An exhaust characterisation study based on regulated and unregulated tailpipe and evaporative emissions from bi-fuel and flexi-fuel light-duty passenger cars fuelled by petrol (E5), bioethanol (E70, E85) and biogas tested at ambient temperatures of +22°C and -7°C

Final report, March 2008

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Roger Westerholm[1], Peter Ahlvik[2] and Hua Lu Karlsson[3]

[1]Department of Analytical Chemistry, Arrhenius Laboratory, Stockholm University,
SE-106 91, Stockholm, Sweden, e-mail: roger.westerholm@anchem.su.se.
[2]Ecotraffic ERD[3] AB, Floragatan 10B, SE-114 31 Stockholm, Sweden,
peter.ahlvik@ecotraffic.se.
[3]AVL MTC AB, Box 223, SE-136 23 Haninge, Sweden, hua.lu@avlmtc.se.

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Abbreviations, acronyms and glossary

1,3-C_4H_6	1,3-butadiene
A/F	Air/Fuel ratio
ACEA	European Automobile Manufacturers Association
AFR	Air/Fuel ratio
amu	Atomic Mass Units
AQIURP	Auto/Oil Air Quality Improvement Research Program
AR	Artemis Road: the Artemis road, or “rural” driving cycle
ASE	Accelerated Solvent Extraction
AU	Artemis Urban: the Artemis urban driving cycle
B(a)P	Benzo(a)pyrene
BFV	Bi-Fuel Vehicle
BMEP	Brake mean effective pressure
BTU	British Thermal Unit
C_2H_4	Ethene
C_3H_6	propene
C_6H_6	Benzene
C_7H_8	Toluene
CADC	Common Artemis Driving Cycle
CARB	California Air Resources Board
CBG	Compressed biogas
CH_4	Methane
CNC	Condensation Nuclei Counter (equivalent to CPC)
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
CONCAWE	Conservation of Clean Air and Water in Europe, the oil companies’ European association for environment, health and safety in refining and distribution
CPC	Condensation Particle Counter (equivalent to CNC)
CVS	Constant Volume Sampler/Sampling, a dilution device used for dilution of engine/vehicle exhaust for emission measurements.
DEER	Diesel Engine Emission Reduction Conference (USA)
DI	Direct Injection
DISI	Direct Injection Spark Ignition
DMA	Differential Mobility Analyzer
DMM	Dekati Mass Monitor, an instrument (Dekati Ltd. in Finland) for measuring (indirectly) particle mass in real time
DMPS	Differential Mobility Particle Sizer
DNPH	2,4-Dinitrophenyl Hydrazine
DOE	U.S. Department of Energy
DPF	Diesel Particle Filter
DR	Dilution Ratio
E10	Petrol blended with 10 % ethanol
E100	Pure ethanol fuel (possibly blended with some denaturant and small doses of other additives)
E15	Petrol blended with 15 % ethanol
E20	Petrol blended with 20 % ethanol

E3	Petrol blended with 3 % ethanol
E5	Petrol blended with 5 % ethanol
E70	Ethanol blended with 70 % petrol
E75	Ethanol blended with 25 % petrol
E85	Ethanol blended with 15 % petrol
EC	Elemental carbon
ECU	Electronic Control Unit
EEA	European Environment Agency
EEV	Enhanced Environmentally Friendly Vehicle
EGR	Exhaust Gas Recirculation
ELPI	Electrical Low Pressure Impactor, an instrument (Dekati Ltd. in Finland) that measures particle number and particle size distribution in real time
EPA	Environmental Protection Agency (USA)
ESFE	Energy-Specific Fuel Economy
ET	Evaporation Tube
EUCAR	European Council for Automotive R&D, the automotive manufacturer's association for research and development in Europe
EUDC	Extra Urban Driving Cycle, the second part of the European driving cycle
Euro X	Emission limits in EU, e.g. Euro 1, Euro 2, etc...
FAME	Fatty Acid Methyl Esters
FFV	Fuel-Flexible Vehicle
FSI	Fuel Stratified Injection, i.e. VW nomenclature for petrol-fuelled engines with stratified air/fuel mixture using direct injection (DI) late in the compression stroke.
GC-MS	Gas Chromatography Mass Spectrometry
GMP	GM Powertrain
HC	Hydrocarbon
HEPA	High-Efficiency Particulate Air filter
HPLC	High Performance Liquid Chromatography
IANGV	International Association for Natural Gas Vehicles
IDI	Indirect injection
ILCE_LD	Light-Duty Interlaboratory Correlation Exercise
IOF	Insoluble Organic Fraction
JRC	The Joint Research Centre, a research based policy support organisation and an integral part of the European Commission.
KFB	Swedish Transportation Research Board. A Swedish governmental organisation that was closed down a couple of years ago.
LC-GC-MS	Liquid Chromatography- Gas chromatography Mass Spectrometry
LD	Light-duty
LPG	Liquid Petroleum Gas
m.v.	Missing value
M100	Pure methanol fuel (possibly blended with some denaturant and small doses of other additives)
M85	Methanol blended with 15 % petrol
MBT	Maximum Brake Torque: The spark advance that gives the highest torque for a given throttle position and speed.
MMBTU	Billion BTU (see BTU above)
MON	Motor Octane Number. The resistance to knock at high engine speeds. See

	also the abbreviation RON below.
MPG, mpg	Miles per gallon
MPI	Multi Point Injection
Mw	Molecular weight
n.r.	Not regulated
N_2O	Nitrous oxide
Nanoparticle	A particle smaller than 50 nm. Slightly different definitions (of size) are also used.
NEDC	New European Driving Cycle
NGV	Natural Gas Vehicle
NG	Natural Gas
NMHC	Non-Methane Hydrocarbon
NMHCE	Non-Methane Hydrocarbon Equivalent. When alcohol fuels are used, oxygenated compounds in the exhaust are present.
NMOG	Non-Methane Organic Gases
NO	Nitrogen monoxide (commonly referred to as nitrogen oxide)
NO_2	Nitrogen dioxide
NO_X	Oxides of nitrogen
NREL	National Renewable Laboratory
OBD	On-Board Diagnostics system
OMHCE	Organic Matter Hydrocarbon Equivalent
PAH	Polycyclic Aromatic Hydrocarbons
PCV	Positive Crankcase Ventilation
PM	Particulate Matter
PMP	Particulate Measurement Program (the EU programme for developing new measurement methods for particle mass and number)
PND1	The first (hot) dilution stage in the PMP sampling system
PND2	The second (cold) dilution stage in the PMP sampling system
$ppm_{v/v}$	parts per million by volume
$ppm_{w/w}$	parts per million by weight
PUF	Poly Urethane Foam. Plugs of PUF are used for PAH sampling.
RFG	Reformulated Gasoline (petrol)
RON	Research Octane Number. Knock resistance of motor fuels at low engine speed. See also the abbreviation MON above.
RVP	Reid Vapour pressure
RWE	Reactivity-Weighted Emission
SAE	Society of Automotive Engineers
SAPS	Sulphate, Ash, Phosphorous, Sulphur
SHED	Sealed Housing for Evaporative Determination
SI	Spark Ignition
SIF	Soluble Inorganic Fraction
SMD	Sauter Mean Diameter
SMPS	Scanning Mobility Particle Sizer
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
SOF	Soluble Organic Fraction
SR	Specific Reactivity
t.b.d.	To be decided

TD	Thermodenuder, a device that removes volatile aerosols and volatiles adsorbed on solid particles.
TEF	Toxic Equivalence Factor
TEOM	Tapered Element Oscillating Microbalance, an instrument (Rupprecht & Pataschnik) for measuring particle mass in real time
TFSI	VW nomenclature for petrol-fuelled engines with turbocharger and direct injection (DI).
THC	Total HydroCarbon emissions. HydroCarbon (HC) emissions including methane
THCE	Similar as OMHCE, see above.
TWC	Three Way Catalyst
Tygon®	Electrically conducting PVC based polymer material
UDC	Urban Driving Cycle, the first part of the European driving cycle
ULEV	Ultra-Low Emission Vehicle, a nomenclature for vehicles that can fulfil very low emission limits within the California Low Emission Vehicle standards (LEV). The ULEV limits were updated (LEV II) in November 5, 1998. These standards cover the period from 2004 to 2010.
UN ECE	United Nations Economic Commission for Europe
US EPA	United States Environmental Protection Agency
VOF	Volatile Organic Fraction
VPR	Volatile Particle Removal system, i.e. a system comprising hot and cold
VTEC	Variable valve Technology, Honda nomenclature for the more general denotation Variable Valve Timing (VVT)
VVT	Variable Valve Timing
VVT	Variable Valve Timing

Foreword

This present research project consisted originally of three individual but partly overlapping research applications to the Swedish Road Administration from Department of Analytical Chemistry, Stockholm University, Ecotraffic ERD^3 AB, Stockholm and AVL MTC AB, Haninge.

However, after initial discussions with the Swedish Road Administration they suggested that the three initial research applications should be combined and the initial applicants made a new joint research application to the Swedish Road Administration. Project leader of the new research project was Stockholm University and as participants were Ecotraffic ERD^3 AB and AVL MTC AB. The present research report to the Swedish Road Administration is based on findings, results and conclusions obtained in the final revised research application.

SVENSK SAMMANFATTNING (Swedish summary)

Den föreliggande undersökningen har fokuserats på att karakterisera avgaser från fordon (en tvåbränsle och två bränsleflexibla fordon) som körts på biobaserade drivmedel som biogas och bensin/etanol blandningar under olika testförhållanden. Testförhållanden som har undersökts är två olika körcykler, den nya europeiska körcykeln (NEDC) och Artemis körcyklerna samt två testtemperaturer (+22 and -7°C) i NEDC. I ett delprojekt studerades katalysatorernas hållbarhet vad gäller oxidation av metan på tio bilar. Syftet med undersökningen var att generera data och ge vägledning för att användas som bas för framtida användning av alternativa drivmedel på den svenska (och europeiska) marknaden.

Den kemiska karakteriseringen av avgaserna som har gjorts är baserad på både reglerade (i lag) och icke-reglerade avgaskomponenter. Vidare har förångningsemissioner från tvåbränsle och en av de bränsleflexibla personbilarna också mätts. Det måste påpekas att bilarna inte skall jämföras direkt med varandra därför att målsättningen med den aktuella undersökningen var att undersöka inverkan av bränsletyp, körcykel och testtemperatur på avgasemissionerna och att inte vara en utvärdering av de testade bilarna i sig.

För de reglerade emissionskomponenterna som kolmonoxid (CO), kolväten (HC) och kväveoxider (NO_X) var det en relativt liten inverkan av de testade drivmedlen. Vid testerna i motorvägsdelen av Artemistestcykeln var CO emissionerna höga för E5 drivmedlet (5 % etanol), medan E70 och E85, drivmedlen med ett högre etanolinnehåll (70 och 85 % etanol) och biogas uppvisade signifikant lägre nivåer. Denna trend sågs inte för HC emissionerna. Vid låg omgivningstemperatur (-7°C) ökade generellt CO och HC avsevärt. Detta var än mer uttalat för drivmedlen med högre etanolinnehåll (E70 och E85). En av de bränsleflexibla bilarna hade mycket höga NO_X emissioner i NEDC test cykeln vid -7°C. Den biogasdrivna bilen hade mycket höga NO_X emissioner i ett av de två testerna i Artemis motorvägstestcykeln.

I allmänhet var partikelemissionerna (PM) låga vid +22°C utom för Artemis motorvägstestcykeln där nivån var relativt hög för de två bränsleflexibla bilarna när de kördes på E5 drivmedlet, för tvåbränslebilen när den kördes på E5 drivmedlet och i ett av de två testerna på biogas. En sänkning av omgivningstemperaturen från +22 till -7°C ökade generellt PM emissionerna för alla testade drivmedel. PM emissionerna ökade med ökande etanolinnehåll i de testade drivmedlen. Tvåbränslebilen hade mycket lägre PM emissioner när den testades på biogas jämfört med E5, även om starten gjordes på E5 i båda fallen (beroende på inställningarna i motorns styrenhet). Tvåbränslebilen kopplades om till biogas av föraren omedelbart efter att motorn startades i biogasfallet.

Emissionerna av aldehyder (formaldehyd och acetaldehyd) var generellt högre för de bränsleflexibla bilarna när de kördes på E85 jämfört med E5. Denna inverkan var än mer uttalad vid -7°C. Tvåbränslebilen hade låga emissioner av aldehyder oberoende av vilket drivmedel som användes vid testet. En liknande trend för oförbränd etanol som för emissionerna av aldehyder observerades för de bränsleflexibla bilarna. Höga emissioner av ammoniak uppmättes i Artemis motorvägstestcykeln för alla bilar och i NEDC vid -7°C för de två bränsleflexibla bilarna. Emissionerna av eten, propen och 1,3-butadien var generellt lägre för de bränsleflexibla bilarna när de kördes på E85 jämfört med E5 i NEDC testcykeln vid +22°C, utom för en av de bränsleflexibla bilarna, som hade högre emissioner av eten med E85 drivmedlet. Emissionerna av eten, propen och 1,3-butadien för två-

bränslebilen var generellt lägre när den kördes på biogas jämfört med E5 i NEDC testcykeln vid +22°C. Reduktionen av dessa emissioner vid användning av E85 kan förklaras med en utspädande effekt av att blanda in etanol i bensin. Vid -7°C var emissionerna av eten, propen och 1,3-butadien generellt högre än vid +22°C för alla bilar och för alla drivmedel. Skillnaden mellan drivmedlen var relativt liten i dessa fall, förutom för en av de bränsleflexibla bilarna som hade högre emissioner av eten med E85 än med E5. Emissionerna av bensen och toluen var generellt lägre för de bränsleflexibla bilarna när de kördes på E85 jämfört med E5 i NEDC testcykeln vid +22°C, utom för en av de bränsleflexibla bilarna, som hade högre emissioner av eten med E85. Den ovan beskrivna utspädningseffekten är orsaken till den lägre nivån för dessa emissionskomponenter för E85 jämfört med E5. Vid +22°C i NEDC körcykeln var emissionerna av bensen och toluen generellt lägre för både E85- och biogasdrivmedlen jämfört med respektive E5 som referens. Vid -7°C var emissionerna av bensen och toluen generellt signifikant högre än vid +22°C för alla drivmedel. Det var bara små differenser i bensen- och toluenemissioner mellan drivmedlen vid -7°C.

Emissionerna av antal partiklar (PN) mättes enligt det föreslagna mätprotokollet för framtida emissionsförordningar avseende denna emissionskomponent. En god överensstämmelse mellan mätningar av PN med de två instrument (ELPI och CPC) som användes vid PN mätningar noterades. I de flesta fallen var PN emissionerna mätta med ELPI instrumentet något högre än PN emissionerna mätta med CPC instrumentet eftersom ELPI instrumentet mäter partiklar av mindre storlek än CPC instrumentet. Jämfört med +22°C testerna i NEDC uppvisade -7°C testerna högre PN emissioner. Inverkan av drivmedel på PN emissionerna från biogas var alltid lägre än från E5 drivmedlet.

Utvärderingen av partikelstorleksfördelningen med en elektrisk lågtrycksimpaktor (ELPI) visade att antalet partiklar större än 30 nm normalt sett var lägre för E70, E85 och biogas drivmedlen jämfört med E5 drivmedlet. Emellertid var antalet av den minsta storleksklassen av partiklar (<30 nm) i några fall högre i E70, E85 och biogas fallen.

En slutsats från den föreliggande undersökningen är att avgasemissionerna är fordons/motor/avgasefterbehandlingsberoende och beroende av val av kemisk sammansättning av drivmedlen (dvs. etanolinnehåll på 5, 70 och 85 % och biogas). Dessutom varierar emissionsfaktorerna för enskilda emissionskomponenter. Vid sjunkande (omgivnings)temperaturer, ökar kallstartemissionerna (-7°C) av oönskade avgaskomponenter signifikant. Vid omgivningstemperaturer lägre än -7°C förväntas kallstartemissionerna av dessa emissionskomponenter öka än mer påtagligt. Vidare ökar ett högre etanolinnehåll i etanol/bensin bränsleblandningar emissionerna av polycykliska aromatiska kolväten (PAH) vid minskande (omgivnings)temperaturer, dvs. motorns kallstartemissioner. Emellertid observerades en minskning av PAH emissionerna vid normal arbetstemperatur för motorn (Artemis) och en omgivningstemperatur på +22°C med körning på E85 jämfört med E5. Följaktligen existerar det en starttemperatur som kommer att resultera i lika PAH emissioner för E5 och E85.

För att undersöka de observerade ökningarna av kallstartemissionerna mer ingående (-7°C) av PAH med ökande etanolinnehåll i drivmedlet i den föreliggande undersökningen, rekommenderas det att inkludera mellanliggande etanolinnehåll i bränslet (dvs. 10-60 %) i en framtida undersökning förutom E5, E70 och E85. Det här är en fråga av speciellt intresse för länder med låga omgivningstemperaturer vintertid. Emellertid kan det förväntas att den potentiella ökningen av emissionerna vid lägre omgivningstemperaturer kan minskas genom användning av motorvärmare.

En generell slutsats är att varken de bränsleflexibla bilarna eller tvåbränslebilen är optimerade för låga emissioner när de körs på E70/E85 respektive biogas. Det här är speciellt viktigt för de bränsleflexibla bilarna med avseende på kallstartemissioner vid låga omgivningstemperaturer. Användningen av E70 vintertid i stället för E85 ger vissa förbättringar på avgasemissionerna. Litteraturstudien och de resultat som genererats i denna studie har indikerat flera områden där förbättringar kan göras. Ett exempel är en förbättring av luft/bränsleprepareringen genom att t.ex. använda den andra generationens direktinsprutning som har en stor potential att minska kallstartemissionerna vid låga omgivningstemperaturer.

Ombordmätningar av emissioner visade höga nivåer av oförbränd metan för de flesta av de nio tvåbränslebilarna som testades på biogas medan nivåerna var normala med bensin. Endast de tvåbränslebilar som hade en mycket kort körsträcka hade låga metanemissioner. Detta indikerar att det finns ett problem med katalysatorns hållbarhet avseende dess aktivitet på metanoxidation. Den bränsleflexibla bilen hade lika låga emissioner på både bensin och E85.

Det finns ett behov av att uppdatera emissionsfaktorer för reglerade och icke-reglerade emissioner från nya konventionella fordon som körs på standardbensin och dieselbränsle vid +22°C och vid lägre omgivningtemperaturer. Detta kommer att tillåta jämförelser mellan motor/fordonskoncept och nya alternativa drivmedel gällande avgasemissioner. Litteraturstudien visade att det är brist på relevanta uppdaterade emissionsdata för moderna fordon; speciellt gäller det för icke-reglerade emissionskomponter.

SUMMARY

This present research investigation is focused on an exhaust characterisation of vehicles (one bi-fuel vehicle and two fuel-flexible vehicles) run on bio-based fuels such as biogas and gasoline/ethanol fuel blends during different testing conditions. The testing conditions investigated are two different driving cycles, i.e. the new European driving cycle (NEDC), the Artemis driving cycles. Furthermore, two testing temperatures (+22 and -7°C) were used in the NEDC. In a subproject the catalyst durability regarding oxidation of methane was studied on ten cars. The aim of the investigation was to provide data and guidance to be used as basis for the future use of alternative fuels for the Swedish (and European) market.

The chemical characterisation of the exhaust generated is based on both regulated (by law) and unregulated exhaust constituents. Furthermore, evaporative emissions from the bi-fuel vehicle and one of the fuel-flexible light-duty passenger cars were also measured. It must be pointed out that the vehicles should not be compared directly with each other, because the objectives with this present investigation was to investigate the impact from fuel type, driving cycle and test temperature on exhaust emissions and was not an evaluation of the vehicles tested *per se*.

For the regulated emission components of carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NO_X), there was a relatively small impact of the fuels tested. In the Artemis motorway test cycle, the CO emissions were high for the E5 petrol fuel (5 % ethanol) tested, whereas E70 and E85, the fuels with higher ethanol content (70 and 85 % ethanol), and biogas had significantly lower levels. This trend was not seen for HC emissions. At low ambient temperature (-7°C), CO and HC increased substantially in general. This was even more pronounced for the fuels with higher ethanol contents (E70 and E85). One of the fuel-flexible cars had very high NO_X emissions in the NEDC test cycle at -7°C. The biogas-fuelled car had very high NO_X emissions in one of the two tests in the Artemis Motorway test cycle.

In general, particle mass emissions (PM) were low at +22°C, except for the Artemis motorway test cycle where the level was relatively high for the two fuel-flexible cars running on the E5 fuel, for the bi-fuel car running on E5 fuel and in one of the two tests on biogas. A reduction of the ambient temperature from +22°C to -7°C generally increased the PM emissions for all fuels tested. The PM emissions increased by increasing ethanol content of the fuels tested. The bi-fuel car had much lower PM emissions when tested on biogas compared to E5, although the start was made on E5 in both cases (due to settings in the engine control unit). The bi-fuel car was switched to biogas by the driver immediately after the engine started in the biogas case.

Emissions of aldehydes (formaldehyde and acetaldehyde) were generally higher for the fuel-flexible cars running on E85 compared to E5. This impact was even more pronounced at -7°C. The bi-fuel car had low emissions of aldehydes irrespectively of fuel tested. A similar trend for unburned ethanol as for aldehyde emissions was seen for the fuel-flexible cars. High emissions of ammonia were measured in the Artemis motorway test cycle for all cars and in the NEDC at -7°C for the two fuel-flexible cars. Emissions of ethene, propene and 1,3-butadiene were generally lower for the fuel-flexible cars running on E85 compared to E5 in the NEDC test cycle at +22°C, except for one of the fuel-flexible cars,

which had higher emissions of ethene with the E85 fuel. Emissions of ethene, propene and 1,3-butadiene for the bi-fuel car were generally lower when running on biogas compared to E5 in the NEDC test cycle at +22°C. The reduction of these emissions using E85 can be explained by a dilution effect of blending ethanol with petrol. At -7°C, the emissions of ethene, propene and 1,3-butadiene were generally significantly higher than at +22°C for all cars and all fuels. The difference between fuels was relatively small in these cases, except for one of the fuel-flexible cars that had higher emissions of ethene for E85 than for E5. Emissions of benzene and toluene were generally lower for the fuel-flexible cars running on E85 compared to E5 in the NEDC test cycle at +22°C, except for one of the fuel-flexible cars, which had higher emissions of ethene with E85. The dilution effect explained above is the cause of the lower level of these emission components for E85 compared to E5. At +22°C in the NEDC test cycle, the emissions of benzene and toluene were generally lower for both E85 and biogas fuels compared to their E5 baseline, respectively. At -7°C, the emissions of benzene and toluene were generally higher than at +22°C for all fuels. There were only small differences in benzene and toluene emissions between the fuels at -7°C.

Particle number emissions (PN) were measured according to the proposed measurement protocol for future emission regulations regarding this emission component. Good correlations between measurements PN with the two instruments (ELPI and CPC) used for PN measurements were found. In most cases the PN emissions measured by ELPI instrument were somewhat higher than the PN emissions measured by the CPC instrument due to that the ELPI instrument measures particles of a smaller size than the CPC instrument. Compared to the +22°C NEDC tests, the -7°C tests showed higher PN emissions. The fuel dependence on PN emissions for the fuel-flexible cars was relatively small in most cases. The PN emissions originating from the biogas fuel were always lower than from the E5 fuel.

The particle size evaluation using an ELPI instrument showed that the number of particles larger than 30 nm was usually lower for the E70, E85 and biogas fuels compared to the E5 fuel. However, in some cases, the number of the smallest size class of particles (<30 nm) was higher in the E70, E85 and biogas cases.

