.77	4.85	5.64	4.93	**5.14**	0.35	0.01	0.02
Benzo(ghi)perylene	130.91	10.92	83.17	**75.00**	49.32	80.60	100.02	101.93	**94.18**	9.64	4.87	85.90
Dibenzo(a,l)pyrene	2.79	0.15	1.44	**1.46**	1.08	0.00	2.42	1.79	**1.40**	1.03	0.00	0.00
Dibenzo(a,e)pyrene	4.54	0.37	2.80	**2.57**	1.71	0.06	3.01	2.88	**1.98**	1.36	0.00	0.00
Coronene	18.17	0.00	10.13	**9.43**	7.43	7.47	7.48	10.75	**8.57**	1.54	0.00	0.00
Dibenzo(a,i)pyrene	0.00	0.00	0.00	**0.00**	0.00	0.91	0.53	0.00	**0.48**	0.37	0.00	0.00

Table 28. Volatile PAH emissions, vehicle no 2

Volatile PAH	Vehicle no 2, DDF, warm 1	Vehicle no 2, DDF, warm 2	Vehicle no 2, DDF, warm 3	Average	STD		Vehicle no 2, Diesel, warm 1	Vehicle no 2, Diesel, warm 2	Vehicle no 2, Diesel, warm 3	Average	STD		Vehicle no 2, DDF, cold		Vehicle no 2, Diesel, cold
	ng/km	ng/km	ng/km	ng/km			ng/km	ng/km	ng/km	ng/km			ng/km		ng/km
Phenanthrene	132.80	77.39	214.22	**141.47**	56.20		208.67	106.86	189.87	**168.47**	44.24		161.35		414.04
Anthracene	16.26	37.58	29.19	**27.68**	8.77		34.50	11.50	25.87	**23.96**	9.49		19.65		160.20
3-Methylphenanthrene	28.13	25.34	66.81	**40.09**	18.93		79.15	30.65	70.46	**60.09**	21.11		32.95		0.00
2-Methylphenanthrene	32.06	25.47	71.97	**43.17**	20.55		89.30	33.32	81.98	**68.20**	24.84		34.49		0.00
2-Methylanthracene	3.85	3.62	17.14	**8.20**	6.32		20.59	5.98	12.64	**13.07**	5.97		5.41		0.00
9-Methylphenanthrene	25.57	22.24	67.75	**38.52**	20.71		76.65	29.27	66.81	**57.58**	20.42		29.46		103.16
1-Methylphenanthrene	24.28	20.38	57.20	**33.95**	16.51		63.51	24.17	50.45	**46.04**	16.36		21.14		100.15
4H-cyclopenta(def)phenanth	4.13	2.71	5.44	**4.09**	1.12		4.56	2.75	4.15	**3.82**	0.78		6.07		26.32
9-Methylanthracene	6.77	0.00	0.00	**2.26**	3.19		0.00	5.75	0.00	**1.92**	2.71		6.19		32.09
2-Phenylnaphthalene	6.45	0.00	7.98	**4.81**	3.46		6.88	4.17	7.40	**6.15**	1.42		7.06		0.00
3,6-Dimethylphenanthrene	3.36	2.58	6.26	**4.07**	1.58		6.47	2.74	5.65	**4.95**	1.60		3.79		0.00
3,9-Dimethylphenanthrene	15.45	13.23	41.12	**23.27**	12.66		37.76	16.57	37.24	**30.52**	9.87		18.29		0.00
Fluoranthene	25.42	16.49	23.47	**21.79**	3.83		16.39	14.91	17.00	**16.10**	0.88		27.54		55.75
Pyrene	23.59	18.79	23.33	**21.90**	2.20		16.76	13.77	16.66	**15.73**	1.39		25.64		64.45
9,10-Dimethylanthracene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
1-Methylfluoranthene	1.50	0.66	0.00	**0.72**	0.61		1.56	0.00	0.00	**0.52**	0.74		1.33		0.00
Benz(a)fluorene	0.94	0.45	1.35	**0.91**	0.37		1.11	0.90	1.20	**1.07**	0.12		1.28		0.00