A conclusion from the present investigation is that exhaust emissions are vehicle/engine/exhaust aftertreatment dependant and depending on selection of chemical contents of the fuels (i.e. ethanol contents of 5, 70 and 85 % and biogas), cold start temperatures and driving cycle. Furthermore, the emission factors for individual emission components vary. With decreasing (ambient) temperatures, exhaust cold start emissions (-7°C) of unwanted exhaust components emitted increases substantially. At ambient temperatures lower than -7°C, cold start emissions of these exhaust components are expected to increase even more substantially. Furthermore, increased ethanol content in the ethanol/petrol fuel blends increases emissions of polycyclic aromatic hydrocarbons (PAH) at decreasing (ambient) temperatures, i.e. engine cold start emissions. However, at normal engine working temperature (Artemis) and at 22°C ambient conditions a decrease of PAH emissions were observed when running on E85 compared to E5. Consequently, there exist an ambient starting temperature which will result in similar PAH emissions for E5 and E85.

To fully investigate the increased cold start exhaust emissions (-7°C) of PAH observed in this present investigation with increased ethanol content of the fuel, it is recommended to include intermediate ethanol contents of the fuel to be tested (i.e. 10 to 60 %) in a future investigation besides E5, E70 and E85. This is a question of special interest for countries with low winter ambient temperatures. However, it is expected that the potential emission increase at lower ambient temperatures can be reduced by the use of engine block heaters.

A general conclusion is that either the fuel-flexible cars or the bi-fuel car are optimised for low emissions when running on E70/E85 or biogas, respectively. This is particularly important for the fuel-flexible cars regarding cold start emissions at low ambient temperatures. The use of E70 during wintertime instead of E85 provides some improvement of the exhaust emissions. The literature survey and the results generated in the present study have indicated several areas in which improvements could be made. One example is an improvement of the air/fuel preparation by, e.g., using second generation direct injection that has a great potential to reduce cold start emissions at low ambient temperatures.

The on-board emission tests showed high levels of unburned methane for most of the nine bi-fuel cars when tested on biogas, while the levels were normal for petrol fuel. Only the bi-fuel cars with very low odometer readings had low methane emission levels. This indicates that there is a problem with catalyst durability regarding its activity on methane oxidation. The fuel-flexible car had similarly low emissions on both petrol and E85 fuels.

There is a need for updated emission factors of both regulated and unregulated exhaust emissions from new conventional vehicles run on standard petrol and diesel fuels at +22°C and at low ambient starting temperatures. This will allow intercomparisons with new engine/vehicle concepts and new alternative fuels regarding exhaust emissions. The literature survey showed that there is a lack of updated relevant emission data for modern cars; in particular for non-regulated emission components.

1 INTRODUCTION

Exhaust emissions from motor vehicles have impact on the local, regional and global level. The effect of emission components such as hydrocarbons (HC) and particulate matter (PM) are examples that cause an impact on the local level, e.g. by affecting people's health. Impact on the regional level is emission compounds such as sulphuric acid and oxides of nitrogen (NO_X) that do contribute to acidification. Finally, emissions of carbon dioxide (CO_2) and methane (CH_4) are emission components that cause global impact, i.e. global warming.

Exhaust emission limits that foresee the use of so-called three-way catalysts (TWC) were first introduced in some European countries in the late 1980's. Sweden was one of these examples. Here, emission limits as stringent as to require TWC was introduced as a voluntary measure in 1987 (A11 Regulation). In 1989, all cars certified according to the − then mandatory − Swedish A12 Regulation had to fulfil these levels. Although subsequent even more stringent emission limits have been introduced later, the ambient air quality in the most densely populated cities is still not satisfactory. Frequently, ambient air quality standards are not fulfilled.

Exhaust emissions from vehicles in general are defined as regulated and unregulated exhaust emissions. Regulated (by law) exhaust emissions are unburned fuel hydrocarbons (HC), nitrogen oxides (NO_X), carbon monoxide (CO) and for diesel cars particulate matter (PM) (EU, 1998a). The regulated exhaust emission according to the current EU legislation is shown in **Table 1**.

Table 1. *Current emission limits in the EU (g/km).*

Directive	**CO**	**HC**	**NO_X**	**HC+NO_X**	**PM**
Euro 4, petrol	1,0	0,10	0,08	n.r.[a]	n.r.[a]
Euro 4, diesel	0,50	n.r.[a]	0,25	0,30	0,025

Notes:

[a] Not regulated: n.r.

Unregulated exhaust emissions are compounds present in the exhaust for which no legislative emission limits exists, however, they may contribute to the unburned fuel hydrocarbon emissions but not as individual compounds. When certifying vehicles, the ambient temperature in the test cell is normally in the range 20 to 30°C (EU, 1998a) typically 22 to 24°C and a special certifying fuel is used. This implies that when the temperature is lowered and other fuels than the certifying fuel are used, the exhaust emissions can be negatively affected resulting in increased emissions from vehicles and results in increased ambient air levels of air pollution. The average temperature for Sweden is in the range of +7 °C and in the wintertime it is not unusual the temperature reaches below –20°C, especially in the northern parts of Sweden.

Cold start extra emissions (regulated and unregulated exhaust emissions, below 20°C vehicle temperature) from vehicles are strongly dependent on four major parameters. The combustion principle (Otto/diesel), legislative level, ambient temperature (i.e. vehicle/engine start temperature) and test cycle. In this present study a fifth parameter has been studied having an impact on regulated and unregulated exhaust emissions. This is the fuel parameter ethanol content. The ethanol content in petrol studied in the present investigation was 5 % (E5), 75 % (E70) and 85 % (E85) in petrol. In a fairly recent publication by Weilenmann (Weilenmann et al., 2005) studied exhaust emissions using chassis dynamometer tests at three ambient temperatures +23, -7 and –20°C on pre-Euro-1, Euro-3 petrol and Euro-2 diesel cars. The cars were borrowed from private owners taken strait from the road without maintenance with goal to measure real word emissions at three ambient temperatures. Conclusions from the investigation (diesel cars excluded in this present summary) were: Emissions of HC and CO cold start emissions of the pre-Euro-1 cars were higher than for the Euro-3 petrol cars. The driving patterns had less impact on the exhaust emissions than lowering the ambient temperature. At a temperature of –20°C, the cold start emissions from the Euro-3 petrol cars were approximately 15 times higher compared to emissions generated at +23°C. Cold start emissions of benzene from the pre-Euro-1 cars and the Euro-3 petrol cars was not substantial. Furthermore, Mulawa and co-workers (Mulawa et al., 1997) investigated particle emissions from light duty Otto engine catalyst equipped vehicles switching from regular petrol without ethanol and 10 % ethanol in petrol (E10). The vehicles were investigated on a chassis dynamometer at ambient temperatures of 24, -7, -18 and –37°C, respectively. A general conclusion was that particle emissions increased for both fuels tested with decreased ambient temperatures. For regular petrol the particle emission was increased from 8 times to 29 times when lowering the temperature from 24 to –37°C. Corresponding values for the E10 fuel ranged from 13 times to 58 times. However, the results are vehicle dependent. A TWC car (Volvo 855 model year 1994, Swedish Environmental class C2) was investigated with respect to exhaust emissions at three ambient temperatures (22, -7, and –22 °C) (Ludykar et al., 1999). The vehicle was run on legislative petrol fuel and it was found that the mutagenic Polycyclic Aromatic Hydrocarbons (PAH) benzo(a)pyrene (B(a)P) was increased more than 100 times while CO and HC only increased 5 to 20 times at the lowest ambient temperature studied.

A study by Poulopoulos and co-workers (Poulopoulos et al., 2001) have investigated fuel impact on regulated and unregulated exhaust emissions using petrol, 3 % ethanol (E3) and E10. As expected, the ethanol blending to the neat petrol increased both Research Octane number (RON) (from 95,5 to 98,9) and the Reid Vapour Pressure (RVP) (from 61,4 to 65,9 kPa). The exhaust was sampled at engine and catalyst outlet with respect to methane, hexane, ethylene, acetaldehyde, acetone, benzene, 1,3-butadiene, toluene, acetic acid and ethanol emissions. Conclusions drawn were: Adding ethanol to the petrol increased acetaldehyde emissions but reduced emissions of aromatic compounds. Methane and ethanol were the most stable compounds with respect to catalytic oxidation, while ethylene was substantially reduced in the TWC. The major compounds present in the exhaust after the TWC was methane, acetaldehyde and ethanol. Corresponding compounds prior the TWC was ethylene, methane acetaldehyde and ethanol.

Evaporative emissions from petrol fuelled cars in Australia have been studied by Ye and co-workers (Ye et al., 1998). They identified and quantified emissions of 1,3-butadiene in both petrol and in the evaporative emissions using Sealed Housing Evaporative Determination (SHED) tests. Ye concludes that evaporative emissions contribute to approximately 4 % of the total (exhaust and evaporative emissions) of 1,3-butadiene. This implies that exhaust emissions of 1,3-butadiene is the dominating source of 1,3-butadiene from petrol fuelled vehicles. By using carbon canisters, the evaporative emissions of 1,3-butadiene will be further reduced. The US EPA lists 1,3-butadiene as carcinogenic to humans by inhalation (EPA, 2002).

In a study by Schramm (Schramm, 2004) the use of biodegradable lubricant oil was compared to conventional mineral base lubricating oil used in Fuel Flexible Vehicles (FFVs, two Ford Focus model year 2002) with respect to PAH emissions. Two fuels were used in the investigation; E85 and petrol. The cars were tested at normal ambient conditions. A conclusion from the study was that less PAH emissions was emitted when using the E85 fuel compared to petrol. Furthermore, particle emissions were also lower using the E85 fuel. However, PAH emissions were lower using mineral base lubricating oil compared to the biodegradable lubricant oil.

From the Auto/Oil Air Quality Improvement Research Program (AQIRP) three fuels were compared with respect to exhaust emissions (Benson et al., 1995), **Table 2**. The tree fuels were; Fuel A blended to represent 1988 national average composition, Fuel C2 reformulated petrol and E85 fuel was made by blending 85 % ethanol to the same fuel specification as fuel C2. Three vehicles were investigated i.e. Chevrolet Lumina (V1), Ford Taurus (V2) and Plymouth Acclaim (V3) Conclusions from the investigation was that E85 reduced NO$_X$ emissions but increased total air toxics (sum of benzene, 1,3-butadiene, formaldehyde and acetaldehyde) by increased acetaldehyde emissions. Insignificant effects were observed for carbon monoxide, OMHCE reactive weighted exhaust emissions and hot soak evaporative emissions and reactivity.

Table 2. *Auto/Oil Air Quality Improvement Research Program (Benson et al., 1995).*

Vehicle	**V1**	**V1**	**V1**	**V2**	**V2**	**V2**	**V3**	**V3**	**V3**
Mass Emissions, g/km	Fuel A	Fuel C2	E85	Fuel A	Fuel C2	E85	Fuel A	Fuel C2	E85
OMHCE	0,264	0,175	0,190	0,314	0,241	0,357	0,317	0,260	0,299
NMOG	0,224	0,172	0,199	0,254	0,204	0,392	0,260	0,215	0,334
CO	3,586	1,849	1,126	3,538	2,798	4,293	4,309	3,216	6,818
NO$_X$	0,600	0,521	0,238	0,521	0,326	0,225	1,571	1,315	0,900
Ethanol	-	-	0,138	-	-	0,182	-	-	0,190
Toxics, mg/km									
Benzene	18,685	4,695	1,110	12,703	7,558	2,106	12,494	7,397	2,332
1,3-butadiene	1,544	0,884	0,177	1,335	0,933	0,257	1,399	1,142	0,193
Formaldehyde	4,052	3,538	6,046	3,891	4,052	10,275	4,036	4,116	6,770
Acetaldehyde	1,351	0,949	27,191	1,029	1,093	44,928	1,431	1,077	31,436
Reactivity									
RWE w/o CO+CH_4, gO_3/km	0,815	0,572	0,526	0,897	0,690	1,031	1,031	0,730	0,818
RWE with CO+CH_4, gO_3/km	0,999	0,666	0,590	1,084	0,841	1,240	1,248	0,909	1,179
SR, gO_3/gNMOG	3,657	3,331	2,642	3,531	3,382	2,626	3,957	3,382	2,449
Fuel Economy									
Volumetric mpg	17,6	16,8	12,9	21,9	20,6	14,9	22,4	22,1	16,1
ESFE, mi/MMBTU	153	151	158	191	185	182	195	199	196

Notes:

[a] OMHCE: Organic Matter Hydrocarbon Equivalent
[b] NMOG: Non-Methane Organic Gases
[c] RWE: Reactivity-Weighted Emission
[d] SR: Specific Reactivity
[e] ESFE: Energy-Specific Fuel Economy
[f] MMBTU: Billion British Thermal Unit (BTU)

A relatively recent comprehensive literature review by Niven (2005) focused on the following five environmental impacts: air pollutant emissions; subsurface impacts; greenhouse gas emissions; energy efficiency and sustainability. The study focused on the following ethanol petrol blends: E10, E15, E20 and E85, which were compared. The author was, in general, very critical to the use of low-level blended petrol, i.e. E10 compared to neat petrol with respect to the five environmental impacts discussed in the paper. However, Niven addresses the use of E85 as a means to reduce greenhouse gas emissions but concludes that it will increase air pollution with respect to acetaldehyde.

Chandler and co-workers (Chandler et al., 1998) report average emissions from two FFVs compared with two regular standard petrol fuelled vehicles, **Table 3**. From the table, almost all exhaust emissions determined emanating from E85, except CO and NO_X, increases. The largest increase was for acetaldehyde emissions (+3 700%) and the largest decrease was for NO_X emissions (-60%).

Table 3*.* *Average exhaust emissions from 2 FFV and 2 petrol vehicles.*

Vehicle type	**FFV**	**Petrol vehicle**	**% Relative emission**
Fuel **Emissions**	**E85**	**Reformulated gasoline, RFG**[a]	**RFG emissions set to 100%**
NMHCE, g/km	0,24	0,18	130
THCE, g/km	0,30	0,21	140
CO g/km	2,14	2,24	96
NO_X, g/km	0,14	0,35	41
Formaldehyde, g/km	3,63	2,04	180
Acetaldehyde, g/km	20,94	0,56	3700

<u>Note:</u>

[a] California phase 2 Certification gasoline
[b] NMHCE: Non-Methane Hydrocarbon Equivalent
[c] THCE: Similar to OMHCE

1.1 Use of alternative fuels

On the international market, LPG and ethanol are the two alternative fuels that, on an energy basis, are used in largest quantities. Since LPG is a fossil fuel, it is not discussed further here. Worldwide, ethanol is the mostly used biofuel. The main markets are the USA and Brazil. Biodiesel (e.g. fatty acid methyl esters, FAME) is the dominating biofuels within EU. Biogas is the third biofuel that is commercially available in any larger quantities in the EU. However, its use is relatively limited in comparison to biodiesel and ethanol, and it is currently used only in a few EU member states. The use of biogas in vehicles is greatest in Sweden of all EU member states. Most of the biogas produced in other EU member states is used for other purposes; e.g. heat or combined heat and power generation. Instead, compressed natural gas (CNG) is used in vehicles in several countries in Europe.

In 2003, the European Union passed a directive with an aim to substitute 5,75 % biofuels (on energy basis) for petrol and diesel fuel in 2010 (EU, 2003a). Sweden has taken this challenge seriously and has set this level as a national target. Several other measures have been made to remove barriers (e.g. legislative and economic) to facilitate this development.

In Sweden, a law was passed in late 2005 that set an obligation on the distributors of petrol and diesel fuel to also have a biofuel available on the refuelling stations. This law has been introduced stepwise from April 1, 2006 and was intended to have full effect in 2010. Then more than 2 000 refuelling stations should have a biofuel option available. Due to lack of capacity in building this infrastructure, it is likely that these plans will be somewhat delayed. Since E85 is the cheapest alternative biofuel available for the moment, most fuel distributors are likely to choose this option over the other alternatives. Additional and dedicated funding has been made available for the biogas option, which is a much more expensive fuel to distribute in comparison to the E85 fuel.

1.1.1 Background to fuel-flexible alcohol vehicles

Passenger cars running on alcohol fuels were first introduced on a larger scale around the early 1990's in the USA. Most of the engines were initially dedicated for methanol fuel (M85) only. However, FFVs were later considered more practical, since they could also be fuelled with petrol besides M85. First, these engines were optimised for M85 and petrol but since they could run on any proportion between these fuels, E85 was also an option, since its energy content is in between M85 and petrol.

Around mid 1990's the interest in the methanol option was declining while the interest in ethanol was rising. Consequently, the alcohol engines introduced after that period were intended for E85 only rather than both E85 and/or M85. While the first generation of alcohol engines could run on both alcohol fuels, as mentioned above, these later generations of engines can use only E85, petrol and any proportion of E85 and petrol. The energy content of M85 is lower than E85 and thus, a higher fuel flow is needed to achieve the same power and torque. Consequently, an optimisation of the engine for using E85 fuel and petrol practically excludes the use of M85 but not vice versa in the other case.

Today, there were more than 6 million fuel-flexible vehicles in operation in the USA (DOE AFDC, 2007). In 2006, close to 1,3 million light-duty FFVs were sold in the USA. However, most of these vehicles are running on petrol fuel, since the fuel infrastructure for E85 was not developed at the same rate as vehicle sales. In September 2007, the number of stations in the USA surpassed 1 200. That is roughly as many as in Sweden at the same time (>1 000). It should be noted that most of the ethanol consumed in the USA and in Sweden is via low-level blending. During recent years, the evolution of the market for E85 cars has also being fast in Brazil. In this case, the fuel infrastructure is already in place and consequently, the likelihood that these vehicles will be run on ethanol is greater than in the USA.

As in the USA and Brazil, the sale of E85 cars has increased in Sweden during recent years. Initially, the development was hampered since there was only one car model (Ford Focus) available on the Swedish market. Even until spring 2007, the market was limited to basically three car models. Besides the Ford Focus/C-MAX twins, Volvo and Saab also had one model each on the market. However, later in 2007, several new models have been introduced and in 2008, additional cars are to be introduced on the market. Consequently, there will be less limitation in customer's options of suitable vehicles.

1.1.2 Background to vehicles fuelled by biogas and natural gas

The interest for natural gas as motor fuel has shown an increasing trend in the USA and in Europe since the early 1990's. There has already been a natural gas grid available in many countries for a long time. This was the case in, for example in the USA and in many countries on the European continent, and in several countries new grids have been built. Due to the foreseen decline of domestic production of natural gas on the European continent, long distance pipelines are being built or planned. Likewise, the import of liquefied natural gas (LNG) to the European continent is increasing, while a few countries, such as Norway, are increasing their export of LNG.

The availability of natural gas in many countries has spurred the development to utilise this fuel also in vehicles. According to the lobbying organisation International Association for Natural Gas Vehicles (IANGV), Argentina, Pakistan and Brazil have the most number of vehicles fuelled by natural gas; i.e. approximately 1,5 million in each of the three mentioned countries (IANGV 2007). Italy, with over 400 000 vehicles, is the country in the EU that has the highest market penetration of natural gas vehicles (NGVs). Germany has the second largest fleet of CNG cars in EU. In 2006, the fleet was about 55 000 cars. In comparison to the countries mentioned above, the number of vehicles on other markets in the EU, including Sweden, is relatively small. Germany is a country where the refuelling capacity is increasing the most and this country has a project with the aim of reaching 1 000 refuelling stations. Today, there are approximately 700 refuelling stations in operation in Germany. In contrast to Germany, the market in Italy has been more or less stable for the last decades.

In Sweden, the natural gas grid covers only a small part of the country. Therefore, biogas has been the only option for using gaseous-fuelled vehicles. Thus, several municipalities and associated companies have started to produce biogas from, e.g. sewage sludge and waste. Some of this biogas is upgraded to vehicle quality and distributed on the local level. In some cases, the natural gas grid is also used for distribution of biogas, via the so-called "green gas" concept. Biogas is mixed into the grid but the customer has a choice to pay for either natural gas or biogas, i.e. in analogy with green electricity. No more biogas than actually produced can be sold.

1.2 Engine and aftertreatment technology

In this section, an overview is made of the engine and aftertreatment technology used to meet current and future emission limits, as well as the development carried out to decrease fuel consumption and energy use.

1.2.1 E85 engine technology

Emission potential of fuel-flexible alcohol engines

The emission potential for regulated emissions from E85 vehicles must be considered as relatively well-known. Numerous tests have been conducted and reported in the public domain literature. Many of these tests have been carried out in Sweden. Instead, a couple of studies where the emission potential has been assessed and several problem areas have been identified are discussed below.

A fundamental study about the emission potential was made in a study by the US federal laboratory SwRI (Dodge, 1998a, 1998b). In this project reported, a 1993 model year of a Ford Taurus FFV was used as the baseline engine build. Some additional background information about this car, which was not included in this publication, is provided here. The car was the first generation of the Ford Taurus FFV, of which a few also were imported to Sweden as the first fuel-flexible car to be introduced in Sweden. However, most of the Ford Taurus FFVs used in Sweden represent the later generation, which was introduced in 1996. When discussing the results from the study by SwRI below, one should keep in mind that the engine technology used on this car in the baseline build is quite “outdated” compared to new cars today. The Ford 3-litre V6 engine originates from an engine family that once comprised both V4 and V6 versions. It was first conceived in the early 1960’s and has since then been used in many Ford vehicles around the world. The engine has two valves per cylinder, a bathtub-shaped combustion chamber, over-square cylinder dimensions (i.e. an emission drawback) and moderate power density. Modern engines today do differ quite substantially from this engine in many areas.

Based on previous work at SwRI, seven areas were identified by Dodge and co-workers where improvement could be made to reduce exhaust emissions. These were listed in the reports as follows:

1. *Cranking and engine start-up process can be improved to reduce hydrocarbon emissions resulting from misfires.*
2. *Engine-out emissions must be maintained at very low levels while the catalyst(s) is heating to operating temperature.*
3. *Catalyst(s) must achieve chemical activation very quickly, and/or the hydrocarbons (and possibly CO) must be stored until the catalyst is active.*
4. *Accurate air-fuel ratio control must be maintained during transients, requiring accurate open-loop estimates of air and fuel flow into the cylinders.*
5. *Misfires during engine decelerations due to low intake manifold pressures must be avoided.*
6. *The best air-to-fuel (A/F) ratio switching point, amplitude, and frequency for the exhaust gas A/F closed loop control must be determined to limit both NO, and CO.*
7. *Exhaust gas recirculation (EGR) schedules must be adjusted to meet* NO_X*, goals and fuel economy targets without increasing hydrocarbons beyond emissions goals.*

In the following, some of the results generated in the SwRI project are discussed. In addition, the authors of this study have made assessments as to whether the issues listed above have been addressed or not on the latest generation of FFV cars (shown in italic style text below).

1. Cranking: Under the first point on the list above, air/fuel mixture preparation during cranking of the engine is essential for achieving low emissions. The normal fuel injectors used on the baseline engine build gave droplets having a Sauter Mean Diameter (SMD) of 120 µm. To improve mixture preparation and to provide for as rapid fuel evaporation as possible, prototype air-assist injectors replaced the stock injectors. The first test version of these injectors could achieve an SMD of 18 µm but there were some issues with irregular fuel delivery that had to be solved. The second version, where this had been addressed, had an SMD of about 25 µm. Although improvements have been made of conventional non-air-assisted injectors for port and manifold injection, they cannot achieve anyway near such small droplet diameters as the air-assist injector used in the study mentioned. Air-assisted injectors are not used commercially on passenger car engines of this kind today. Thus, there is still a significant improvement potential to be further exploited in this field. It could also be noted that injectors for direct injection of petrol are much better than port injectors in this respect. Other improvements discussed in the project were: increased compression ratio, rapid synchronisation of the engine crank angle and improvements regarding the prime injection pulse. *With the exception of an increased compression ratio, most of the other improvements of the cranking phase of a cold start seem to have been implemented on modern FFV engines.*

2. Engine-out emissions: Three measures in combination minimize emissions during catalyst heat-up. The air-assist injection was already described above. The engine was operated in a rich mode while air was pumped to the exhaust to promote oxidation. The third measure was to compensate the fuel injection for transients. *All these measures have already been exploited on modern FFV engines.*

3. Catalyst: Rapid exhaust port oxidation is achieved by the measures listed under issue 2 above. The second approach was to use close-coupled catalysts. *Today this is a standard feature on most petrol-fuelled cars as well as on FFV cars.*

4. Air/fuel control: A model based control system was used to control air/fuel ratios during transients. *This is a standard feature today on most modern cars.*

5. Misfires during decelerations: Misfires can occur during decelerations when the throttle is closed. This was avoided on the studied engine by using better idle air control and an improved exhaust gas recirculation (EGR) valve. *These and/or similar measures is assumed to be applied on modern engines.*

6. Air/fuel switch: The switching point of the air/fuel control was biased using speed and load as input. The bias was to the fuel-rich side of stoichiometric. *It is likely that modern engines are optimised to take this emission-reduction option into account.*

7: EGR transient control: The use of EGR was necessary to meet the NO_X target. EGR limits are typically determined by transient response rather than steady-state performance. An improved EGR valve and better control of the EGR rate was applied on this engine. *These measures have been applied on modern engines.*

Saab E85 engines

A description of the Saab fuel-flexible engine technology for the GM Powertrain (GMP) engine used in the Saab 9^3 car was made at the 28th Vienna Engine Symposium (Bergström et al., 2007). The 2-litre engine (as well as the 2,3-litre engine) used in the Saab 9^5 car originates from an older engine family from Saab and was conceived earlier than the engine used in the Saab 9^3. To our knowledge, there is no such comprehensive technical/scientific publication on the Saab 9^5 engines as the mentioned publication on the GMP engine available in the open literature. However, the information provided in the paper mentioned is of great importance to discuss here. It is also conceivable that the technical solutions used on both engines are relatively similar so, thus, the paper is of great relevance also to the results generated in the present study.

The power and torque of the 2-litre Saab engine are shown in **Figure 1**. This graph illustrates that both power and torque can be raised for an E85 engine compared to its petrol-fuelled baseline. At the highest speed, the fuel flow capacity of the injectors limits the maximum power of this engine. It should be noted that identical injectors are used on both the E85 and the petrol versions of the engine.

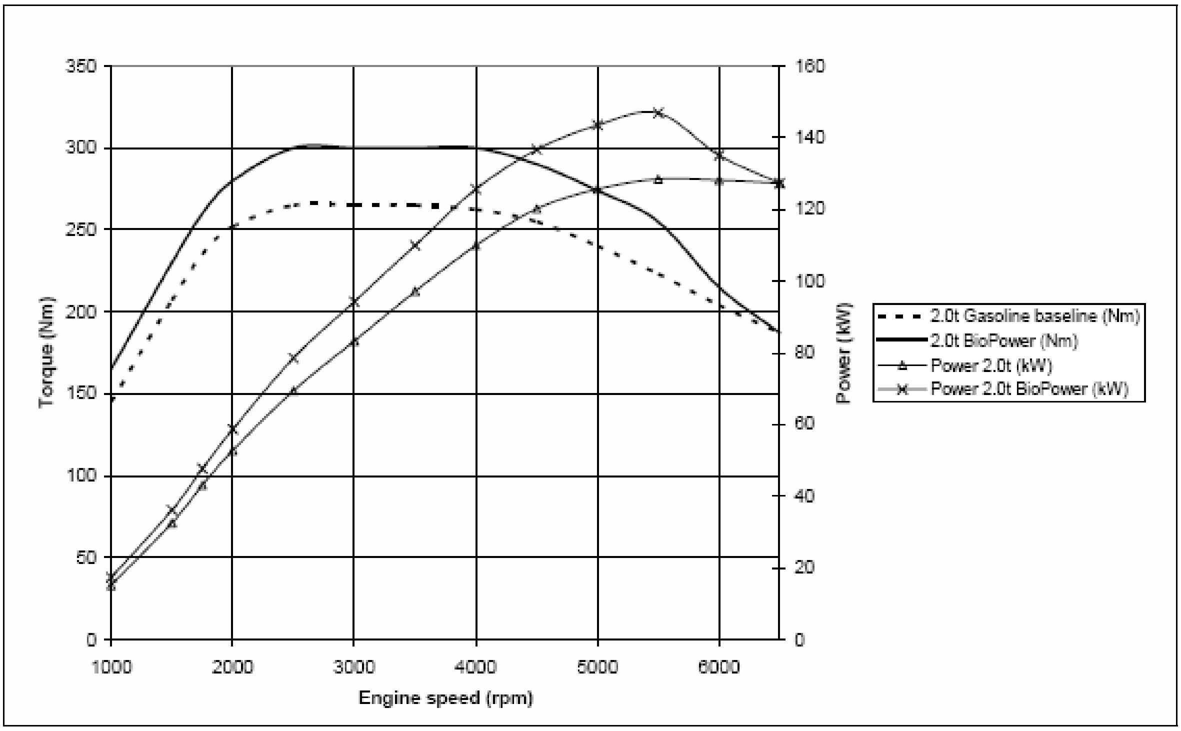

Figure 1. *Power & Torque for the Saab 2.0t BioPower engine (Bergström, et al., 2007).*

The development targets of the 2-litre Saab E85 engine in comparison to its petrol-fuelled counterpart are listed in **Table 4**.

***Table 4**. Development targets for the Saab ethanol engine.*

Engine	**Petrol – Baseline**	**BioPower – Targets (On E85)**
Displacement	2,0 L	2,0 L
Max Torque	265 Nm at 2500-4000rpm	300 Nm at 2500-4000 rpm
Max Power	129kW/175Hp at 5500rpm	147kW/200Hp at 5500rpm
Max cylinder pressure	80 Bar	80 Bar
Startability	-29°C unassisted	-15°C unassisted
	-40°C assisted (block heater)	-40°C assisted (block heater)
Ethanol sensing	-	Virtual, no sensor
Fuel consumption and CO_2	<9,2 l/100km (CO_2 < 221g/km)	<140 g/km CO_2 Net[a]

Note:

[a] The authors of the present study assume that the intention here is, although not explicitly described by Bergström (Bergström et al. 2007), that the CO_2 emissions target in a life cycle perspective for E85 should be lower than the voluntary limit of 140 g/km adopted by the ACEA members for CO_2 emissions in 2008 (ACEA, 2008).

A number of issues that had to be solved for E85 adaptation were:

- Valves and valve seats, e.g. valve recession.
- Cylinder head durability, i.e. cracks in highly stressed zones.
- Spark plugs.
- Piston ring and liner wear.
- Polymer materials.
- Positive Crankcase Ventilation (PCV) and oil dilution.
- Electronic control unit (ECU) calibration.

Most of the issues related to materials (metals and polymers), e.g. valve recession and resistance of polymers, were solved by changing to other materials. The cylinder head durability problem originates from that part of the cylinder head runs cooler with ethanol fuel and this induces an increase of the thermal stresses. Change in aluminium alloy composition and the casting process solved this problem. The wear of the cylinder liner increases with E85 but can be maintained at an acceptable level. The PCV system did not need any modification. Oil dilution is greater for E85 than for petrol but is not harmful as long as the engine is given time to reach normal operating temperatures, preferably within ten cold starts. Many new algorithms for the engine control unit had to be specified and developed for E85 operation. The ECU does not use an ethanol sensor but relies on a virtual sensor instead.

Since ethanol has a higher octane number and higher heat of vaporisation, the spark can generally be more advanced. Similarly, the power can also be increased by increasing the boost pressure. Due to the faster combustion of ethanol in this engine type, the spark may at some operating points be somewhat retarded compared to petrol operation but it is still at its optimum for maximum brake torque (MBT). At a smaller operating area, the spark advance had to be limited due to spark plug temperature. Considering the cylinder pressure limit of maximum 80 bar for this particular engine, the spark advance at higher load cannot be maintained at MBT, in spite of the high octane rating of E85. There is an obvious improvement potential here if the engine structure could be modified to increase the cylinder pressure limit. Further downsizing could then also be implemented to decrease the fuel consumption.

The fuel consumption in the New European Driving Cycle (NEDC) test cycle for the Saab cars using the 1.8t E85 engine discussed above was published in the paper from the Vienna symposium. A calculation of the petrol equivalent fuel consumption and the relative difference compared to petrol has been carried out in the present report (**Table 5**). The data for energy contents and fuel densities for each fuel has been collected from the paper mentioned. The data on fuel consumption for the Saab car are shown in **Table 5**.

Table 5. *Fuel consumption in NEDC for the 1.8t and 1.8t BioPower in Saab* 9^3.

			E85 fuel consumption		
		Petrol	**E85**	**Pet. eq.**[a]	**Difference**
Car body	**Transmission**	(l/100km)	(l/100km)	(l/100km)	%
9^3 Sedan	Manual – 5 speed	7,7	10,2	7,32	-4,9
	Automatic – 5 speed	8,5	11,3	8,11	-4,5
9^3 Wagon	Manual – 5 speed	7,9	10,5	7,54	-4,6
	Automatic – 5 speed	9,2	12,2	8,76	-4,8

Notes:

[a] Petrol equivalent fuel consumption

In volumetric terms, the fuel consumption with E85 was, of course, higher than for petrol. On the other hand, the petrol-equivalent fuel consumption was lower, as was the energy use. The relative difference was in the order of 4,5 to 5 %. The authors of the present report can conclude that the current generation of E85 cars do not utilise the full potential of the E85 fuel.

Saab has also published emission data for a car equipped with manual transmission. The car had a catalyst that was aged for 50 000 km. These results are summarised in **Table 6**. E85 has slightly higher HC emissions. CO is about a factor of two higher, while NO_X is a factor of two lower.

Table 6. Average emission results from a car with 50 000 km aged catalyst (manual transmission).

Fuel / limits	**CO (g/km)**	**HC (g/km)**	**NO_X (g/km)**
E85	0,86	0,09[a]	0,02
E5 Petrol[b]	0,43	0,077	0,041
Limits (Euro 4)	***1,0***	***0,1***	***0,08***

Notes:

[a] HC as measured by a FID instrument. The ethanol part of the organic gases is some 30 to 40 %.

[b] The 95 octane petrol in Sweden contains 5 % ethanol since 2001.

The cold start problem

It is obvious from many publications that alcohol-fuelled engines do have a serious cold start problem both regarding emissions but also when it comes to starting the engine.

Below a certain ambient temperature, an alcohol engine cannot be started at all. Electric engine block heaters or fuel heaters are mounted on all cars sold in Sweden to overcome this problem. Although convenient, this does not completely solve the problem, since it is not an autonomous solution. Variations on this theme exist, such as, e.g. heaters operated on the fuel in the car and thermal storages. Both provide some autonomy (heat store) or full autonomy (fuel heaters). Fuel heaters are used in some extent on modern vehicles but are expensive. Heat stores have been used in limited production but have never reached a real breakthrough.

Regarding exhaust emissions, it should be noted that this problem plagues petrol-fuelled engines as well, but to a smaller extent. Still, vast improvements will be necessary in this field so it is of interest to elaborate on this subject in some more detail.

There are various known ways to improve the cold start emissions from alcohol-fuelled engines. Literature gives several examples of such methods. One of these would be to use heating elements in the inlet ports to enhance evaporation. Another means could be to use heated injectors, which could accomplish a similar improvement of air/fuel preparation. However, the most interesting option would be to use direct injection of the fuel so this option is discussed in more detail below. Already in the 1980's and 1990's, several fundamental studies were conducted in this field.

Direct injection has generally been an option intended to improve fuel consumption of petrol and diesel engines compared to conventional combustion concepts. Direct injection has not yet been used on alcohol-fuelled cars in production but do provide similar – or greater – advantages than for petrol, an option discussed more thoroughly below. An additional advantage of direct injection would be that the cold start properties could be vastly improved in comparison to conventional port injection. This was demonstrated already in the 1980's by, e.g. Sievert and Groff at GM (Sievert and Groff, 1987). The test engine used by these researches could achieve unassisted cold starts down to -29°C by using direct injection of neat methanol (M100). This was the lowest temperature that that particular test cell could achieve, indicating that the real cold start limit could have been even lower. Thus, direct injection could be a very elegant way of overcoming the cold start problem.

Direct injection was pioneered in the 1950's but was re-introduced on passenger cars already in 1996 by Mitsubishi. However, probably only the second generation of injection systems would have the features necessary to achieve low emissions and unassisted cold starts on alcohol fuels. Such injection systems are now being introduced on the market by, e.g. BMW and Mercedes. Thus, this fuel injection system should be available to apply also on alcohol-fuelled engines. Saab has recently announced that they are developing such a concept that would also be capable of using E100 and M100 besides E85, M85 and petrol. Several injection equipment suppliers (e.g. Bosch, Siemens and Delphi) also claim that they will have ethanol-compatible direct injection systems of the second generation available for production in the near future.

Future improvement potential of E85 engine technology

One obvious possibility to improve engine efficiency would be to use the diesel cycle instead of the otto cycle. There are a couple of examples of such engine development in the literature. Most of this development has been focussing on heavy-duty engines but there are some examples from light-duty engines as well. During the late 1980´s and early 1990´s two development projects of alcohol-fuelled passenger car engines are of interest to comment. Both these engines were primarily intended for methanol use (M100) but in some cases, also fuels such as M85 and ethanol were tested. The light-duty engines mentioned used glow-plug ignition. One of the two alcohol-diesel engine concepts mentioned was developed by the engine consultant company AVL (Kapus et al., 1990; Zelenka et al; 1992; Quissek et al., 1992). The other prototype concept was developed by the consultant company FEV (Pischinger et al., 1990; Bruetsch et al., 1992; Bartunek et al., 1993; Hilger et al., 1991). The AVL engine was based on a 2,3 litre Opel direct injection diesel engine prototype that apparently never reached production, whereas the FEV engine was based on a VW 1,9 litre TDI diesel engine[1]. Both cars performed very well in emission tests in relation to the emission standards at that time. In one case, cold start tests also proved the ability to start at very low ambient temperatures and achieving low exhaust emissions at the same time; a specific problem on ethanol-fuelled otto engines. Since the early 1990's, little interest has been focussed on the diesel option for light-duty ethanol engines. Although the emission potential and the fuel consumption were very promising, these engines cannot be made fuel-flexible. Consequently, the interest for this solution is limited until a well-established fuel infrastructure for alcohol fuels is available.

By assessing the literature, it is obvious that substantial improvements of the E85 engines could be made to reduce both fuel consumption and exhaust emissions. From the data published by Bergström and co-workers, it can be concluded that the fuel consumption of a turbocharged engine could be decreased if the engine was downsized (Bergström et al., 2007). Even if no downsizing would be used, there is still some potential for further reduction of fuel consumption and energy use. For example, Saab could not utilize the potential for spark timing optimisation, since their petrol-fuelled baseline engine had a cylinder pressure limit of 80 bar (Bergström et al., 2007). Generally, naturally aspirated and moderately supercharged spark-ignited engines do not have an engine structure that is well-

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[1] This engine was derived from the Audi 5-cylinder 2,5-liter diesel engine, i.e. the first DI diesel engine from the VW group to reach production in late 1989 in the Audi 100 model. The 1,9-liter engine entered production in 1992 for the Audi 80 and two ears later in VW-badged cars.

adapted for high cylinder pressures. However, there are a couple of examples of production engines intended for higher pressures. One example is the petrol-fuelled engines with turbocharger and direct injection (TFSI[2]) from the Volkswagen group. Today, such state-of-the-art engines can tolerate about 130 bar in cylinder pressure (Deacon, 2007). In these cases, gray cast iron is used in the engine block instead of aluminium. For the sake of comparison it could be noted that state-of-the-art diesel engines for passenger cars can tolerate about 180 bar in cylinder pressure[3]. This leads to the conclusion that E85 (or E100) engines would need an engine structure of similar design, but not necessarily cast iron as a material, to utilise the full potential of reducing fuel consumption and energy use. One example of diesel engines with aluminium engine block capable of high cylinder pressures (180 bar) is the new BMW engine family comprising 4 and 6 cylinder versions (Steinparzer, 2007).

One particular feature of alcohol fuels is the so-called “charge cooling” effect. Utilising the full potential of this option is very interesting. If direct injection is used and provided that the droplet size of the fuel spray is small enough, there is a good prospect of utilising this feature to gain the advantage of a much cooler cylinder charge just before ignition. A lower temperature suppresses knock. Thus, the compression ratio and/or the charge pressure for supercharged engines could be increased. A higher power density could be utilised to downsize the engine, with further gains in fuel economy.

Calculations carried out by MIT in the USA have shown that the potential of decreasing the fuel consumption by using this option is substantial (Cohn et al., 2005); Bromberg et al., 2006). By using the data from one of the two mentioned reports (Cohn, 2005), the results in the graph in **Figure 2** has been depicted.

Previously, many authors in the open literature have pointed out the impact of fuel evaporation on charge temperature. However, as can be seen in **Figure 2**, the impact on the temperature decrease by alcohol fuels is significantly higher than for petrol. In the ethanol case, it is a reduction of 138 K and for methanol even higher (246 K). This improves the anti-knock properties substantially to the level of equivalent to an octane number of 129 in the ethanol case[4]. If this feature was utilised on a turbocharged engine to increase power density and further on for downsizing of the engine to reach the baseline power and performance. The two reports cited have calculated that the energy consumption could be reduced by some 25 % compared to a conventional petrol engine. The gain of 25 % is roughly equivalent to the relative difference between petrol and diesel engines in such vehicles. Bearing in mind that the average (relative) increase in efficiency of the engine has been about 0,5 % per year over the last 75 years or so, an improvement of this magnitude would be monumental.

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[2] The original nomenclature for “FSI” by VW referred to “Fuel Stratified Injection”, i.e. direct injection of petrol late in the compression stroke to create non-homogenous air/fuel mixture. Later engines have reverted to early injection that provides a homogenous air/fuel mixture so the term “stratified” is not justified any more.

[3] The maximum cylinder pressure level for state-of-the-art heavy-duty and marine 4-stroke engines is even higher. In the former case, approaching 200 bar and similar, or even higher for marine engines. Such high cylinder pressures require steel pistons (as a substitute for aluminium), a technology not yet commercially applied on passenger car engines.

[4] For sake of making the summary of properties complete, it could be mentioned that methanol had RON level of 133.

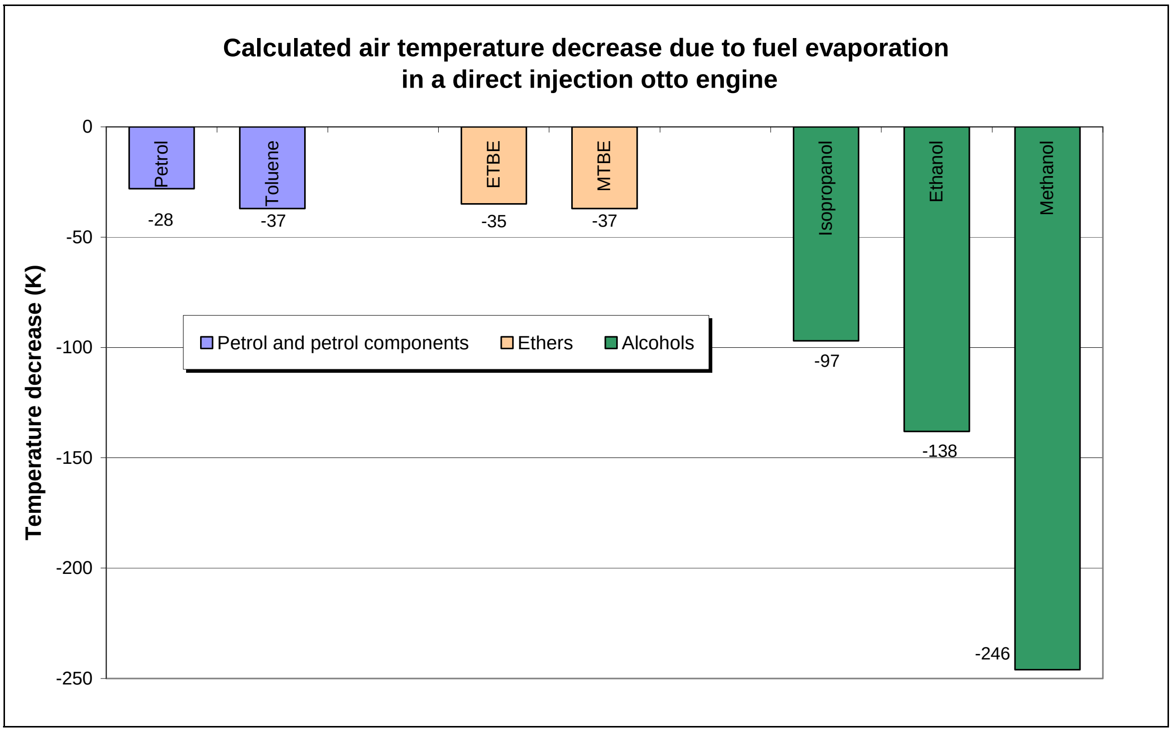

Figure 2. *Temperature decrease of the air due to fuel evaporation.*

The potential of radical improvement of engine efficiency by using direct injection has also been recognised by other researchers. Two such examples are Brewster at Orbital (Brewster, 2007) and Fraidl and co-workers at AVL (Fraidl et al., 2007). Besides a significantly higher power output, also substantially lower NO_X emissions and lower fuel consumption were achieved by Fraidl and co-workers (Fraidl et al., 2007). The improvement potential in cold start properties was recognised.

Another interesting property of alcohol fuels is their great tolerance to charge dilution, i.e. increase in excess air ratio and/or increased EGR. Brusstar and co-workers conducted a study of great interest for future engine development of alcohol-fuelled engines (Brusstar et al., 2002). A 1,9 litre VW TDI diesel engine was used in these experiments. Engine modifications included port fuel injection and spark ignition. Cooled EGR using a low-pressure long route (after turbine to before compressor) EGR system was used instead of the standard EGR system. Compression ratios between 17:1 and 22:1 were tested but the nominal compression ratio of 19,5:1 was used during most of the test series.

Ethanol and methanol have relatively high octane numbers and tolerate heavy EGR in spark-ignited otto engines without creating problems with combustion instability, which is a limiting factor for the EGR rate. Increasing the compression ratio further from the normal level increases the EGR tolerance even further. EGR suppresses knock, which enables further increase of the compression ratio. By utilising these features, it was possible to run the engine at *full load without knocking combustion* at the very high compression ratios mentioned. Throttling was essentially avoided, except at very low load. The engine could operate at stoichiometric conditions for the full speed and load range.

The methanol-fuelled engine had a peak efficiency of nearly 43 %, i.e. higher than the diesel-fuelled baseline engine, and the high-efficiency range was also broader than in the diesel case. Fuelled by ethanol, the engine had comparable peak efficiency to the diesel-fuelled engine. The knock sensitivity when operating on ethanol prevented the engine from achieving as high efficiency as when it was run on methanol.

Due to the stoichiometric combustion system and the use of a three-way catalyst, very low levels of gaseous emissions were achieved throughout the whole load and speed range. PM and aldehyde emissions were not measured but earlier work at US EPA has showed that using an oxidation catalyst can control these emissions.