Benz(b)fluorene	0.31	0.00	1.17	**0.49**	0.50		0.00	0.65	1.00	**0.55**	0.41		0.90		0.00
2-Methylpyrene	1.14	0.00	0.00	**0.38**	0.54		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
4-Methylpyrene	1.63	1.19	1.56	**1.46**	0.19		1.59	1.12	1.43	**1.38**	0.20		1.84		0.00
1-Methylpyrene	0.76	0.59	0.83	**0.73**	0.10		0.80	0.43	0.77	**0.67**	0.17		0.76		0.00
Benzo(ghi)fluoranthene	2.94	2.58	3.25	**2.92**	0.27		0.00	1.87	1.97	**1.28**	0.91		0.00		0.00
Benzo(c)phenanthrene	21.92	0.41	24.08	**15.47**	10.69		0.51	0.00	10.88	**3.80**	5.01		3.59		0.00
Benzo(b)naphto(1,2-d)thiop	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.33	**0.11**	0.16		3.14		0.00
Cyclopenta(cd)pyrene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
Benz(a)anthracene	0.00	1.38	0.09	**0.49**	0.63		0.00	0.00	0.80	**0.27**	0.38		0.00		0.00
Chrysene	2.28	0.00	4.58	**2.29**	1.87		4.79	0.00	0.00	**1.60**	2.26		0.00		0.00
3-Methylchrysene	0.65	0.00	0.00	**0.22**	0.31		0.13	0.00	0.12	**0.09**	0.06		12.29		1.13
2-Methylchrysene	0.76	0.00	0.00	**0.25**	0.36		0.72	0.00	0.49	**0.40**	0.30		1.66		3.24
6-Methylchrysene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
1-Methylchrysene	0.87	0.00	1.21	**0.69**	0.51		1.37	0.00	0.65	**0.68**	0.56		4.23		0.00
Benzo(b)fluoranthene	0.08	0.05	0.03	**0.05**	0.02		0.64	1.67	0.95	**1.08**	0.43		2.60		0.00
Benzo(k)fluoranthene	1.48	2.74	0.00	**1.41**	1.12		2.23	0.41	0.86	**1.17**	0.77		0.00		0.00
Benzo(e)pyrene	0.83	0.52	0.92	**0.76**	0.17		0.65	0.55	0.49	**0.56**	0.07		0.37		1.32
Benzo(a)pyrene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.22	**0.07**	0.10		0.00		0.00
Perylene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
Indeno(1,2,3-cd)fluoranthe	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.38	**0.13**	0.18		2.82		1.95
Indeno(1,2,3-cd)pyrene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
Dibenz(a,h)anthracene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
Picene	0.02	0.20	0.11	**0.11**	0.07		0.33	0.05	0.07	**0.15**	0.13		0.08		1.67
Benzo(ghi)perylene	1.02	1.15	0.00	**0.72**	0.51		0.17	0.15	0.76	**0.36**	0.29		0.00		0.00
Dibenzo(a,l)pyrene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
Dibenzo(a,e)pyrene	0.11	0.43	0.14	**0.22**	0.14		0.18	0.24	0.09	**0.17**	0.06		0.49		4.58
Coronene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
Dibenzo(a,i)pyrene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00
Dibenzo(a,h)pyrene	0.00	0.00	0.00	**0.00**	0.00		0.00	0.00	0.00	**0.00**	0.00		0.00		0.00

Table 29 Particulate PAH emissions, vehicle no 3

Particulate PAH	Vehicle no 3, warm 1	Vehicle no 3, warm 2	Vehicle no 3, warm 3	Average	STD	Vehicle no 3, cold
Phenanthrene	71.44	37.01	28.24	45.56	18.64	19.02
Anthracene	15.21	19.89	12.29	15.80	3.13	9.92
3-Methylphenanthrene	17.73	7.03	5.61	10.12	5.41	3.89
2-Methylphenanthrene	24.63	10.15	7.93	14.24	7.41	5.29
2-Methylanthracene	2.22	1.49	0.93	1.55	0.53	0.65
9-Methylphenanthrene	16.26	5.82	4.79	8.95	5.18	3.44
1-Methylphenanthrene	16.54	6.77	5.36	9.56	4.97	3.75
4H-cyclopenta(def)phenanth	3.81	2.72	2.48	3.00	0.58	1.31
9-Methylanthracene	0.00	0.00	1.08	0.36	0.51	0.00
2-Phenylnaphthalene	7.44	4.43	3.38	5.09	1.72	2.07
3,6-Dimethylphenanthrene	1.82	0.74	0.63	1.06	0.53	0.48
3,9-Dimethylphenanthrene	11.77	4.67	3.54	6.66	3.64	3.03
Fluoranthene	45.86	29.37	23.78	33.00	9.38	15.73
Pyrene	41.12	27.73	23.37	30.74	7.55	15.38
9,10-Dimethylanthracene	0.00	0.00	0.00	0.00	0.00	0.00
1-Methylfluoranthene	4.65	3.53	2.85	3.68	0.74	1.97
Benz(a)fluorene	1.89	1.57	1.46	1.64	0.18	0.83
Benz(b)fluorene	0.70	0.72	0.70	0.71	0.01	0.37
2-Methylpyrene	2.46	1.84	1.48	1.93	0.41	1.05
4-Methylpyrene	3.96	2.91	2.27	3.05	0.70	1.68
1-Methylpyrene	2.18	1.81	1.66	1.88	0.22	1.05
Benzo(ghi)fluoranthene	16.32	13.97	11.64	13.98	1.91	8.29
Benzo(c)phenanthrene	3.83	3.30	2.41	3.18	0.58	1.56
Benzo(b)naphto(1,2-d)thiop	0.48	0.34	0.24	0.35	0.10	1.56
Cyclopenta(cd)pyrene	9.91	12.52	8.35	10.26	1.72	7.11
Benz(a)anthracene	9.55	13.37	11.93	11.61	1.58	6.86
Chrysene	18.72	18.33	15.23	17.42	1.56	10.14
3-Methylchrysene	0.87	0.52	0.39	0.59	0.21	0.27
2-Methylchrysene	1.56	1.27	1.33	1.39	0.13	0.88
6-Methylchrysene	0.31	2.03	1.02	1.12	0.71	1.24
1-Methylchrysene	1.54	1.78	1.59	1.64	0.10	1.07
Benzo(b)fluoranthene	16.51	16.66	14.18	15.78	1.14	9.38
Benzo(k)fluoranthene	4.25	4.93	4.28	4.49	0.31	3.08
Benzo(e)pyrene	11.03	12.02	9.58	10.87	1.00	6.65
Benzo(a)pyrene	6.98	11.88	11.34	10.07	2.19	6.21
Perylene	1.77	2.69	1.97	2.15	0.39	1.61
Indeno(1,2,3-cd)fluoranthe	1.23	1.35	1.19	1.26	0.06	0.68
Indeno(1,2,3-cd)pyrene	6.81	8.45	7.52	7.59	0.67	4.26
Dibenz(a,h)anthracene	1.14	1.37	1.12	1.21	0.11	0.74
Picene	0.73	0.82	0.66	0.74	0.06	0.34
Benzo(ghi)perylene	10.71	13.84	12.27	12.27	1.28	7.88
Dibenzo(a,l)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,e)pyrene	0.00	0.00	0.00	0.00	0.00	0.06
Coronene	4.52	5.05	4.05	4.54	0.41	2.83
Dibenzo(a,i)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,h)pyrene	0.00	0.00	0.00	0.00	0.00	0.00