1.2.2 Biogas engine technology

First, it should be noted that the engine technology for both compressed natural gas (CNG) and compressed biogas (CBG) is similar. On the international market, CNG is totally dominating over CBG in terms of vehicle use. Thus, most of the vehicles intended for methane operation have been developed for CNG, not CBG. The energy content of biogas is generally some 10 % lower than that of natural gas, although the energy content can vary substantially in both cases. This variation of natural gas composition between different markets implies that gas engine technology has to provide some fuel flexibility if the engines are to be marketed on several markets. Consequently, most of the vehicles intended for CNG can also run on CBG[5]. The enabling technology is adaptive electronic fuel control systems. With this feature, operation on CBG can generally also be tolerated, even if the vehicle was intended for CNG in the first place.

Emission potential of gaseous-fuelled engines

Many publications on the development and the emission potential of methane-fuelled vehicles have been made. Several of these publications cover in-use emission test results from various fleets of vehicles. However, that no attempt to summarise them all has been made here.

An interesting paper published by Honda one decade ago, discuss the development of a CNG car intended for very low exhaust emissions (Suga et al., 1997). The emission target for the Honda Civic GX developed was one tenth of the Californian ULEV emission limit at that time[6]. The Honda vehicle was dedicated for CNG and did not have bi-fuel capabilities so a couple of compromises between these fuels could be avoided.

Since natural gas occupies some 10 % of the cylinder air/fuel charge, a significant loss of power is generally associated with operation on CNG. Variable valve technology (VTEC) was applied by Honda to overcome this problem, i.e. a feature not applied on the baseline engine. The VTEC engine has also higher tolerance to EGR than the conventional engine. Due to the high octane number of CNG, the compression ratio was increased from 9,4:1 to 12,5:1. As for the E85 engine technology described above, valve and valve seat wear is higher for CNG than for petrol. Thus, improved materials were used in these components to decrease the wear.

The Honda engine had a number of features intended to reduce exhaust emissions. Some of these were common with a petrol-fuelled ULEV car and some were specific to the CNG car. In **Table 7**, the emission results from the Honda CNG car are shown. Conversions to

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[5] It is foreseen here that CBG fulfils the applicable fuel specification. In Sweden, a specification for biogas to be used in vehicles was adopted already in 1999 (SIS, 1999).

[6] The Californian Low Emission Vehicle (LEV) emission standards that applied in the 1990's have later been revised (LEV II). In both these standards, there is one level called ULEV. To distinguish between those, the later one is usually referred to as ULEV II. The limit referred to in the present report is ULEV I.

SI units have been made to allow comparison with the data generated on the Saab car above, although is should be remembered that the driving cycles are different.

Table 7. *Exhaust emission test results on the Honda Civic GX.*

	CO	**NMOG**[a]	**NO_X**
Mileage	**g/mi (g/km)**	**g/mi (g/km)**	**g/mi (g/km)**
100 000 miles	0,11 (0,069)	0,0013 (0,00081)	0,019 (0,012)

Note:

[a] Non-Methane Organic Gases (NMOG)

Note that all emission components in **Table 7** were on a very low level even compared to today's standards. The ULEV limit in 1998 for NO_X was 0,2 g/mile, so the achieved level was only one tenth of that level. The NO_X level was comparable to level reached on the Saab 9^3 car, as discussed previously. Since CNG is a gaseous fuel that does not have to evaporate during air/fuel preparation, as liquid fuels must do, cold start properties are excellent, and thus, CO and NMOG levels were also very low.

Generally, the determination of NMOG emissions instead of total HC (THC) gives much lower values for CNG cars than for most other fuels, since the contribution of methane to the THC emissions is great; i.e. >90 % or sometimes >95 %. The level for THC emissions was not stated in the paper cited.

Cold start properties

Cold start emissions is a problematic area for petrol-fuelled engines and even more so for current alcohol-fuelled engines. Gaseous fuels have, as mentioned above, a substantial advantage in this field, since these fuels are in gaseous state already during fuel injection and mixture preparation. This is on the condition, though, that a bi-fuel engine is started on the gaseous fuel and not on petrol. However, the latter is mostly the case today. Since most of the emissions from catalyst-equipped otto-engine vehicles are generated during the cold start phase, there will be little difference in emission level between operation on petrol or CNG/CBG for these engines.

The potential for very low cold start emissions at low ambient temperatures with gaseous fuels was demonstrated already in 1995 in a study by Nylund and co-workers at the Finnish research Institute VTT (Nylund et al., 1995). In this case, the CNG-fuelled engines were started on CNG. Compared to cars fuelled by petrol, E85 and M85, the CNG cars had significantly lower emissions of CO, HC and most harmful unregulated emission components. Future improvement potential of biogas engine technology would utilise a technology where the engine starts directly on the gaseous fuel.

As for the alcohol fuels, methane has several interesting properties that differ from petrol and that could provide options for improvements of the energy efficiency. A high octane number and generally high (though not as high as for alcohols) tolerance for EGR levels are two of those properties. However, in contrary to ethanol, gaseous methane has no charge cooling effect[7] and the flame speed is slower. Thus, the theoretical potential for reducing fuel consumption is somewhat less than in the ethanol case.

Since the octane number is higher for methane than for petrol, improvements in fuel efficiency could be achieved on supercharged engines by either raising the compression ratio and/or increasing the charge pressure in combination with downsizing. Supercharging by using a mechanical supercharger (Mercedes) or a turbocharger (Opel) is used on CNG/CBG vehicles by some car manufacturers to reach similar power level as for conventional petrol engines.

A new CNG/CBG engine announced by VW is based on the 1,4-litre TFSI engine family (Leohold, 2007). This baseline petrol engine uses a combination of a supercharger and a turbocharger. The current petrol engine is available in several power ratings. By increasing the charge pressure, the power and torque of the gaseous-fuelled engine can be restored in contrast to conventional engines where the gaseous-fuelled engines have reduced power density in comparison with their petrol counterparts. The higher octane rating of methane allows this improvement without having to reduce the compression ratio. This engine will most likely be introduced on the market in 2008.

Fraidl and co-workers recognised the potential for reducing fuel consumption in gaseous fuelled engines by using direct mixture preparation (the equivalent to direct injection of liquid fuels) instead of mixing in the inlet port (Fraidl et al., 2007). No commercial injection system to utilise this potential has yet been developed.

Catalyst durability

In the past, it has been shown that the catalyst durability on gaseous-fuelled vehicles has not always been up to the same standard as for the aftertreatment for conventional fuels, such as petrol and diesel fuels. It was shown already in 1996 by Lampert co-workers that small quantities of sulphur originating from the fuel and lubricating oil significantly decrease the catalyst activity for methane oxidation (Lampert et al., 1996). However, this study was made on heavy-duty engines where the operating conditions and the base engine is quite different from the TWC and otto engine used on passenger cars.

In general, methane is a difficult molecule to oxidise in a catalyst, which might be one reason for the problems experienced with catalyst durability. When the catalyst activity on methane decreases, it does not necessarily decrease the activity on other emission components in a similar way. This implies that the impact on harmful emission components might not be affected as much as for methane.

1.3 Fuel composition

The fuel composition of petrol and diesel fuels are regulated in the so-called EU directive 2003/17/EC (EU, 2003b). The fuel specification for petrol is listed in **Table 8**.

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[7] Charge cooling could, indeed, be achieved with methane by using direct injection of cryogenic methane instead of using gaseous injection. However, the use of cryogenic fuels in passenger cars is not likely to gain broad acceptance in this vehicle category so this option is not discussed any further here.

Table 8. *Specification of petrol (directive 2003/17/EC, amending Directive 98/70/EC).*

Parameter[a]	**Unit**	**Min limits**[b]	**Max limits**[b]
Research octane number		95[c]	–
Motor octane number		85	–
Vapour pressure, summer period[d]	kpa	–	60[e]
Distillation			
- Percentage evaporated at 100°C	% v/v	46,0	–
- Percentage evaporated at 150°C	% v/v	75,0	–
Hydrocarbon analysis			
- Olefins	% v/v	–	18,0[f]
- Aromatics	% v/v	–	35,0
- Benzene	% v/v	–	1,0
Oxygen content	% m/m	–	2,7
Oxygenates			
- Methanol	% v/v	–	3
- Ethanol	% v/v	–	5
- Iso-propyl alcohol	% v/v	–	10
- Tert-butyl alcohol	% v/v	–	7
- Iso-butyl alcohol	% v/v	–	10
- Ethers containing five or more carbon atoms per molecule	% v/v	–	15
- Other oxygenatesg	% v/v	–	10
Sulphur content	% mg/kg	–	10
Lead content	g/l	–	0,005

Notes

[a] Test methods shall be those specified in EN 228:1999. Member States may adopt the analytical method specified in replacement EN 228:1999 standard if it can be shown to give at least the same accuracy and at least the same level of precision as the analytical method it replaces.

[b] The values quoted in the specification are “true values”. In the establishment of their limit values, the terms of ISO 4259 “Petroleum products -Determination and application of precision data in relation to methods of test” have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account (R = reproducibility). The results of individual measurements shall be interpreted on the basis of the criteria described in ISO 4259 (published in 1995).

[c] Unleaded regular grade petrol may be marketed with a minimum motor octane number (MON) of 81 and a minimum research octane number (RON) of 91.

[d] The summer period shall begin no later than 1 May and shall not end before 30 September. For Member States with arctic or severe winter conditions, the summer period shall begin no later than 1 June and shall not end before 31 August.

[e] For Member States with arctic or severe winter conditions the vapour pressure shall not exceed 70 kPa during the summer period.

[f] Unleaded regular grade petrol may be marketed with a maximum olefin content of 21 % v/v.

[g] Other mono-alcohols and ethers with a final boiling point no higher than that stated in EN 228:1999.

In **Table 9**, the Swedish specification for biogas to be used as motor fuel is shown.

Table 9. *Specification of biogas as motor fuel (SS 155438, 1999).*

Parameter	**Unit**	**Limits**	**Analysis method**
Energy contents	MJ/m^3	43,9-47,3	SS-ISO 6976
Methane	% v/v	97±2	ISO 6974
Motor octane number		130	
Pressure compensated dew point at highest storage pressure T = lowest monthly average temperature	°C	t-5	ISO 6327
Water content	mg/m^3	32	SS-EN ISO 10101-1,-2,-3
CO_2+O_2+N_2, max.	% v/v	5,0	ISO 6974
O_2 max.	% v/v	1,0	ISO 6974
Total sulphur	mg/m^3	23	ISO 6326,-1,-2,-4 SS-EN ISO -3,-5
Total nitrogen compounds (exclusive N_2) counted as NH_3	mg/m^3	20	Modified ISO 6974

Currently, work in going on to prepare a standard for E85 fuel in the EU. In Sweden, a national specification for E85 (including winter quality, such as E70) was adopted in 2006. This fuel has been introduced on the market by the oil companies in the autumn of 2007. The specification of Swedish E85 is shown in **Table 10**.

Table 10. *Swedish E85 specification (SS 155480, 2006).*

Parameter	**Unit**	**Limits** **min**	**max**	**Analysis method**
Octane number Research method, RON		95,0	–	SS-EN ISO 5164
Octane number Motor method, MON		85,0	–	SS-EN ISO 5163
Sulphur	mg/kg	–	10,0	SS-EN ISO 20846 SS-EN ISO 20884
Oxidation stability	min	360	–	SS-EN ISO 7536
Resin number (solvent washed)	mg/100 ml	–	5	SS-EN ISO 6246
Appearance		Clear and bright, no visible contaminants		Ocular inspection
Higher alcohols C3-C8	%	–	2,0	SS-EN 13132

Parameter	Unit	Limits		Analysis method
		min	max	
(volume content)				
Methanol (volume cont.)	%		1,0	
Ethers, C5 or more (volume content)	%	–	5,2	
Water (volume)	%		0,3	SS-ISO 760 SS-EN ISO 12937 ASTM E 1064
Inorganic chlorine	mg/l		1	SS-ISO 6227
pH$_e$		6,5	9,0	ASTM D 6423
Copper corrosion (3 h at 50°C)	according to scale	Class 1		SS-EN ISO 2160
Acid number (weight) or (calculated as acetic acid)	% (mg/l)	–	0,005 (40)	ASTM D 1613

1.4 Emission legislation

The background to European emission legislation was described already in the introduction above. Worldwide, the emission limits in the USA and particularly in California and other states that have applied similar limits as California, are regarded as the most stringent emission norms in the world. The development of the EU emission legislation has generally followed a similar path as these norms but have a different approach in some cases. For example, there are separate limits for vehicles with positive ignition (e.g. petrol-fuelled cars) and vehicles with compression ignition. In California and the USA, the emission limits are – or will become – both fuel-neutral and technology-neutral. EU is likely to follow this trend but the proposed future emission limits in Euro 5 and 6 regulations currently under discussion do not fully apply this concept but have only minor differences between fuels in some cases.

The emission components in the legislation are generally denoted as “regulated” while emission components where no limits yet applies, are called “unregulated”. There has been considerable debate about the health effects from the unregulated emission components and it is likely that some of them will end up on the list of regulated components in the future. Often, there are issues regarding the measurement methods and instrumentation associated with measuring unregulated emission components. Methods that rely on complicated and difficult-to-handle laboratory equipment are not likely to enter the emission legislation in the foreseeable future.

Some types of emission reducing devices, such as e.g. catalytic aftertreatment, can sometimes cause the formation of undesired unregulated emission components. To date, there is no particular legislation against such devices. Sometimes the manufacturers themselves apply an own censorship in that sense that these devices are not used.

There are also measures other than introducing limits for unregulated emission components that can have an impact on the level of such components. Some of these methods are somewhat indirect. One such approach is to limit specific components in the fuel that either can be found as unburned components in the exhaust or else, can form new harmful emission components. Examples of such limits in the fuel are olefins, total aromatics and benzene in petrol and polycyclic aromatic hydrocarbons in diesel fuel. Sulphur is an example of a substance in the fuel that has a negative impact on catalytic aftertreatment. The use of additives in the fuels is another issue to discuss. Some additives are desired while they, for example, keep injection valves clean and thereby, reduce the emissions over the lifetime of the vehicle. Other additives might cause the deterioration of catalytic aftertreatment. An example of such a fuel additive is lead, which was limited to practically zero when catalytic aftertreatment was introduced on petrol-fuelled cars.

Two important categories of driving cycle exist. First, there are driving cycles for whole vehicles. Passenger cars usually use this kind of driving cycles. The emissions are expressed per vehicle km driven, or as g/km. Second, there are driving cycles for engine dynamometers. The emissions in these driving cycles are expressed per work performed by the engine (g/kWh or g/bhp-hr). Driving cycles can be stationary (steady-state) or transient. Usually, most driving cycles for vehicles are transient. For heavy-duty engines both a stationary test cycle and a transient test cycle is used.

1.4.1 Regulated emissions

Previously, European emission limits were mostly referred to using the directive number. Lately, the norms are usually referred to as “Euro X”, where X refers to a number. In the literature, both Roman and Arabic numerals are used for the emission limits. In the following, we will use Roman numerals when referencing to European standards for heavy-duty engines (Euro I, II,…), and reserve Arabic numerals for light-duty vehicle standards (Euro 1, 2,…).

Today, there are emission limits for most categories of on-road vehicles and/or engines in the EU. Passenger cars were the first category of vehicles where emission limits were introduced. Initially, catalytic aftertreatment on petrol-fuelled cars was not necessary to fulfil the limits. In the late 1980’s some European countries introduced emission limits that practically required the use of the three way catalyst on petrol-fuelled cars. For some time diesel-fuelled cars could meet the limits without aftertreatment but in the early 1990’s, oxidation catalysts were used more and more frequently on diesel cars. Later, the emission limits in the European Union were harmonised by the introduction of the 91/441/EEG directive, which was later named “Euro 1”.

The emission limits in the EU for passenger cars from Euro 1 and onwards are presented in **Table 11**, below.

On May 30 2007, the European Council adopted the Euro 5 and Euro 6 emission standards for light-duty vehicles and the new regulation was published in June 30, 2007 (EU, 2007). It is likely that the regulation will be amended later due to introduce limits for particle number (PN) and to change the limits for particle mass to take into account the improved measurement methodology derived from the European PMP programme.

Table 11. *Emission limits values in the EU.*

				Emission component and limit						
Directive		**Term**[a]	**Time**[b]	**CO** (g/km)	**HC** (g/km)	**NMHC**[c] (g/km)	**NO_X** (g/km)	**$HC+NO_X$** (g/km)	**PM**[d] (g/km)	**PN**[e] (#/km)
91/441/EEG		Euro 1	6/92 1/93	2,72	---	---	---	0,97	0,14	---
94/12/EG, petrol		Euro 2	1996-01	2,2	---	---	---	0,5	---	---
94/12/EG, diesel IDI[f]				1,0	---	---	---	0,7	0,08	---
94/12/EG, diesel DI[g]			1997-01	1,0	---	---	---	0,9	0,10	---
98/69/EG, row A petrol[h]		Euro 3	2000-01	2,3	0,20	---	0,15	---	---	---
98/69/EG, row A diesel[i]			2001-01	0,64	---	---	0,50	0,56	0,05	---
98/69/EG, row B petrol[h]		Euro 4	2005-01	1,0	0,10	---	0,08	---	---	---
98/69/EG, row B diesel[i]			2006-01	0,50	---	---	0,25	0,30	0,025	---
Regulation 715/2007[k]	petrol	Euro 5	2009-09[i]	1,0	0,10	0,068	0,06	---	---	---
	diesel		2010-09	0,5	---		0,18	0,23	0,005[l]	t.b.d.[m]
Regulation 715/2007[k]	petrol	Euro 6	2014-09	1,0	0,10	0,068	0,06	---	0,005[l]	---
	diesel		2015-09	0,5	---	---	0,08	0,17	0,005[l]	t.b.d.[m]

Notes:

[a] In this column, the regulations have been denoted with the designations (Euro 1, 2, etc.) commonly used by laymen but lately also very often by both officials and the industry.

[b] The two dates in the table refer to that the implementation is stepwise. The first date is for new type approvals and the latter date is for all type approvals.

[c] NMHC: non-methane hydrocarbons, valid only from Euro 5 and 6 for engines with positive ignition (otto engines).

[d] PM: particle emissions. These limits are from only valid for diesel-fuelled vehicles and, from Euro 5 and 6, for petrol vehicles using direct injection.

[e] PN: Particle number emissions. P is regulated only for diesel vehicles in Euro 5 and 6, i.e. no limit is set to petrol-fuelled vehicles although there is a limit for particulate matter (PM) emissions (see above) for direct injected petrol cars.

[f] IDI: indirect injection, i.e. injection in a prechamber (or swirl chamber).

[g] DI: direct injection, i.e. injection directly in the cylinder (combustion chamber).

[h] The directive 98/69/EG (2000/2001 and 2005/2006, respectively) are based on the new European driving cycle (NEDC), which uses a modified start procedure (at +20 – +30 °C) compared to the older driving cycle. Therefore, the CO limit (2,3 g/km) in the directive 98/69/EG is actually stricter than the limit in the directive 94/12/EG directive (2,2 g/km) that uses the older European driving cycle (EDC). Since also the HC emissions are higher in the NEDC driving cycle, the reduction in $HC+NO_X$ emissions that can be calculated from the data in the table (from 0,50 till 0,45 g/km) much greater than the levels indicate.

[i] Diesel engines are less affected by the modified start procedure in the new NEDC driving cycle than petrol-fuelled engines. Therefore, the comparison between older and newer limits is more relevant in this case than for the petrol-fuelled cars.

[j] 2010-09 for vehicles > 2 500 kg.

[k] When this report was written, the regulation for Euro 5 and 6 was not finalised.

[l] The first proposal for a new PM limit according to the PMP protocol was 3 mg/km. However, the latest unofficial proposal for a PM limit is 4,5 mg/km (Matatko ,2007).

[m] The first proposal for to limit PN was 5×10^{11} per km but this has later been changed to 6×10^{11} per km (Matatko ,2007).

From Euro 3 and 4 on, the emission certification in the EU has included also gaseous-fuelled (LPG an NG) light-duty vehicles (EC, 1998b) besides petrol and diesel fuels. E85 was not addressed in this directive[8]. The Euro 5 and 6 regulations are the first legislation where the emission certification of E85-fuelled vehicles will be possible to carry out in the EU.

Cold start emissions for CO and HC emissions are regulated in the EU at -7°C (EU, 2001) in the urban part of the NEDC test cycle. Limits for evaporative emissions were not shown in **Table 11**. The limit values for both cold start and evaporative emissions are shown in **Table 12**.

Table 12. *Cold start and evaporative emission limits in the EU (g/km and g/test, respectively).*

Test	**CO** (g/km)	**HC** (g/km)	**SHED HC** (g/test)
Cold start at -7°C	15	1,8	-
Evaporative emissions	-	-	2,0

In conjunction with the emission limit values above, durability standards are also set in order not to allow that the emission limit values are exceeded after vehicle operation over a certain driving distance or time:

- Euro 3, 80 000 km or 5 years (of which comes first). The manufacturer may as an option to a deterioration cycle chose determined factors according to: 1,2 for CO, HC, NO_X (petrol), or 1,1 for CO, NO_X, HC+NO_X, and 1,2 for PM (diesel).
- Euro 4, 100 000 km or 5 years (of which comes first).
- Euro 5 (proposed), 160 000 km or 5 years (of which comes first).

In addition to the requirements above, the 2000/2005 requirements also include:

- The member states in the EU have the right to introduce tax reductions for vehicles introduced prior to 2005 meeting the Euro 4 requirements.
- Emission limit values for CO and HC for petrol vehicles at -7°C from year 2002.
- Introduction of an on-board diagnostic (OBD) system for monitoring error codes in the exhaust after treatment system.

With the introduction of Euro 3, all vehicles must be equipped with an OBD-system informing the driver if errors in the exhaust after treatment system occur that may lead to exceeding the emission limit values. The threshold values for the European OBD have is higher than the corresponding emission limits.

A similar approach as for those that could meet Euro 4 in advance has also been used for the limit on particulate mass anticipated for Euro 5 in 2009. This limit was set to 5 mg/km by the European Commission in an announcement published January 13, 2005. The limit

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[8] It could be noted that the former Swedish A14 regulation also included methanol-fuelled vehicles (e.g. M85), as well as the provision to use other alcohol-fuelled vehicles (e.g. E85). When the EU emission directives were adopted when Sweden joined the EU, this option was no longer available.

can be used for fiscal incentives by the EU member states. This has also been implemented in many member states, for example in Sweden, where the yearly circulation tax for diesel cars fulfilling the limits above, was reduced by SEK 6 000 (approximately € 550) from July 1 2006 to the end of 2007. The tax is set to zero initially, or at reduced level, when appropriate, for a number of years until this amount has been accumulated.

1.4.2 Unregulated emissions

As previously stated in the introduction section, unregulated exhaust components are not regulated by law so no exhaust emission limits exists. However, identification and determination of selected unregulated exhaust components in the present report are based on selection on potential and known health effects to the public and selected green house gasses.

Methods to characterize combustion particles

Individual particles from engine exhaust are typically made up by a core of carbonaceous spherules agglomerated to build up highly branched 3-dimensional structures with various hydrocarbons, ash, and sulphur compounds adsorbed or associated.

Ash (e.g. inorganic salts and metal oxides) originates either from the fuel (smaller contribution) or from the lubricating oil (larger contribution). It may be in the vapour phase in the combustion chamber due to high temperatures but supersaturates as exhaust temperatures decreases on exit from the cylinder. These particles can be a source of nucleation for volatile particles formed in the cooling and dilution process of the exhaust.

Sulphur in the exhaust originates from the fuel and from the lubrication oil. Sulphur will be found in the gaseous phase after combustion in the form of sulphur dioxide (SO_2) or sulphur trioxide (SO_3) that eventually will react with water vapour to form sulphuric acid. Sulphuric acid has a boiling point of around 350°C and may therefore nucleate or condense when the temperature drops. Water vapour and traces of ammonia facilitates nucleation considerably.

Another group of potentially nucleating substances is made up of uncombusted fuel residues and vaporized lubrication oil. Lubrication oil contains hydrocarbons with higher carbon numbers than the fuel. Therefore, hydrocarbons from lubrication oil are more prone to nucleation and adsorption than hydrocarbons from fuel. In addition, mineral-based lubricating oil may contain sulphur concentrations of 4 000 to 9 000 ppm but low SAPS (Sulphate, Ash, Phosphorous, Sulphur) lubricating oil contain in the range of 200 to 300 ppm (Roos, 2007). Lubricating oil can also contain high concentrations of metal additives such as calcium and zinc.

The physical size of the particle may be given by one parameter only if the particle is spherical, e.g. a liquid droplet. However, since particles often have irregular shape, it is common to describe the particle size as having a diameter according to a specific definition. One definition is the so called “aerodynamic diameter” which is the diameter of a sphere of unit density that has the same settling velocity as the particle in question. Another common definition is the “electric mobility diameter”. In this case, the diameter of the particle is equivalent to that of a sphere moving in an electric field.

An idealized particle distribution is shown in **Figure 3** (Kittelson et al., 2002a), which illustrates the difference between mass distribution and number distribution. If the particles are spherical with a known density, it is possible to calculate e.g. the number- or surface concentration distribution from the mass concentration distribution or vice versa. Combustion aerosol particles from or particles in ambient air often follow a log-normal, trimodal size distribution as shown in **Figure 3**, where each peak represents a “mode”. The concentration in any size range is proportional to the area under the corresponding curve in that range.

Since the position of a “mode” is dependent on the aerosol history, the phenomenological definitions, “nucleation-”, “accumulation-” and “coarse” mode particles are usually used.

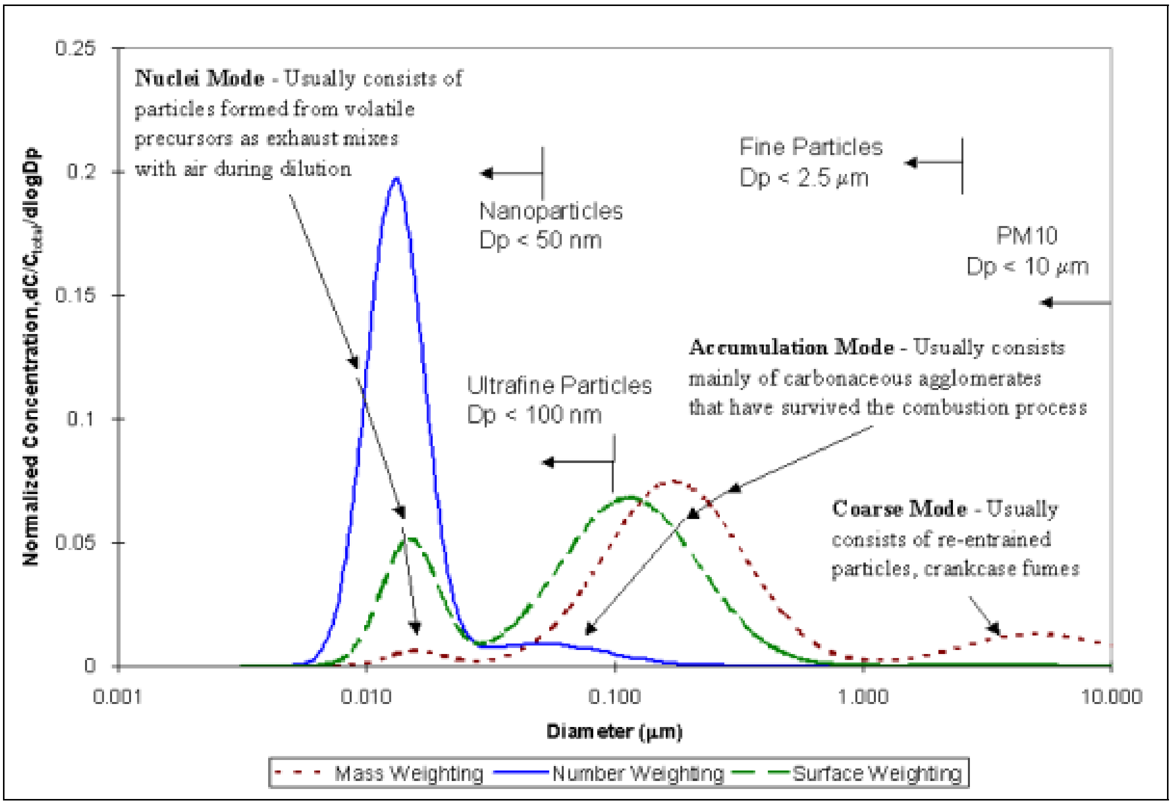

Figure 3. Typical particle mass and number size distribution of engine exhaust.

The highest particle numbers are usually found in the nucleation mode with particle diameters smaller than 0,1 µm or 100 nm. The size range below 100 nm is generally called “ultrafine particles”. Definitions may vary but a somewhat general definition is that particles smaller than 50 nm are referred to as “nanoparticles”. The mass represented by the nucleation mode particles is low (1 to 20 %). Most of the particulate mass is found in the accumulation mode with particle diameters between 0,1 µm and 1,0 µm. The coarse mode with particle sizes lager than 1,0 µm represents 5 to 20% of the particulate mass, while the particle number in this mode is low.

Nucleation mode particles may grow by coagulation and condensation into the region known as the accumulation mode. Growth by coagulation slows down in this mode because the particle concentration drops and because particles become so large that their diffusion rate decreases. Small particles may still diffuse to the larger “accumulation” mode particles but their influence on the resulting particle size is small because they contribute with little mass. Homogeneous nucleation, growth by condensation and coagulation are not consecutive processes but occur concurrently e.g. in vehicle exhaust. The “coarse” mode consists of particles larger than 2,5 μm with an upper limit of around 100 μm. These, relatively large aerosols come from re-entrained particles, which has been deposited e.g. on surfaces in the exhaust system or on the road. The main removal process for particles in this mode is by sedimentation or by wash out.

As the particles are emitted from the tailpipe into ambient air, the dilution ratio (DR) changes drastically (up to a factor of 1 000 within a few seconds), and thus temperature and the concentration of particles and gaseous exhaust species are reduced. Consequently, the effectiveness of coagulation and nucleation processes is to a great extent halted. If however, the emissions occur in a normal laboratory dilution tunnel system (CVS, Constant Volume Sampler), the dilution ratio is typically in the range from 5 to 50. Under these conditions, the onset of nucleation may be rapid which drastically changes the number concentration of particles as high numbers of new particles are formed (Kittelson *et al.,* 1998).

The legislated emission limits are gradually becoming more stringent, there are also reasons to expect that a common regulation for particulate matter from diesel and petrol vehicles will be set in the future. Currently, both Europe Union and the United States use particulate filter mass as the regulating parameter. The Environmental Protection Agency in the United States (US EPA) is keeping particulate mass as the measure for the new tight emission limits for the 2007 to 2010 timeframe for both light-duty vehicles and for on-road heavy-duty diesel engines. They have imposed tighter control of the dilution and weighing and thus lowered the detection limit of the standard CVS system. These enhancement will probably also be applied for the light duty vehicles. In the EU the proposed Euro 5 and Euro 6 regulation include particle number emission limit values for diesel cars. The emission limit for particulate matter (PM) will be reduced for diesel cars and is also introduced for direct injection petrol cars at the same levels as for the diesels. However, the limits for particle number only apply on diesel cars.

Methods to characterize aerosols

Some methods and equipment to characterize aerosols are briefly described below. However, this compilation did not have the scope of providing a comprehensive and complete overview of the subject, so the information provided should only be considered as examples.

The classical way of expressing amount of particles is by “mass concentration”. This is a simple metric that requires little equipment and moderate expertise to implement. Particle-containing gas is drawn at a constant, known rate through a filter of suitable material. The filter is weighed before and after exposure. The mass concentration is the weight difference divided by the filtered gas volume.

The current PM sampling method used for certification purposes for passenger cars uses two 47 mm filters in series at a sampling temperature below 52°C. In this method, sampling could be performed by dividing the certification driving cycle (NEDC) in two phases: the urban driving cycle (UDC) and the extra urban driving cycle (EUDC) phases.

The PMP project aims to develop a revised filter method to measure PM emissions at lower levels with an improved limit of detection, higher repeatability, and less artefacts from collected condensed volatile organic species. The PMP method has been evaluated in the interlaboratory correlation exercise (ILCE) (Andersson et al., 2007).The PMP method differs from the older certification method by using a single 47 mm diameter high efficiency filter kept at a controlled temperature of 47±5°C. A cyclone, or similar device, removes larger particles that come from re-entrained particles from the sampling and dilution system. Although these particles also originate from the engine, the measurement repeatability is significantly improved if these particles are removed, so this measure might be considered appropriate. Removal of the back-up filter (2nd filter) reduces the so-called filter artefact, caused by adsorption of volatiles from the exhaust. Test results have shown that the combined effects of the PMP measures reduce PM levels by 30 % to 50% relative to the current filter method. The two methods have also been compared in parallel for petrol/ethanol cars in the NEDC showing similar results with about 50% lower PM values for the PMP method (de Serves, 2005).

Particle inertia may be used to separate particles into size intervals to obtain a mass size distribution. The particle-containing gas stream is accelerated trough a nozzle and then deflected by a plate close to the nozzle exit. Particles too big to follow the streamlines will impact on the plate and stick. This is the principle behind a device known as a “cascade impactor”. By passing the gas through a series of nozzles with decreasing diameter, a division into size intervals may be obtained. This device is known as a “cascade impactor”. The result of a measurement may be obtained by weighing the plates before and after exposure.

The mass concentration is sensitive to large particles since the mass of one 100 μm particle is the same as the mass of 10^6 particles of 1 μm or 10^{12} particles of 0,01 μm diameter, assuming the same density of all particles.

The mass concentration obtained in this way is an average over the collection time. However, real-time mass measurement instruments exist (e.g. DMM or TEOM).

In order to gain information about aerosols that contain small particles it is necessary to count the particles. This can be done by physical methods in real time. Light scattering is the method of preference. Typically, the aerosol is led through a small, intensely illuminated volume. Each time a particle passes the volume, it scatters light in all directions. A light sensitive device registers the scattered light pulse. Each pulse represents one particle and the intensity is related to the particle size. Typically, particles between 10 and 0,5 can be counted in this way. This type of instrument is known as an “optical particle counter”. To be able to detect even smaller particles, these particles must be grown by condensation in a saturation chamber as in the Condensation Nuclei Counter (CPC). This instrument is described in the experimental section of the present report.

To obtain information about number-size distributions it is common to use a particle mobility spectrometer known as a Differential Mobility Analyzer (DMA),. Briefly, the particles of the aerosol to be investigated are made electrically charged. Since a charged particle moves in an electrical field and its velocity depends on its size and the field strength, it is possible to select a certain mobility (i.e. size) range by e.g. selecting the proper field strength. The arrangement is often of cylindrical symmetry and then consists of two concentric tube electrodes with the field created in the annular space between the electrodes. The particles in the selected mobility range are led to a CPC for counting while the rest of the aerosol is sent to waste. By sequentially measuring adjoining size intervals it is possible to collect data to allow calculation of a number-size distribution. Differential Mobility Particle Sizer (DMPS) and Scanning Mobility Particle Sizer (SMPS) are often names given to this type of instrument.

Another size resolving and counting device is the Electrical Low Pressure Impactor (ELPI). This instrument is described in the experimental section of the present report.

Figure 4. DMA by TSI

From collected particulate samples, analyses of the chemical composition of the particulate phase may be performed. The particulate composition varies with engine and exhaust after-treatment technology, but also with for example engine load and the method and the position used for the collection of the particulate samples. The latter, since volatile material to a higher extent is found in the particulate phase at lower sampling temperatures as a result of condensation, thus affecting both particulate mass and chemical composition. Due to the complex chemical composition e.g. of engine exhaust particles, it has been common practice to split filter samples into fractions by extraction. The Soluble Organic Fraction" (SOF) or Organic Carbon (OC) is extracted from the sample by a suitable organic solvent. It contains more or less volatile hydrocarbons. The Soluble Inorganic Fraction (SIF) is a water extract that contains salts and mineral acids, e.g. nitrates, sulphates and sulphuric acid. The Insoluble Organic Fraction (IOF) is mostly soot.

2 EXPERIMENTAL

2.1 Measurement methodology

The measurement programme in this project is very comprehensive. In the present study, the following emission components and other parameters were measured:

- Regulated emission components: CO, HC and NO_X
- Particulate matter according to the modified PMP draft method
- Particles: particle number, size distribution and mass (alt. method)
- Particle number according to PMP
- Fuel consumption and energy use
- Aldehydes: formaldehyde and acetaldehyde
- Olefines: ethene, propene and 1,3-butadiene
- Light aromatic compounds: benzene and toluene
- PAH: particulate-associated PAH, filter samples
- PAH: semivolatile-associated PAH, poly urethane foam plugs (PUF)
- Ethanol
- Methane
- Nitrogen monoxide and nitrogen dioxide (NO & $NO_{2)}$
- Nitrous oxide (N_2O)
- Ammonia

2.2 Test conditions

2.2.1 Driving cycles

A set of different driving cycles were used in the study. The driving cycles represent cold engine start (as cold start NEDC) and warm engine start, different speeds and transient behaviours (Artemis and overtaking cycles).

The denotation ”off-cycle” emissions generally refers to emissions outside the legislated emission test cycles. In the EU, the only test cycle used in current emission directives is the NEDC cycle. For the cold start testing according to this directive, there is one deviation from this in that only the first part of the test NEDC cycle is used.

It was of interest to characterise exhaust emissions not only in the NEDC test cycle but also according to other test cycles. Therefore, the three Artemis test cycles were used.

These test cycles provide more variation in engine load and speed compared to the NEDC test cycle. In addition to the Artemis test cycles, a full acceleration test was used to simulate overtaking of a long-distance lorry. Presumably, this should be the most severe condition regarding engine load.

Also the tests at low ambient conditions (i.e. -7°C) can be considered an off-cycle test condition. It is of particular interest to the Nordic countries. In the current EU emission directive, only CO and HC emissions are limited at low ambient temperature in urban part of the NEDC test cycle. Furthermore, these limits only apply on petrol-fuelled cars, i.e. they are not enforced on cars fuelled with diesel fuel or alternative fuels. In this project, a full emission characterisation of all emission components was made at this temperature.

By characterising the emissions under conditions with greater variation than in the legislated test cycles, more relevant data for assessing the impact on health and environment can be obtained.

NEDC

The legislative NEDC cycle (**Figure 5**) is the test cycle currently applied for emission certification of light duty vehicles. The basis for the NEDC driving cycle originates from the 1970's and thus, it has very "sharp edges" with little variation (transients) in between. The NEDC driving cycle comprise two phases; i.e. the "urban" and "highway" phases.

The first 780 s includes four identical cycles, representing the Urban Driving Cycle (UDC). This part may be further divided into two parts of 390 s each (Phase I as UDC1 and Phase II as UDC2) in order to compare vehicle emissions from a cold engine and exhaust system with those from the engine and exhaust system at a proper operating temperature. The period from 780 s to the cycle end at 1 180 s represents the higher speed part of the cycle, the Extra Urban Driving Cycle (EUDC, Phase III).

The NEDC tests were performed both at room temperature (22°C) and at -7°C in the present project. Prior to each NEDC test, the vehicle was preconditioned by driving a NEDC cycle, and then the vehicle was soaked for 6 to 12 h before testing. Double tests were performed for each vehicle with respective fuels. Note that for the CBG fuel only one cold climate test of the BFV was succeeded since the vehicle was not able to switch to gas fuel in the repeated tests.

Artemis cycles

The Artemis driving cycle used in the present study comprise three cycles which are referred to as Artemis Urban (AU, **Figure 6**), Artemis Road (AR, **Figure 7**), and Artemis Motorway (MW, **Figure 8**). The Artemis cycles were originally developed by INRETS as Real World Cycles and have been used in the Artemis project. The cycles describe various current driving conditions encountered frequently in Europe as they were derived from a database of real-world driving conditions for a set of 80 cars from different European countries.

The Artemis tests were performed at +22°C. Double tests were performed for each car with respective fuels. The cycles are all warm start cycles and include a preconditioning part of different lengths for the different cycles (73 s for AU, 102 s for AR, and 177 s for MW). For the MW cycle there is also a post-conditioning part of the cycle from 912 s and onwards. During precondition and post-conditioning parts of the cycles, no measurements are performed. All results presented and discussed in the following report only treat the valid part of the cycle. In the real-time charts presented, the valid part of the cycle is marked by a line and/or stated in the text.

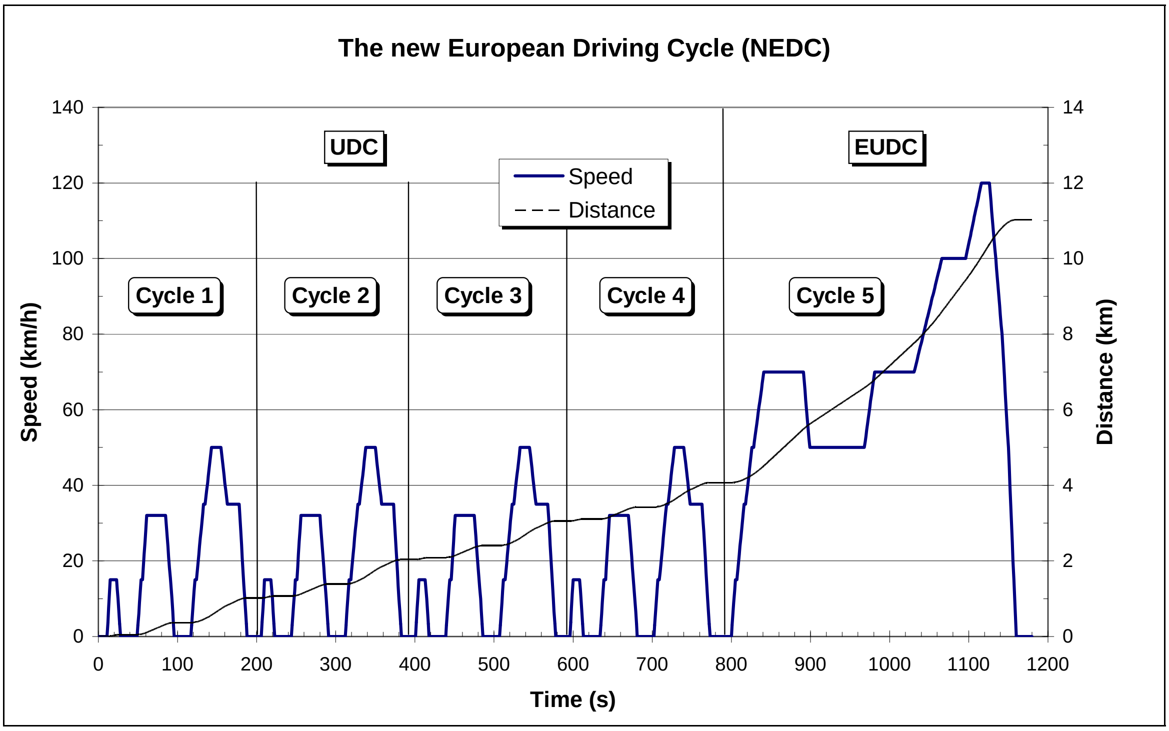

Figure 5. *The NEDC driving cycle.*

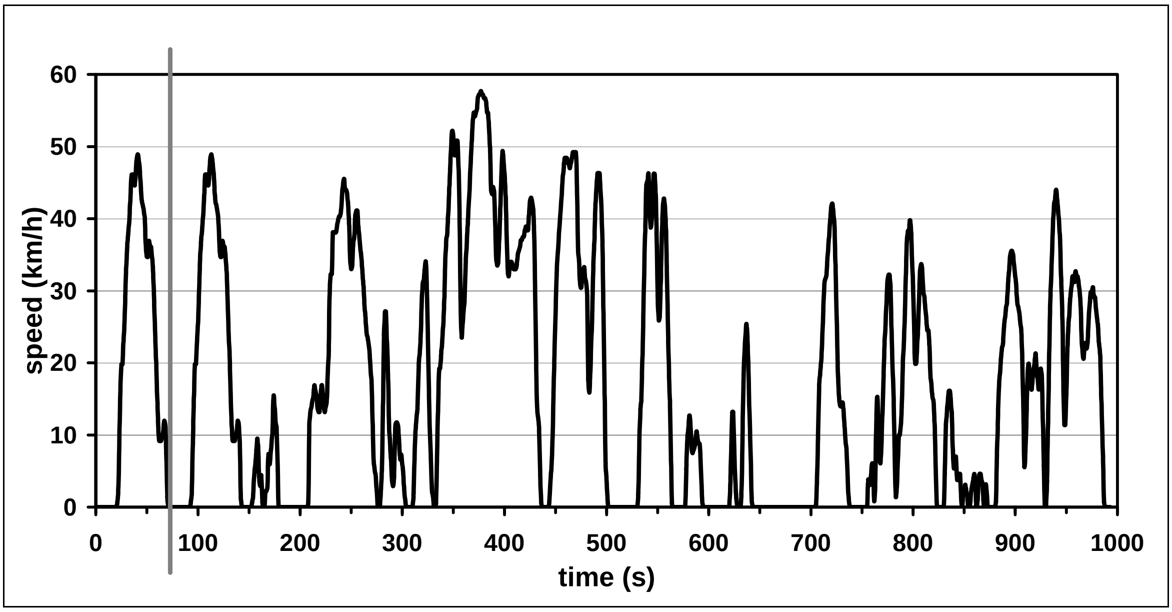

Figure 6. *The AU driving cycle, with the valid part of the driving cycle from 73 to 993 s.*

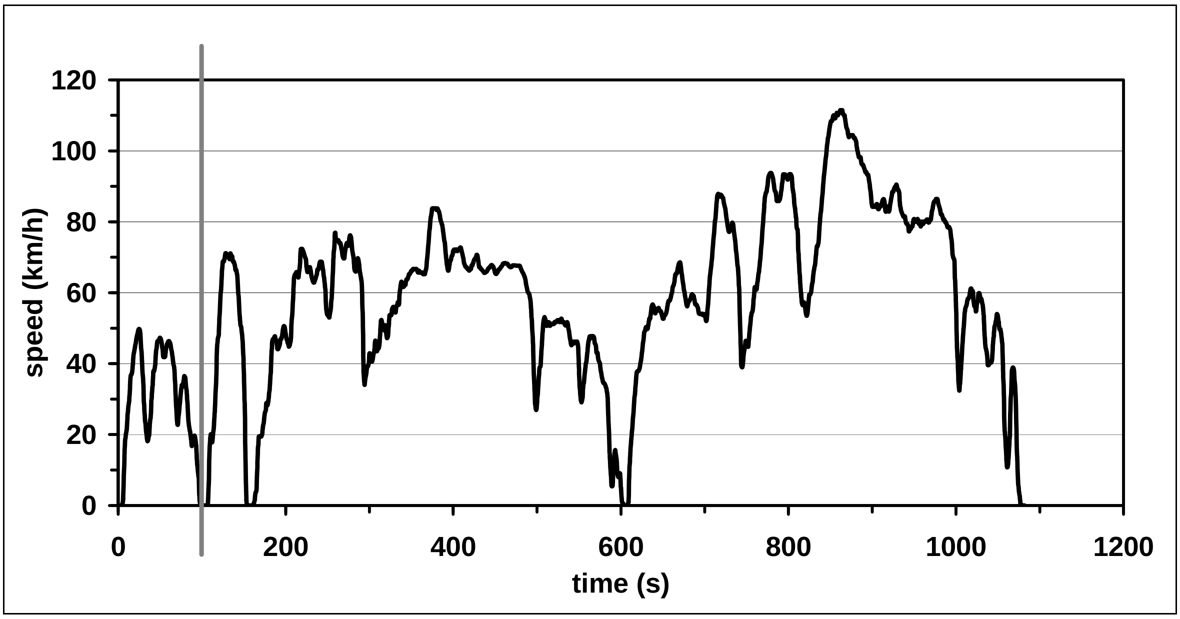

Figure 7. *The AR driving cycle with the valid part of the driving cycle from 102 to 1082 seconds.*