Table 30 Volatile PAH emissions, vehicle no 3

Volatile PAH	Vehicle no 3, warm 1	Vehicle no 3, warm 2	Vehicle no 3, warm 3	Average	STD	Vehicle no 3, cold
Phenanthrene	557.40	204.71	223.70	328.60	161.97	181.44
Anthracene	8.93	12.35	14.64	11.97	2.35	16.92
3-Methylphenanthrene	140.07	22.40	19.22	60.56	56.24	21.01
2-Methylphenanthrene	172.30	27.33	22.36	73.99	69.54	25.15
2-Methylanthracene	13.20	2.59	2.35	6.05	5.06	3.31
9-Methylphenanthrene	133.45	18.96	15.13	55.84	54.90	17.83
1-Methylphenanthrene	111.78	19.59	16.47	49.28	44.21	17.67
4H-cyclopenta(def)phenanth	27.32	12.76	11.39	17.15	7.21	10.97
9-Methylanthracene	0.00	0.00	0.00	0.00	0.00	0.00
2-Phenylnaphthalene	25.75	10.88	11.24	15.96	6.92	9.68
3,6-Dimethylphenanthrene	12.37	2.39	2.01	5.59	4.80	2.34
3,9-Dimethylphenanthrene	66.13	11.28	10.72	29.38	25.99	12.32
Fluoranthene	83.86	44.94	48.03	58.94	17.67	42.36
Pyrene	76.86	40.93	41.26	53.02	16.86	39.46
9,10-Dimethylanthracene	0.00	0.00	0.00	0.00	0.00	0.00
1-Methylfluoranthene	3.44	2.09	2.43	2.65	0.57	1.82
Benz(a)fluorene	1.30	0.84	1.06	1.07	0.19	0.66
Benz(b)fluorene	0.44	0.26	0.33	0.35	0.07	0.11
2-Methylpyrene	1.75	0.88	0.93	1.19	0.40	0.00
4-Methylpyrene	2.86	1.62	1.58	2.02	0.59	1.20
1-Methylpyrene	1.48	0.97	1.03	1.16	0.23	0.74
Benzo(ghi)fluoranthene	3.75	2.74	3.77	3.42	0.48	3.77
Benzo(c)phenanthrene	1.64	0.69	0.96	1.10	0.40	0.81
Benzo(b)naphto(1,2-d)thiop	0.39	0.00	0.00	0.13	0.18	0.00
Cyclopenta(cd)pyrene	1.06	0.54	0.55	0.72	0.24	0.48
Benz(a)anthracene	0.40	0.21	0.60	0.40	0.16	0.00
Chrysene	2.71	0.68	1.78	1.72	0.83	1.83
3-Methylchrysene	0.20	0.04	0.03	0.09	0.08	0.24
2-Methylchrysene	0.47	0.06	0.10	0.21	0.19	0.04
6-Methylchrysene	0.00	0.00	0.00	0.00	0.00	0.00
1-Methylchrysene	0.41	0.00	0.00	0.14	0.19	0.00
Benzo(b)fluoranthene	0.88	0.40	0.41	0.56	0.23	0.59
Benzo(k)fluoranthene	0.42	0.06	0.10	0.19	0.16	0.10
Benzo(e)pyrene	0.48	0.23	0.19	0.30	0.13	0.24
Benzo(a)pyrene	0.00	0.08	0.05	0.04	0.03	0.00
Perylene	0.14	0.04	0.04	0.07	0.05	0.09
Indeno(1,2,3-cd)fluoranthe	0.00	0.00	0.00	0.00	0.00	0.01
Indeno(1,2,3-cd)pyrene	0.15	0.00	0.00	0.05	0.07	0.00
Dibenz(a,h)anthracene	0.00	0.00	0.00	0.00	0.00	0.00
Picene	0.01	0.00	0.00	0.00	0.00	0.01
Benzo(ghi)perylene	0.66	0.63	0.09	0.46	0.26	0.00
Dibenzo(a,l)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,e)pyrene	0.01	0.01	0.02	0.01	0.00	0.02
Coronene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,i)pyrene	0.00	0.00	0.00	0.00	0.00	0.00
Dibenzo(a,h)pyrene	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 4, Gas composition

Table 31. Gas composition of LBG at Lidkoping Biogas (DDF vehicle)

Parameter	Unit	Upgraded	LBG*
Wobbe-index	MJ/Nm^3	45,1 – 46,8	45,9 – 47,3
Lower Heating Value	kWh/Nm3	9,6-9,8	9,6-9,8
Lower Heating Value, medi-um	kWh/Nm3	9,7	9,74
Lower Heating Value	kWh/kg		13,1-13,6
Lower Heating Value, medi-um	kWh/kg		13,4
Methane	Volume-%	97 ± 1	97,7 ± 1
Density, 0,5 barg	kg/m^3		419
Density, 2,0 barg	kg/m^3		404
Density	kg/Nm^3	0,76	
Motor Octane Number.		133,9 – 138,6	
Dew point	°C	-	-
Water content	mg/Nm^3	26	22
Max. $CO_2 + O_2 + N_2$	Volume-%	2,9 ± 0,6	1,6 ± 0,3
O_2	Volume-%	0,2 ± 0,1	0,4 ± 0,1
CO_2	Volume-%	1,7 ± 0,3	< 0,1
N_2	Volume-%	1,0 ± 0,2	1,2 ± 0,3
Total sulphur	mg/Nm^3	< 2	< 1
Total nitrogen compounds (exkl. N_2) counted as NH_3	mg/Nm^3	20	< 7
Ethane	Volume-%	0	0
Propane	Volume-%	0	0
n-Butane	Volume-%	0	0
i-Butane	Volume-%	0	0
n-Pentane	Volume-%	0	0
i-Pentane	Volume-%	0	0
Hexane	Volume-%	0	0
Heptane	Volume-%	0	0
Hydrogen	Volume-%	0,02 ± 0,02	0,02 ± 0,02
Hydrogen Sulphide	ppmv	< 1	< 1
Mercury	$\mu g/Nm^3$	0	0

*Analysis of gas to Cold Box