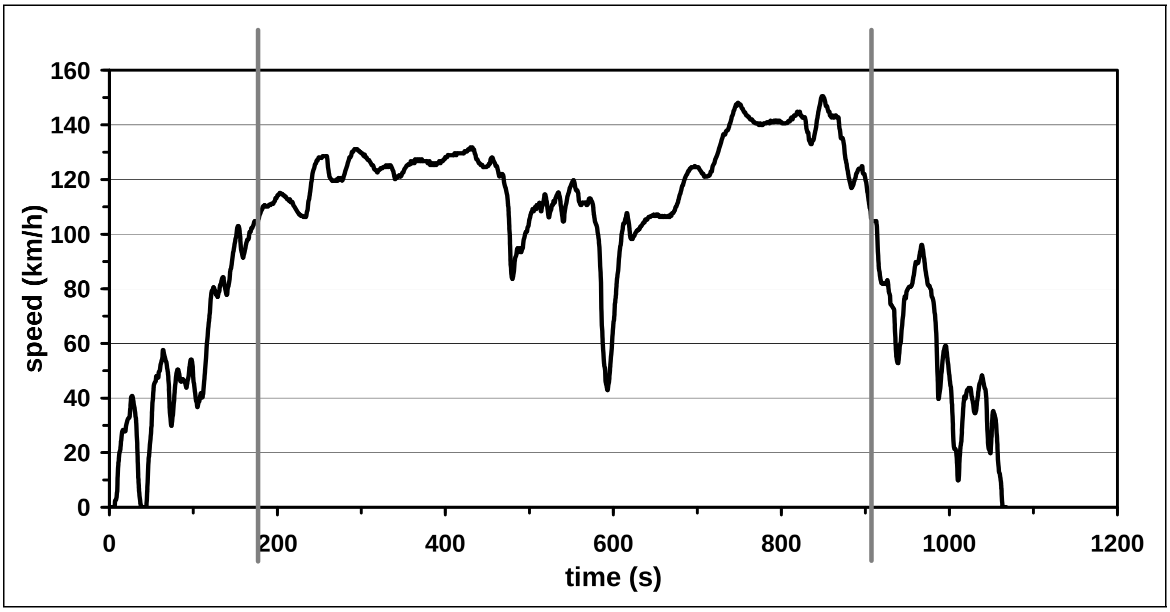

Figure 8. *The Artemis Motorway driving cycle with the valid part of the driving cycle from 177 to 912 s.*

Overtaking cycle

A driving cycle was previously designed in a previous project to simulate a passenger car overtaking a truck (Ahlvik, 2002). The overtaking cycle includes an acceleration phase (from 70 km/h to 110 km/h) and a constant speed (110 km/h) phase (**Figure 9**). The following parameters and formula were used in designing the cycle:

v: 70 km/h, starting speed of the passenger and the speed of the truck.
L-truck: 24 m, truck length.
v_{ov}: 110 km/h, overtaking speed.
d_{rel}: 174 m, the relative distance between the car and the truck during overtaking, including 3 s with 70km/h, 3 s with 110 km/h and the truck length.
t_{acc}: Time used for full acceleration from 70 km/h to 110 km/h, the values were obtained via testing each car with respective fuel.
d_{acc}: Driving distance during acceleration.
d_{kon}: Driven distance during the car driving 110 km/h.
t_{kon}: Time used by the car while passing the truck with 110 km/h.
t_{tot}: Total time used for overtaking.
d_{tot}: Total distance for overtaking.

$d_{acc} = [v + (v_{ov} - v)/2] * t_{acc}$
$d_{kon} = d_{rel} - d_{acc}$
$t_{kon} = d_{kon} / [v_{ov} - v]$
$t_{tot} = t_{acc} + t_{kon}$
$d_{tot} = d_{rel} + v * t_{tot}$

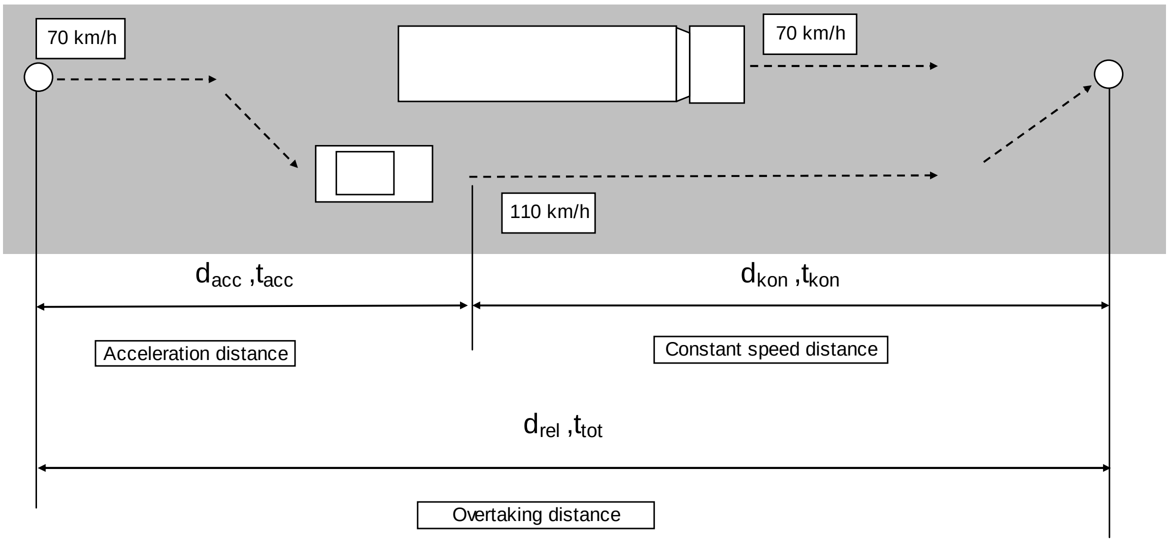

Figure 9. Schematic drawing of the overtaking process.

2.2.2 Chassis dynamometer

The vehicles were tested on an electric Clayton DC500 500 mm double roller chassis dynamometer. The dynamometer settings were applied according to the corresponding regulation 98/69/EC (EU, 1998a).

2.2.3 Evaporative emissions

Hydrocarbon vapours or fumes not emitted by the exhaust system, but escaping from the fuel tank, fuel injection system and crankcase are counted as evaporative emissions, and are normally measured using Sealed Housing for Evaporative Determination (SHED) method. The testing is performed while the vehicle is placed in the SHED with the engine and all other equipment turned off. The door to the SHED was then closed and sealed. Thereafter, selected emissions such as hydrocarbon were measured at the beginning and end of a fixed time period.

The SHED test method is described in detail in the currently applicable directive for Euro 3 and 4 regarding emissions from light-duty vehicles (EU, 1998a). The limits for evaporative emissions apply only to vehicles that have engines with positive ignition (otto engines) and in this case, only on cars running on petrol fuel. This implies that the emission limit for HC in this test of 2,0 g/test will only apply on FFV and BFV cars when they are running on petrol. For E85 fuel, there is no limit for evaporative emissions.

Regarding the specific tests carried out in this project it should be noted that the reference fuel in the current EU directive is specified as a fuel with no ethanol content (E0), whereas the test fuel used in this project is commercially available Swedish E5 petrol. In the current proposal for Euro 5 and 6, E5 will be used as reference fuel for evaporative emission testing.

2.3 Test vehicles

2.3.1 Test vehicles in chassis dynamometer tests

The three tested vehicles, two flex fuel vehicles and one bi-fuel vehicle are presented in **Table 13**. In this report the Saab vehicle is termed Fuel Flexible Vehicle 1 (FFV1), the Volvo vehicle is termed Fuel Flexible Vehicle 2 (FFV2) and the BFV vehicle is termed Bi Fuel Vehicle (BFV), respectively.

It must be pointed out that the vehicles should not be compared with each other, because the objectives with this present investigation was to investigate fuel-related exhaust emissions at two ambient starting temperatures (i.e. +22°C and –7°C) and was not an evaluation of the vehicles *per se*.

Some specific features of the vehicles are discussed briefly below. The odometer reading was relatively low for all three vehicles but high enough to avoid the so-called “green cat” effect. This phenomenon gives low emissions for a new catalyst but the level stabilises after a certain driving distance, i.e. usually less than 5 000 km. The FFV1 car has higher power and torque running on E85 than on petrol, while the BFV car has lower power and torque running on CBG/CNG compared to petrol. No difference in power is stated for the Volvo car although it could be anticipated that there is a negligible advantage for E85 over petrol. Since the FFV1 engine is turbocharged its BMEP level is significantly higher than for the other cars. Turbocharging also requires a lower compression ratio than naturally aspirated engines. The difference compared to the FFV2 car is two units.

Fuel-flexible E85 cars that are marketed in Nordic countries − or other parts of the world with cold climate − are generally equipped with electric engine block heaters. This ensures that the engine can be started at very low ambient temperatures. The use of a block heater generally reduces exhaust emissions substantially which has been shown in many studies (e.g. Ahlvik et al., 1997a; 1997b; Laurikko, 1998). The impact on block heaters has also been studied on cars fuelled with E85 with favourable results regarding cold start emissions (de Serves, 2005). It was decided not to use engine block heaters in the present study.

***Table 13**. Vehicle specifications.*

Parameter / **Car**	**FFV1**	**FFV2**	**BFV**
Car, model	Saab 9-5 Biopower	Volvo V50 1.8 F	BFV Punto
Registration No.[a]	XLB 416	XLS 340	WMJ 932
Model year, month	2005-12	2005-12	2004-12
Certification	Euro 4	Euro 4	Euro 4
Odometer (km)	34 354	11 826	20 696
Inertia mass (kg)	1 670	1 420	1 130
Engine type	L4[b]	L4[b]	L4[b]
Displacement (cm^3)	1 985	1 798	1 242
Power (kW)[c]	110/132	92	44/38
Torque (Nm)[c]	280	165	102/88
Max BMEP[c,d] (bar)	17,7	11,5	10,3/8,9
Compression ratio	8,8:1	10,8:1	9,5:1
Certification data on exhaust emissions			
- CO_2 emissions (g/km)	218	179	119
- CO emissions (g/km)	0,42	0,427	0,45
- HC emissions (g/km)	0,04	0,050	0,046
- NO_X emissions (g/km)	0,01	0,023	0,036
- Fuel cons. (l/100 km)[e]	9,2/7,2/12,8	7,5/10,4/5,9	6,3/7,3/5,3
Gearbox	M5[f]	M5[f]	M5[f]
Fuel	E5/E85	E5/E85	E5/methane

Notes:

[a] More information on the tested cars can be obtained from the Swedish Road Administration (www.vv.se) or from Bilvision (www.bilvision.se).

[b] In-line 4-cylinder engine (L4)

[c] Higher numbers are for E85 (Saab) or petrol (Fiat); lower for petrol (Saab) or CBG/CNG (Fiat)

[d] Brake mean effective pressure (BMEP)

[e] Fuel consumption: average, city and road.

[f] Manual, five-speed transmission (M5)

2.3.2 Test vehicles in on-board tests

On board measurements on nine CBG-fuelled and one ethanol-fuelled (E85) light-duty vehicles have been carried out. The ethanol-fuelled and fuel-flexible car was of a similar model Saab 9[5] (FFV1) as used in the chassis dynamometer tests. The vehicles fuelled on CBG were bi-fuel vehicles, i.e. they could run on either CNG/CBG or petrol. Of these vehicles, three were VW Golf Variant 2.0 Biofuel, five VW Pick-up and one VW Transporter. For more details, please refer to Appendix 1.

2.4 Emissions

2.4.1 Regulated emissions

Exhaust sampling system

A Constant Volume Sampler (CVS) (Horiba, CVS-9300T) was used in the study. The dilution tunnel has a total length of 3 150 mm with an inner diameter of 250 mm and is connected to the tailpipe via a 5 m long section of 110 mm diameter insulated stainless steel transfer tube. The transfer tube is connected to the tailpipe with flexible stainless steel tubing. Cleaned and HEPA filtered test cell air is introduced to the transfer tube into the exhaust stream. The dilution tunnel flow rate is controlled by use of a 9 or12 m^3/min critical venturi.

Regulated emission measurements for NEDC and Artemis tests

The regulated emissions were measured according to the test procedures corresponding to the current emission regulation (98/69/EC). A Horiba Mexa 9000 series (9400D) was used for CO, HC, NO/NO_X, and CO_2 analysis. The measurement principles for the different components are given in **Table 14**. Bag samplings were applied using a set of 3 bags for exhausts and 3 bags for dilution air sampling for NEDC tests, using one bag for exhausts and one bag for dilution air sampling for individual Artemis tests. Note that the HC emissions were always calculated to hydrogen/carbon ratio of 1,85 for petrol and alcohol fuel.

According to the Euro 4 directive, the type I approval test of FFV vehicles is based on petrol fuel only. In the Euro 5 and Euro 6 proposal the type I approval test of FFV will be performed both upon petrol and E85 fuels. The Euro 4 directive describes the hydrogen and carbon ratio for petrol fuel as $C_1H_{1,85}$ whereas in the Euro 5 and Euro 6 proposal, the fuel ratios for petrol and E85 are $C_1H_{1,89}O_{0,016}$ and $C_1H_{2,74}O_{0,385}$, respectively, consequently new gas density for these two fuels are given as 0,631 and 0,932 g/l. Note that in this report, the HC emissions are calculated as grams $C_1H_{1,85}$ per km for petrol, E85 and E70 fuels, even though we are aware of that the HC emissions from different fuel have different compositions.

The particulate mass measurement was carried out using 47 mm diameter TX40 filters (PTFE bonded glass fibre filters, recommended by Particle Measurement Programme protocol). The samplings were performed using single filter. One filter set was applied for the whole NEDC driving cycle, and one for individual Artemis tests. The filters were weighed with a balance (Sartorius) with a resolution of 0,1 µg.

Table 14. Measurement principles.

Emission component	Measurement principle
Hydrocarbons (HC) Total hydrocarbons (THC)	HFID (heated flame ionization detector, 190°C)
Carbon monoxide (CO)	NDIR (Non-dispersive infrared analyzer)
Nitrogen oxides (NO, NO_2, NO_X)	CLA (Chemi-luminescence)
Carbon dioxide (CO_2)	NDIR (Non-dispersive infrared analyzer)
Fuel consumption (FC)	Carbon balance of HC, CO and CO_2

Online measurements of regulated components

Emissions of HC, CO, and NO_X were measured via sampling from CVS tunnel. The same Horiba instrumentation used for bag measurements was applied. In the overtaking tests, emissions were calculated by integrating the on-line data.

2.4.2 Unregulated emissions

Sampling system used for particle number, size distribution and real-time particle mass measurements

The PMP-protocol for particle number measurements was presented above. The system is designed to generate number concentration measurements of aerosol particles from which volatile material is removed from the particulate phase by heating and dilution of the aerosol. In brief, the system may be described as: a sampling probe inside the CVS-tunnel; a unit to remove coarse particles (e.g. a Chinese hat); a dilution unit to provide a dilution factors (DF) in the range of 1:1 to 1:1 000; an evaporation tube (ET) to heat the aerosol; a second dilution stage to provide DF 1-30 and an instrument to measure the particle number concentration (Andersson et al., 2007; GRPE, 2007).

In this project, it was decided to use a sampling system corresponding to the draft PMP protocol. No commercially available system could claim that they fulfilled the PMP protocol in late 2006 when the testing was in preparation. The PMP protocol was far from being finalised at that time and substantial modifications in the protocol has been made since the tests were conducted. Still, it is anticipated that the prototype system could fulfil most of the requirements in the latest draft protocol and that the results obtained will be fairly representative of those from a “true” PMP system corresponding to the final PMP protocol.

Figure 10. *DMM and FPS in a rack*

The system used was based on the standard Dekati FPS-4000 dilution system with some additional hardware to fulfil the PMP requirements. The FPS-4000 was mounted in a mobile 19’’ rack in combination with a DMM-230 instrument for real-time measurement of particle mass emissions. The measurement system is shown in **Figure 10**. An axial dilutor is another option for final dilution but the ejector diluter was used in this case. The dilution ratio of the FPS can be varied in discrete steps from 1:20(10) to 1:200 and with one additional ejector diluter (or axial diluter[9]) a total dilution ratio of up to 1:2000 can be achieved.

The FPS-4000 operating principle is based on using a perforated tube for the first dilution stage and an ejector diluter for the second stage. Control of the dilution ratio is provided with the valve unit via a PC (e.g. a laptop) using an application in LabView software.

A conditioning device for drying and filtration of dilution air was used to achieve filtration quality unit corresponding to High-Efficiency Particulate Air filter (HEPA) level, which is an important feature for measuring on engines with very low emission levels.

In contrast to CVS and mini tunnels with varying dilution ratio and temperatures, the FPS provides controlled sampling. Temperatures and pressures are monitored and the dilution ratio is recorded second-by-second. The control and valve units control and monitor dilution air flows, cooling and heater operation, temperatures and pressures.

The FPS is designed with a straight flow path through the whole system all the way from the sampling point at pre-probe to the flow divider at the end. It has no bends, no contractions or any other kind of obstructions or moving parts in the flow path. Thus, the particle losses are minimised. Another feature to reduce the particle losses is that the perforated tube in the first dilution stage creates a film of clean sheath air at the walls of the tube, which further reduces the losses. A second function of the perforated tube is to provide mixing in order to minimize the potential for impingement of particles at the ejector nozzle in the second dilution stage. Heating of the pre-probe reduces the thermophoretic losses in the part of the dilution system where the concentrations are the highest.

Since the removal of volatile particles in a PMP measurement system is of such great importance, it is appropriate to make some comparisons to the draft PMP protocol and the setups there.

Schematics of the proposed PMP measurement system have been documented in several publications, e.g. the latest draft of the PMP light-duty report (Andersson et al., 2007) or in the regulation No. 83 by the United Nations Economic Commission for Europe (UN ECE, 2007). A schematic picture of the PMP setup is shown in **Figure 11**.

The measurement system comprises, among other things, a volatile particle remover (VPR). The VPR has a hot stage of dilution (PND1) and a cold stage (PND2) with an evaporation tube (ET) in between. The evaporation tube, which must operate at a fixed temperature level between 300ºC and 400ºC, evaporates the potentially remaining volatiles from the hot stage of dilution.

In **Figure 12**, a schematic representation of the VPR in the Dekati PMP system is shown. The two dilution stages (PND1 and PND2) have been highlighted. In between is the evaporation tube (ET). The setup shown above was tested in the light-duty interlaboratory correlation exercise (ILCE_LD) tests (Andersson et al., 2007).

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[9] Customer specified dilution ratios can be made for the axial diluter.

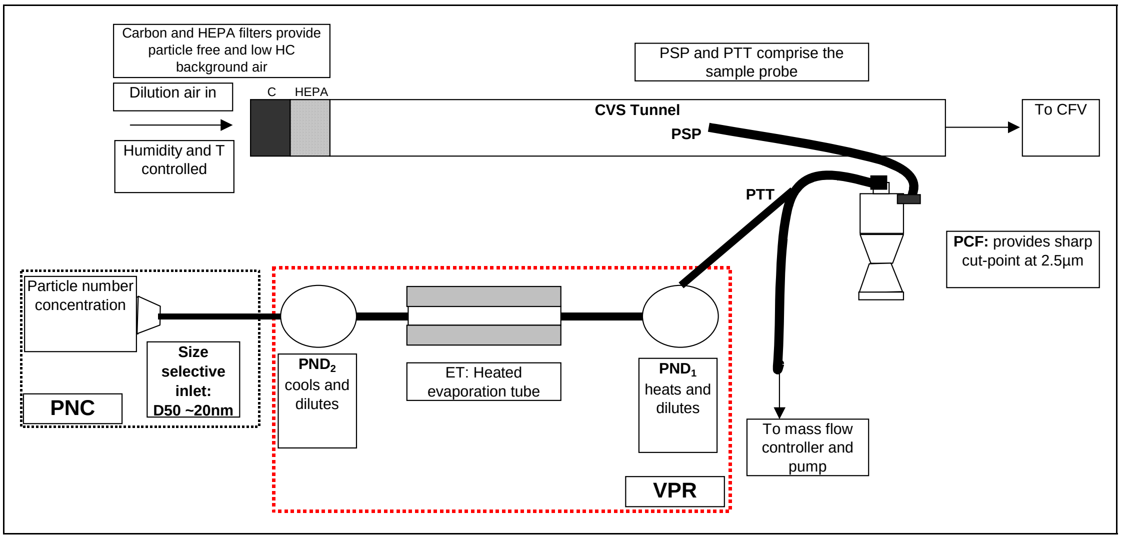

Figure 11. *Schematic of the golden PMS (Andersson et al., 2007).*

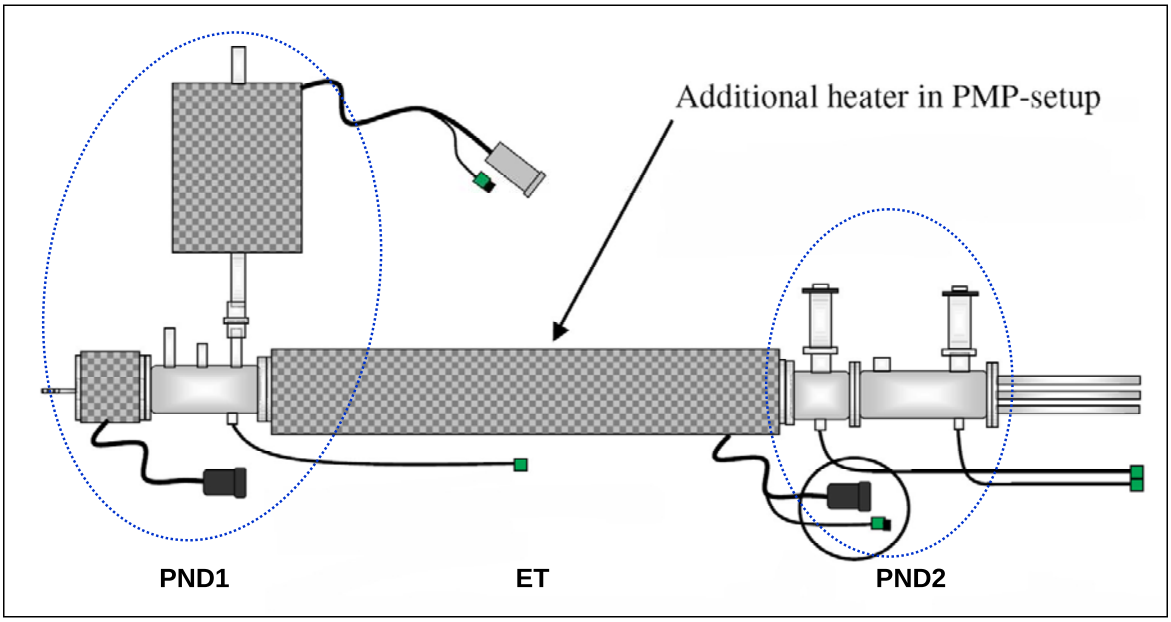

Figure 12. *Schematic of the VPR setup used in the present tests.*

As mentioned above, the PMP protocol has not been finalised yet. The recent modifications in the protocol allow for more focus on meeting the criteria rather than specifying the geometry of a system. This gives more freedom in the design of a system. The information the authors have received indicate that Dekati will respond to this new opportunity and make further improvements and simplifications of the PMP measurement system. However, at the time this report was prepared, no official data on the new system was provided.

In ***Figure 13*** and **Figure 14**, photos of the setup at AVL MTC are shown. The main parts, as the two first dilution stages (PND1 & PND2), the evaporation tube (ET) and the additional ejector diluter (DD) are indicated in the photos. No cyclone was used in this testing. It was simply not considered necessary. Petrol-fuelled cars have, as their ethanol and gaseous-fuelled counterparts, very low particulate emissions in comparison to diesel cars without DPFs. Therefore, the amount of particles that could be deposited and re-leased during the test was considered negligible. The FPS probe was not flange mounted as preferred but instead it was connected via a short metal pipe and electrically conducting tube (Tygon®).

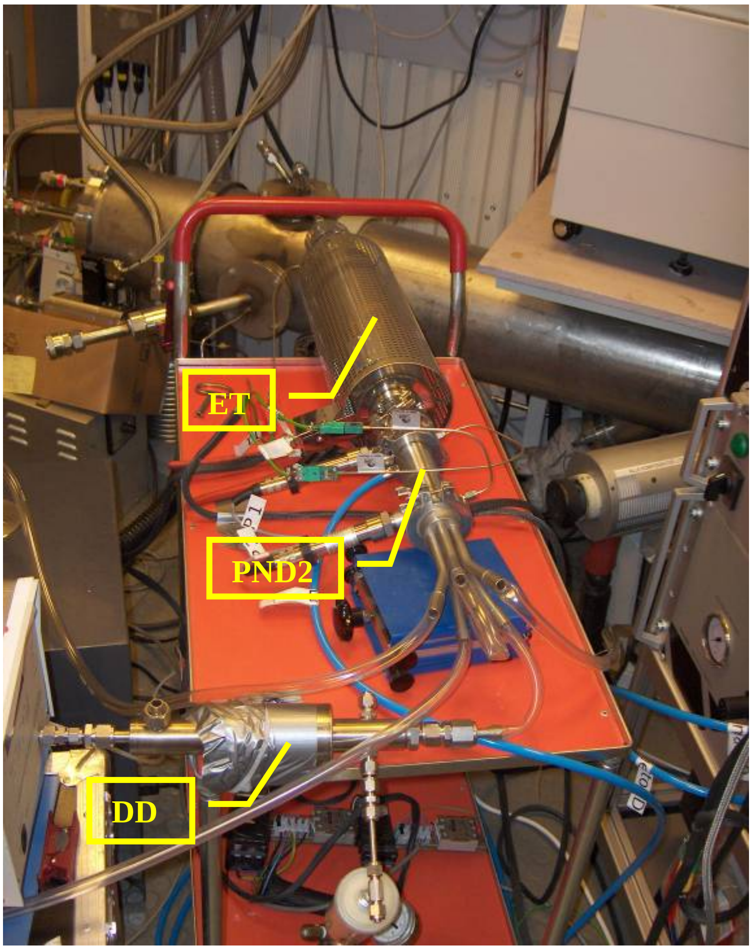

Figure 13. *Photo 1 of the setup of the PMP sampling system.*

When the test setup was discussed, two options were possible. The first option was to have a separate setup for all instruments. The second was to have a setup as similar as possible for all instruments. A compromise was used where the ELPI instrument measured directly from the CVS tunnel and the CPC and the DMM were sampling via the same “chain” of dilution devices. This option causes some problems which are discussed in more detail below.

The same sampling for both measurement of particle number with a CPC and mass with the DMM creates conflicting criteria. However, there are also similarities, since the DMM requires that the particle distribution is mono-modal. This is generally accomplished in a PMP dilution system, where nanoparticles are removed in the VPR system. The conflict stems from the following fundamental differences between the instruments: The CPC has a very good sensitivity but cannot measure at high particle concentrations. Thus, total dilution ratios of up to 1:1000, or higher, are generally necessary. The problem for the DMM is quite the opposite; i.e. it does not have as good sensitivity as a CPC but instead, it can measure at far higher concentrations. A dilution factor of about 1:10 is generally sufficient for the DMM. Thus, sampling is preferably made directly in the tailpipe with very low dilution factors. In this case, the sampling point was in the CVS tunnel and after that, two stages of further dilution was added to remove the volatile particles. Although the DMM instrument was connected before the second ejector diluter (as was used for the CPC), the dilution ration was still far higher than optimum for this instrument. The lowest total dilution ratio was approximately 1:150, i.e. one order of magnitude higher than necessary. This problem has also been seen in previous work in this field (Bosteels et al., 2006a; 2006b). The setup described above was made although the mentioned problems, since it was considered important to have similar sampling and dilution for both the CPC and the DMM.

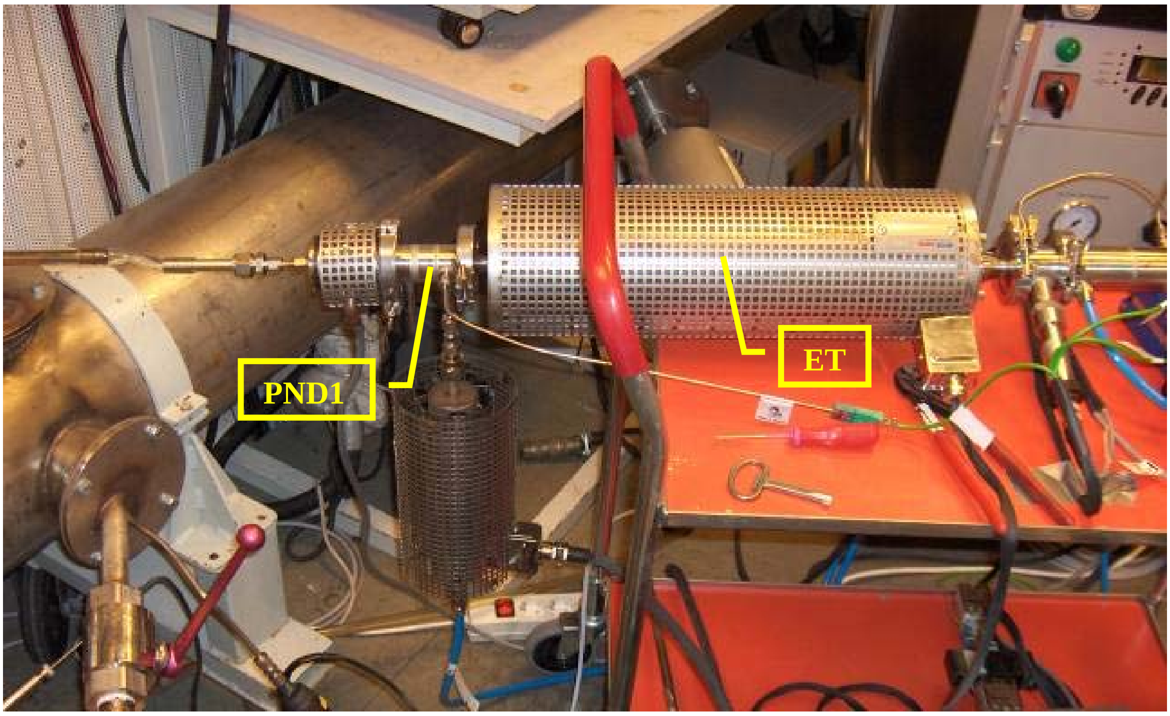

Figure 14. *Photo 2 of the setup of the PMP sampling system.*

DMM

The operation principle of the Dekati Mass Monitor (DMM) is based on particle charging, density measurement, size classification in an inertial low-pressure impactor, and current measurement with sensitive multi-channel electrometers. By combining information about particle mobility size obtained from the charger and the aerodynamic size from the impactor, the effective density of the particles can be determined. This density is required for the calculation of particle mass concentration from the measured current values.

The main interesting feature of the DMM instrument is its ability to measure particle mass emissions in real time. Thus, more information can be obtained than by using conventional gravimetric measurement methods that give only one value for a whole test cycle. The resolution is also better for the DMM than for the gravimetric method. The main drawback of the instrument is that mass is not measured directly.

A specific problem regarding comparisons between DMM data and gravimetric data is the so-called filter artefact that causes substantial measurement errors in gravimetric measurements at very low PM emission levels, such as, e.g. for petrol-fuelled cars.

CPC measurement

The common way to detect such particles smaller than 0,5 µm is to use their property to be able to serve as condensation nuclei. This is used by a device known as a Condensation

Nuclei Counter (CNC) which is equivalent to a Condensation Nuclei Counter (CPC). The particles are led through a chamber where the gas is saturated with a volatile compound, e.g. n-butanol at a temperature slightly above ambient. The saturated gas then continues to a condenser, where the gas temperature is lowered, the gas becomes supersaturated and condenses on the particles present. The particles are allowed to grow to around 10 µm and are then counted optically as described above. Since particles are growing through condensation, no information about particle size can be obtained with this instrument. A common lower limit is 10 nm but equipment exists that can activate particles as small as 3 nm. Particle number concentration is obtained from the number of counted pulses and the known flow rate.

For the PMP particle number measurements a TSI 3010 CPC with an adjusted lower particle cut-off diameter was used. The cut off diameter was set at 23 nm by adjusting the temperature difference between the vapour chamber and the condenser tube to 9°C in accordance with TSI instructions (Bischof, 2004). The measurement range of the CPC is 1-10 000 particles/cm^3 and the time resolution used during data sampling was 1 Hz.

ELPI

Measurements of particle number (PN) and particle size distribution were performed using an ELPI instrument (**Figure 15**). ELPI is a cascade impactor where the entering particles are given an electrical charge. The number of particles impacting on each stage is quantified in real time by measuring the electrical current draining from the stage. The ELPI covers a size range between 30 nm and 10 µm and down to 7 nm with the optional electrical filter stage downstream the impactor, which was used in these tests. A data sampling rate of 1 Hz was selected.

Figure 15. *ELPI by Dekati.*

Aldehyde measurements

Formaldehyde and acetaldehyde were measured by use of DNPH (2,4-dinitrophenyl hydrazine) cartridges (Waters). A single cartridge was used over each individual NEDC and Artemis cycles and thus the emissions are given as an integrated value over the cycle. After sampling the cartridges were stored in a freezer until analysis. The aldehydes were analysed at an external laboratory by extracting the cartridges using acetonitrile with subsequent measurement of the hydrazones using High Performance Liquid Chromatography (HPLC) and UV detection at 254 nm.

Ethanol, ammonia, HC components and nitrous oxide measurements

Ethanol, ammonia, non-regulated HC components namely ethene (C_2H_4) propene (C_3H_6), 1,3-butadiene (1,3-C_4H_6), benzene (C_6H_6) and toluene (C_7H_8) were measured using a low energy secondary ion mass spectrometer (V&F, Austria) sampling from the CVS-tunnel. An Hg ion source was used for ionisation in the mass spectrometer (Villinger et. al 1993). Furthermore, nitrous oxide (N_2O) was measured using a Horiba N_2O analyser.

Evaporative emissions in the VT-SHED

Evaporative HC-emissions were examined for the three cars in a VT-SHED according to the regulated procedure. For the FFVs both E85 and E5 were used in the SHED tests, whereas for the Bi-fuel vehicle only CBG was used. The measurement consists of two parts: the hot soak measures the evaporative emissions during one hour after a NEDC+UDC cycle, and the diurnal measures evaporative emissions during 24 hours.

Sampling and analysis of Polycyclic Aromatic Hydrocarbons

Sampling of both particle-associated and semivolatile-associated PAH was made in diluted exhaust using a CVS dilution tunnel, as previously described. Exhaust particulates were sampled on Teflon coated glass fibre filters (Pallflex Inc., USA) and semivolatile-associated compounds were sampled on Poly Urethane Foam Plugs (PUFs) as described in detail elsewhere (Westerholm et al., 1991). After sampling both filter and PUF samples was stored in a freezer until extraction and chemical analysis was made.

The filter samples were extracted with toluene as solvent by using an Accelerated Solvent Extraction (ASE) technique. The ASE methodology used is described in detail in a publication by Bergvall and Westerholm (Bergvall and Westerholm, 2007). The PUF samples were Soxhlet extracted with acetone as solvent as described in detail elsewhere (Westerholm et al., 1991). Deuterated PAH were used as internal standards which was added to aliquots of raw extract from the filters and the PUFs. The raw extracts was then precleaned individually prior the chemical analysis using gas chromatography mass spectrometry (GC-MS) or on-line liquid chromatography- gas chromatography mass spectrometry (LC-GC-MS). The GC-MS methodology is described in detail in (Westerholm et al., 1991) and the LC-GC-MS methodology is described in detail in (Bergvall and Westerholm, 2006). The GC-MS methodology is used for PAHs with molecular weights ranging from 178 up to 252 amu and the LC-GC-MS methodology is used for PAHs with molecular weights ranging from 252 amu and larger, respectively. In **Table 15** PAH with corresponding molecular weight that are identified and determined in the present project are listed. Identification of PAHs was made by retention time and mass spectra obtained from PAH reference standards. Furthermore, quantification of PAH was made by calculation of response factors for each PAH and deuturated internal PAH standards, **Table 15**, using a PAH standard solution containing all PAH analytes and internal standards.

Calculation of Cancer potency

The most well known carcinogen i.e. benzo(a)pyrene (B(a)P) has relatively recently been classified by International Agency on Research on Cancer (Straif et al., 2005) as a human carcinogen Group I. One way to compare different chemical components with respect to cancer is to use the Toxic Equivalence Factor (TEF) concept. By definition, B(a)P has a TEF value of 1. This means that chemical compounds with a TEF value less than 1 has a lower cancer potency compared to B(a)P and chemical compounds with a TEF value larger than 1 has a larger cancer potency compared to (B(a)P, respectively. In **Table 17**, are shown TEF values for individual PAHs determined in this present research project with TEF values ranging from 0,01 (phenanthrene/anthracene) to 100 (dibenzo(a,l)pyrene) (Boström et al. 2002).

***Table 15**. Identified and determined PAH, Molecular weight (Mw), atomic mass units (amu).*

PAH	**Mw,** amu	**PAH**	**Mw,** amu	**PAH**	**Mw,** amu
phenanthrene	178	anthracene	178	3-methyl phenanthrene	192
2-methyl phenanthrene	192	2-methyl anthracene	192	9-methyl phenanthrene	192
1-methyl phenanthrene	192	9-methyl anthracene	192	2-phenyl naphthalene	204
3,6-dimethylphenanthrene	206	3,9-dimethylphenanthrene	206	fluoranthene	202
pyrene	202	9,10-dimethylanthracene	206	1-methylfluoranthene	216
benzo(a)fluorene	216	retene	234	benzo(b)fluorene	216
2-methyl pyrene	216	4-methyl pyrene	216	1-methyl pyrene	216
benzo(ghi)fluoranthene	226	benzo(c)phenanthrene	228	benzo(b)naphto (1,2-d)thiophene	234
cyclopenta(cd)pyrene	226	benzo(a)anthracene	228	chrysene	228
3-methyl chrysene	242	2-methyl chrysene	242	6-methyl chrysene	242
1-methyl chrysene	242	benzo(b)fluoranthene	252	benzo(k)fluoranthene	252
benzo(e)pyrene	252	benzo(a)pyrene	252	perylene	252
Indeno (1,2,3-cd)fluoranthene	276	Indeno (1,2,3-cd)pyrene	276	benzo(ghi)perylene	276
coronene	300	dibenzo(a,l)pyrene	302	dibenzo(a,e)pyrene	302
dibenzo(a,i)pyrene	302	dibenzo(a,h)pyrene	302	picene	278

***Table 16**. Deuterated internal PAH standards.*

PATH	**Mw,** amu
D10-phenanthrene	188
D10-pyrene	212
bb-binaphtyl[a]	254
D12-benzo(a)pyrene	264
D14-dibenzo(a,i)pyrene	316

Note:

[a] Not deuterated.

Calculation of cancer potency for determined PAH in individual samples are made by multiplying determined emission factor in µg/km with corresponding TEF for each PAH and then adding them together. These values are shown in the cancer potency figures in the present report. Cancer potency for each vehicle is calculated and presented individually for particle associated and semivolatile-associated PAH, respectively.

Table 17. *Toxic equivalence factors, TEF.*

PAH	TEF	Ref	PAH	TEF	Ref
Anthracene	0,01	Nisbet and LaGoy, 1992	Phenanthrene	0,01	RIVM, 1989
Benz(a)anthracene	0,145	Nisbet and LaGoy, 1992	Benzo(c)phenathrene	0,023	Muller, 1997
Chrysene	0,89	RIVM, 1989	Fluoranthene	0,06	RIVM, 1989
Pyrene	0,081	Krewski et al., 1989	B(a)P	1	Boström et al., 2002
Benzo(e)pyrene	0,004	Nisbet and LaGoy, 1992	benzo(b)fluoranthene	0,14	Nisbet and LaGoy, 1992
benzo(k)fluoranthene	0,1	Collins et al., 1998	Cyclopenta(cd)pyrene	0,023	Krewski et al., 1989
Dibenzo(a,h)anthracene	5	Nisbet and LaGoy, 1992	Indeno(1,2,3-cd)pyrene	0,232	Nisbet and LaGoy, 1992
Benzo(ghi)perylene	0,03	RIVM, 1989	Dibenzo(a,l)pyrene	100	Muller, 1997
Dibenzo(a,e)pyrene	1	CARB, 1994	Dibenzo(a,i)pyrene	10	CARB, 1994
Dibenzo(a,h)pyrene	10	CARB, 1994			

TEF ratio

In the present research project, are highly carcinogenic dibenzopyrenes determined in exhaust emissions from FFV and CBG fuelled vehicles for the first time. Dibenzopyrenes determined are: dibenzo(a,l)pyrene, dibenzo(a,e)pyrene, dibenzo(a,i)pyrene and dibenzo(a,h)pyrene. By calculating the TEF ratio (i.e. multiplying determined emission factor for each dibenzopyrene in µg/km with corresponding TEF, added together, and then divided with the B(a)P emission factor times B(a)P TEF=1, (see TEF ratio definition below), is it possibly to estimate relative cancer potency from dibenzopyrenes compared to B(a)P in the exhaust emissions. From the formula below, reveals that the TEF ratio is dimension less. However, if the TEF ratio = 1 the cancer potency for the determined dibenzopyrenes are in the same order as cancer potency from B(a)P only. TEF ratio are defined as:

$$\text{TEF ratio} = \frac{\text{DB(a,l)P} \times 100 + \text{DB(a,e)P} \times 1 + \text{DB(a,i)P} \times 10 + \text{DB(a,h)P} \times 10}{\text{B(a)P} \times 1}$$

Where:
DB(a,l)P = dibenzo(a,l)pyrene emission factor.
DB(a,e)P = dibenzo(a,e)pyrene emission factor.
DB(a,i)P = dibenzo(a,i)pyrene emission factor.
DB(a,h)P = dibenzo(a,h)pyrene emission factor.

Corresponding PAH Toxic Equvivalence Factor see **Table 17**.

2.5 Evaporative emissions

Evaporative HC-emissions were examined for the three cars in a VT-SHED according to the regulated procedure. For the FFVs both E85 and E5 were used for the SHED tests, whereas for the Bi-fuel vehicle only CBG was used. The measurement consists of two parts: the hot soak measures the evaporative emissions during one hour after a NEDC+UDC cycle, and the diurnal measures evaporative emissions during 24 hours.

2.6 On-board emission measurements

As previously discussed, catalyst durability is one important issue on vehicles fuelled with methane fuels (CNG & CBG). Most of these problems have been reported from tests on heavy-duty vehicles but relatively little information has been published on light-duty vehicles. Therefore, it was decided to carry out a “screening test” on 10 vehicles in this project. For the hydrocarbon measurements a FID analyser was used. The analyser was calibrated with 990 ppm methane before and the calibration was checked after the tests. The exhausts were sampled in the end (20 cm, upstream) of the exhaust pipe and pumped through a heated (180°C) sampling probe to the analyser. All test equipment were assembled in a trailer and was powered by an external petrol-fuelled generator (no power from the test vehicles were used).

3 RESULTS AND DISCUSSION

As previously stated in the report, it must be pointed out that the vehicles should not be compared directly with each other, because the objectives with this present investigation was to investigate the impact from fuel type, driving cycles and test temperatures on exhaust emissions and was not an evaluation of the vehicles *per se*.

Note that no N_2O emissions were detected in any of the test cycles and thus no N_2O emission results are presented.

During the BFV test in the MW test cycle, the vehicle was not able to follow the driving cycle when the requested speed was over 110 km/h. Thus, one should be cautious in the assessment of these results.

In the NEDC tests at -7°C, the FFV1 was initially tested on E85 fuel and later on the other fuels. In the subsequent adaptation to these fuels, the vehicle failed to adapt to either E70 or E5 later on. Due to this problem, all these emission tests were considered as failed tests. The car manufacturer was contacted to solve this problem, why additional tests were performed to fulfil the initial research plan. In the additional tests, regulated emissions were carried out in all tests. Measurement and sampling of some unregulated emission components was only made in a limited number of these additional tests. In the figures, missing values are denoted by “m.v.”. In some cases where measurement errors have occurred, or when results have been omitted due to other problems, the denotation “i.d. ” have been used, indicating that these data are not valid (“invalid data”).

Please note that a variation of the scale on the Y-axis can be used in different figures for the same emission component. Note that the error bars in the figures show max and min values of the two tests performed. Where no error bar is shown, only one of the two measurements was approved, or else, one measurement is missing due to technical problems with the particular car (which is discussed in the text whenever applicable).

3.1 Fuel analysis

The fuel analysis of the three liquid fuels was carried out by SGC. Swedish commercial petrol (E5), E85, winter ethanol fuel E70 and biogas (CBG) were used in the tests.

The results from the fuel analysis of the three liquid fuels are presented in **Table 18**. The fuel analysis shows that the fuels used in the tests fulfil the Swedish specifications for each fuel.

Table 18. *Fuel analysis of the test fuels.*

Property	Unit	E5	E85	E70
Density at 15°C	(kg/m^3)	741,4	788,7	777,7[a]
Initial boiling point	(°C)	30,5	60,3	51,6[a]
Ethanol	(%v)	5,0	87,6	78[a]
MTBE	(%v)	0,9	3,2	2,1[a]
Iso-butanol	(%v)	<0,1	0,4	0,4[a]
Vapour pressure	(kPa)	87,2	36,2	45,9
Water	(mg/kg)	390	3400	2600[a]

Note:

[a] Data for E70 provided by Roger Mattebo, Sekab (Mattebo, 2006).

3.2 Emissions

3.2.1 Regulated emissions

CO

Emissions of CO from the test vehicles are presented in **Figure 16** to **Figure 18**.

FFV1. At +22°C, the FFV1 car fuelled with E85 has considerably higher CO emissions in the NEDC test cycle compared to E5 (**Figure 16**). This trend was not expected and the reason for this result could be lack of optimisation of the engine calibration for E85 during the cold start.

The FFV1 car has lower CO emissions in comparison to E5 in all Artemis test cycles, except the in the AU test cycle (**Figure 16**). However, the absolute level is very low for both fuels in the latter test. CO emissions for the FFV1 car running on E5 fuel are high in the MW test cycle. The most likely reason for these results are that the air/fuel ratio for the engines running on E5 is reduced below stoichiometric conditions due to the high engine load during accelerations and high vehicle speed in the MW test cycle. This is usually due to that the engine mapping increase fuelling to reduce the in-cylinder and exhaust temperatures. The CO level for E85 is considerably lower. Presumably this is due to much lower fuel enrichment. E85 runs cooler than petrol and thus, a higher air/fuel ratio can be used, which has the benefit of reduced CO emissions in comparison to E5.

At -7°C in the NEDC test cycle, higher CO emissions with E85 comparing to E5 are observed for FFV1 (**Figure 16**). The FFV1 with E70 has even higher CO emissions than the E85 fuel, although the relative difference is small. Whether this is due to a real effect from engine control system calibration or just measurement scatter cannot be clarified. The higher CO level at -7°C running on E85 and E70 in comparison to E5 can be explained by non-optimal air/fuel preparation. Due to poor evaporation of fuel at low ambient temperatures, the fuelling must be increased for petrol engines during cold starts. This problem is even more pronounced for alcohol fuels that have a lower vapour pressure and a higher latent heat of evaporation in comparison to petrol. Therefore, high ethanol content in the fuel increases the need for additional fuel during the cold start. This is the reason for higher CO (and HC) emissions under these test conditions.

FFV2. In contrast to the FFV1 discussed above, the relative level of CO emissions in the NEDC at +22°C is much lower for E85 than for E5 (**Figure 17**).

CO emissions in all Artemis driving cycles are lower for E85 than for E5 for the FFV2 car (**Figure 17**). It should be noted that CO emissions in the MW test cycle are very high for FFV2 running on E5. This level approaches the level of a non-catalyst car in the NEDC test cycle. As previously discussed, fuel enrichment is the plausible cause of this high CO level. The engine runs cooler on E85 than on E5 and this in turn, reduces the CO emissions for E85 in comparison to E5.

CO emissions in the NEDC test cycle are generally considerably higher at -7°C compared to at +22°C (**Figure 17**). The level is higher for E85 than for E5 but relatively similar for E70 compared to E5. This trend is in contrast to the FFV1 car, where higher ethanol content in the fuel resulted in a higher CO level.

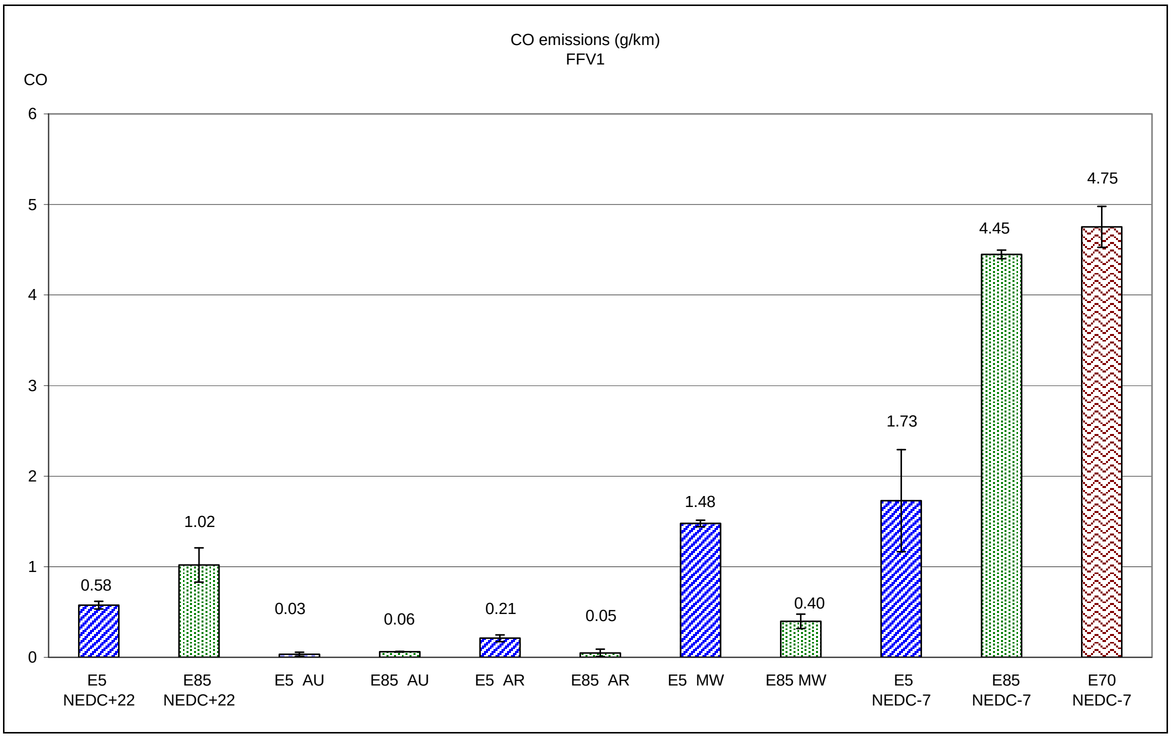

Figure 16. *CO emission from FFV1.*

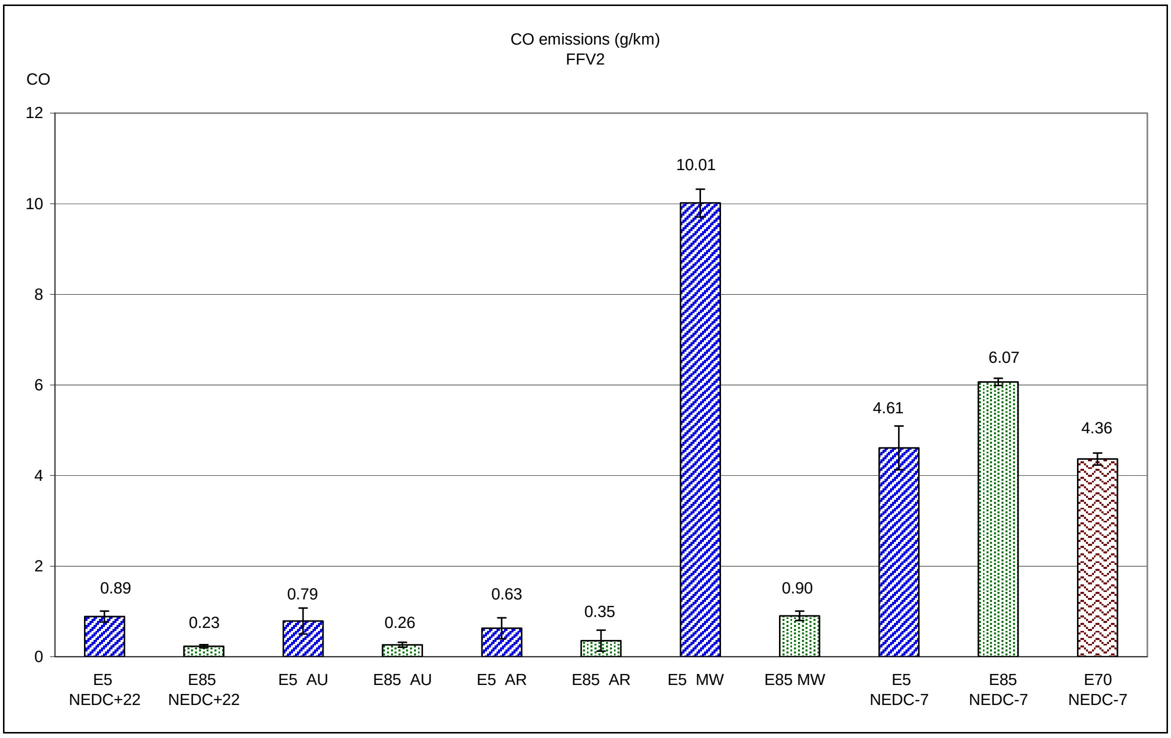

Figure 17. *CO emission from FFV2.*

BFV. First, it should be noted that the *CO level (2,1 g/km) for the BFV car running on E5 is higher than the current Euro 4 limit (1,0 g/km) for CO emissions* **Figure 18**.The graph clearly show that, at +22°C, the BFV fuelled with CBG has lower CO emissions compared to E5.

CO emissions in the MW test cycle are very high for BFV car running on E5 fuel, as for the FFV2 car. As previously discussed, this is due to fuel enrichment during high engine load in the MW test cycle. The CO level on CBG is substantially lower, indicating that the fuel enrichment is much reduced in this case.

At -7°C, the CO emissions for the BFV car running on CBG are marginally higher than for the E5 fuel. The car is started on petrol in both cases and switched over to CBG in the case this fuel is used. However, since most of the CO emissions are generated early in the test cycle, this causes the levels to be roughly equal for both fuels.

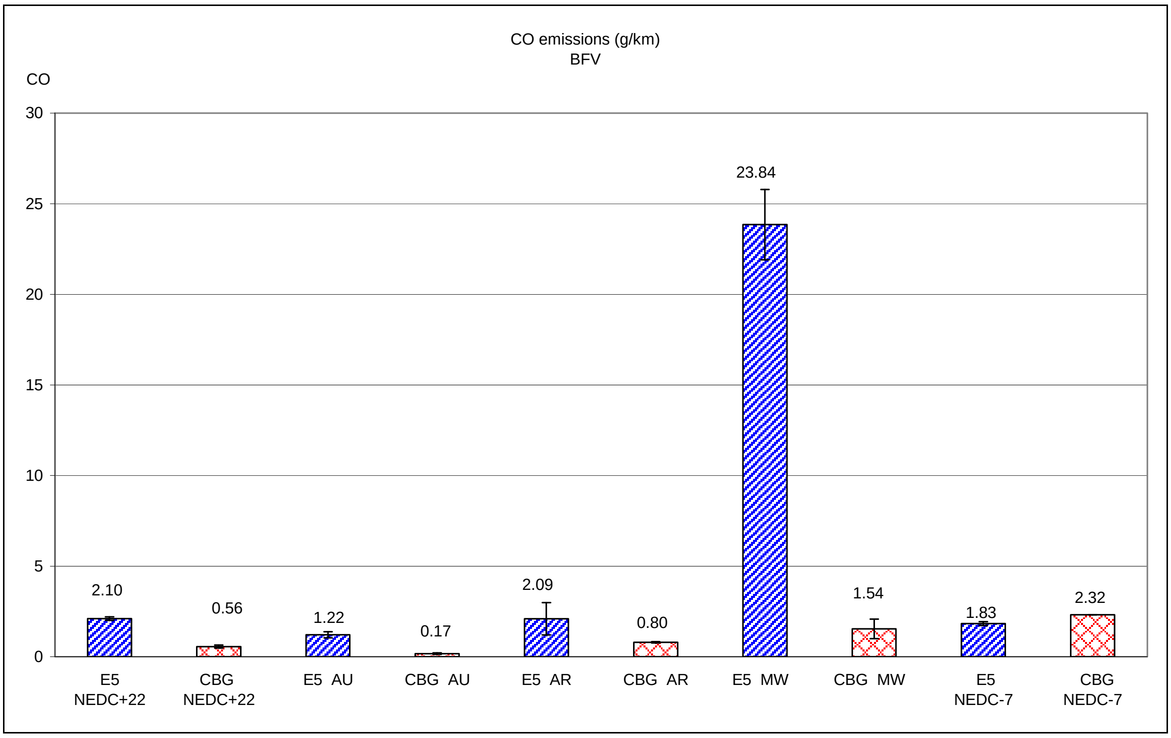

Figure 18. *CO emission from BFV.*

HC

The HC emissions from the test vehicles are presented in **Figure 19**, **Figure 20** and **Figure 21**.

FFV1. For NEDC tests at +22°C, the FFV1 fuelled with E85 has somewhat higher HC emissions in comparison to E5 (**Figure 19**). This is in line with the observation of higher CO emissions for E85, as previously discussed. CO and HC emissions often show this co-variation trend.

HC emissions from the Artemis tests cycles, which are warm start test cycles, were very low for both E85 and E5 fuels (**Figure 19**). Any potential differences seen here are insignificant. This is in contrast to the results for CO emissions as discussed above. The reason for this discrepancy is, most likely, that a warm catalyst will crack hydrocarbons even if the air/fuel ratio is low under certain operating conditions. Thus, conditions with under-stoiciometric air/fuel ratios do not necessarily increase HC emissions in a similar way as for CO emissions.

At -7°C in the NEDC test cycle, HC emissions FFV1 car show an increasing trend for higher ethanol content in the test fuel (i.e., E5 < E70 < E85). The causes for increased CO emissions were discussed above and the same conclusions apply also in the HC case. Since the catalyst is not active during the cold start the catalyst cracking effect seen in the Artemis MW cycle does not apply here.

FFV1. For NEDC tests at +22°C, the FFV2 car fuelled with E85 has lower HC emissions comparing to E5, in contrast to the FFV1 car that showed the opposite trend (**Figure 20**). In both cases, the levels are low and the differences are relatively small.

BFV. Generally, the BFV car has relatively low HC emissions in all test cycles (**Figure 21**). Taking into account the standard deviations between individual tests, negligible differences in HC emission were observed between the E5 and CBG fuels.

s for the FFV1, HC emissions from the Artemis tests were very low for both E85 and E5 fuels (**Figure 20**). The same conclusions regarding CO emissions and HC cracking apply also in this case.

At -7°C in the NEDC test cycle, HC emissions FFV2 car are higher for E85 and E70 in comparison to E5 (**Figure 20**). The average level is lower for E70 than for E85 but the measurement scatter between the two E70 tests are too great to draw a conclusion that the level for E70 should be higher than for E85.

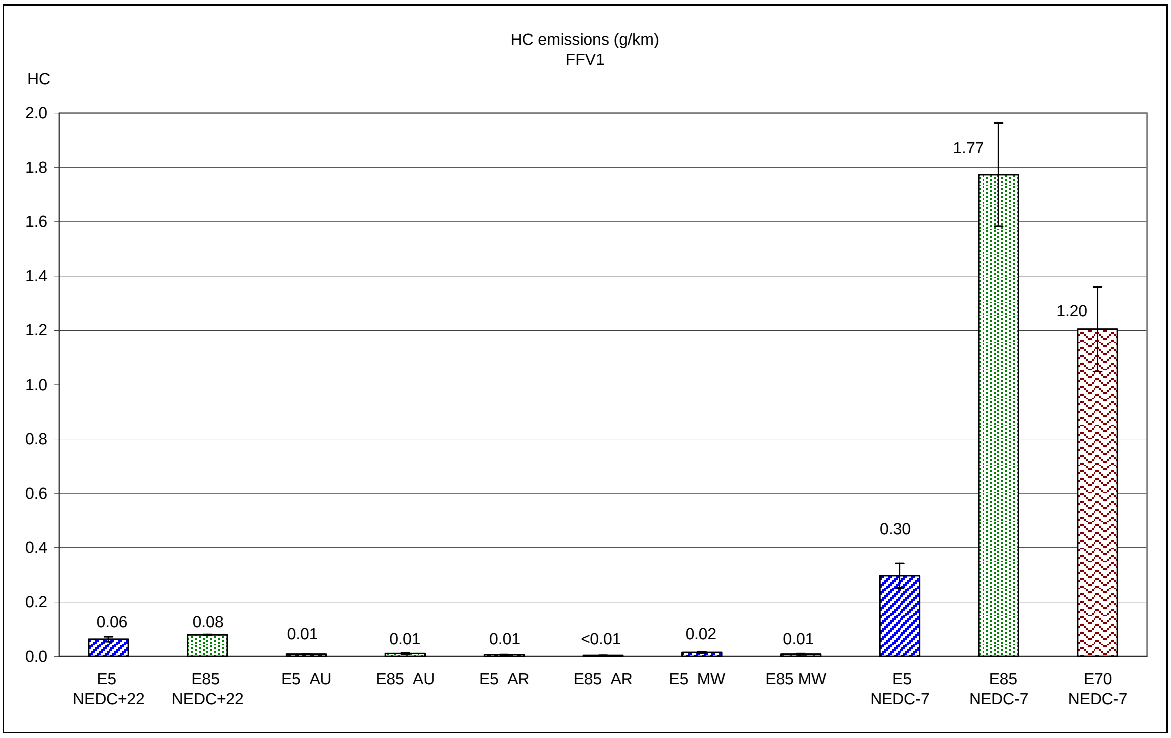

Figure 19. *HC emission from FFV1.*

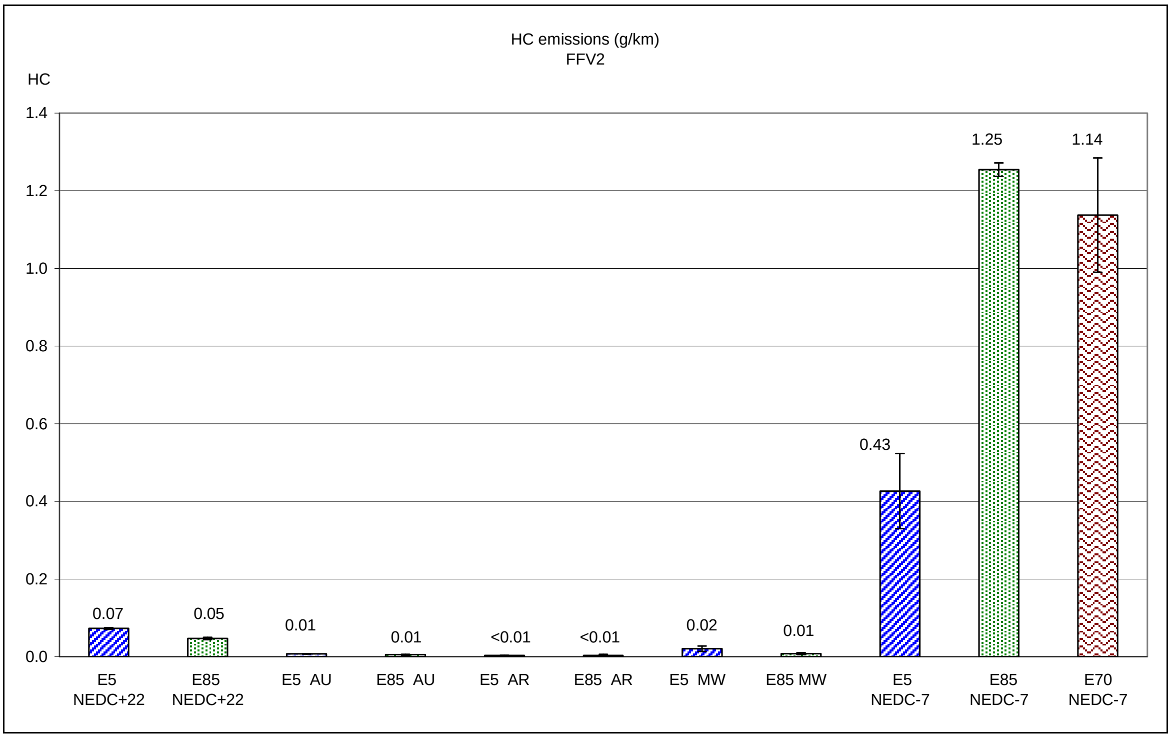

Figure 20. *HC emission from FFV2.*

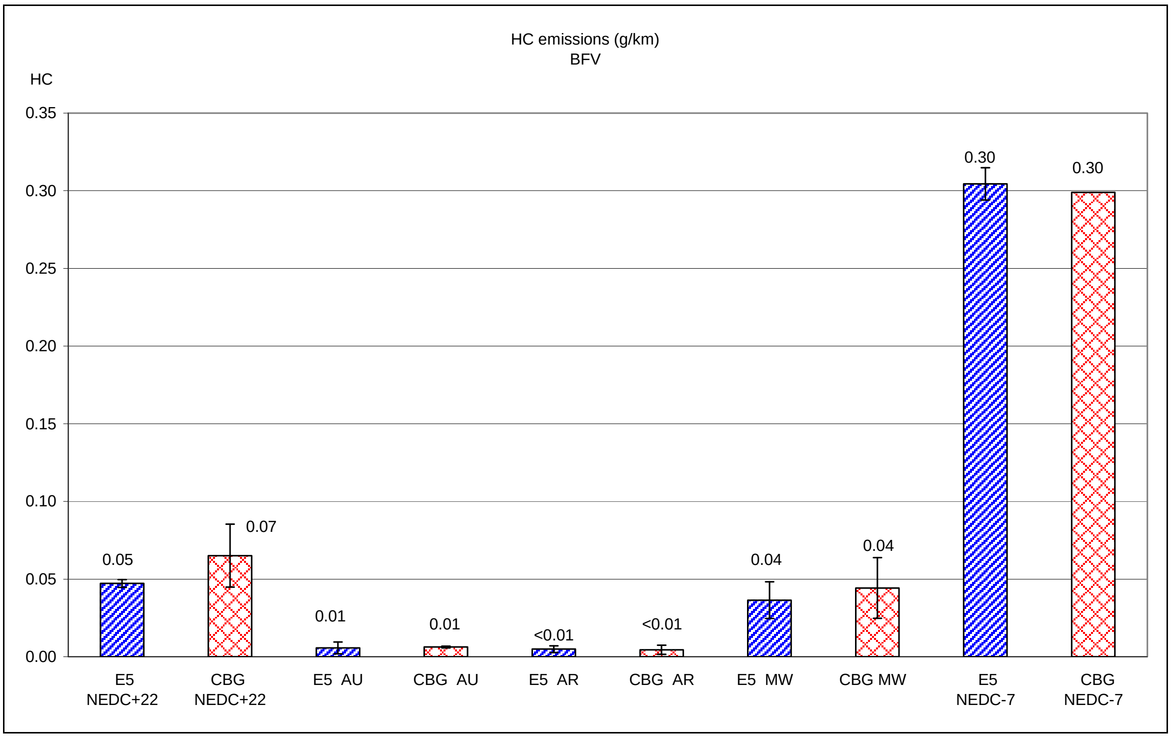

Figure 21. *HC emission from BFV.*

Discussion about HC Emissions from blends of petrol/ethanol fuelled vehicles

In the report by Egebäck and co-workers (Egebäck et al., 2005) they highlighted the need to distinguish between HC and alcohol contents in vehicle exhaust, especially when alcohol/petrol blends are used as fuel. This because, when using petrol/ethanol blends as fuel, the uncombusted fuel constituents in the exhaust includes both unburned petrol (which consists mainly of hydrocarbons) and uncombusted ethanol which is not a hydrocarbon. As hydrocarbons and alcohols have different sensitivity factors (Dietz, 1967) in the Flame Ionization Detector, (FID) it will have an impact on determined HC emissions reported compared to real emissions emitted from the vehicle. This fact will affect HC comparisons in a way that they will not be made on an equal basis.

In **Table 19** HC emissions for FFV1 are shown and in **Table 20** for FFV2, respectively, by the FID in the present project compared to organic material non-methane hydrocarbon equivalent (OMNMHCE). The calculation of OMNMHCE was made using the formula defined below (CARB, 1999):

OMNMHCE = NMHC + (13,8756/32,042) x (methanol) + (13,8756/23.035) x (ethanol) + (13,8756/30,0262) x (formaldehyde) + (13,8756/22,027) x (acetaldehyde)

In the present project the emissions of methanol was not determined why the calculation of OMNMHCE in **Table 19** and **Table 20**, are underestimated. However, increased ethanol contents and decreased test temperature increases OMNMHCE and OMNMHCE/HC ratio, which is expected.

Table 19. *Comparison of OMNMHCE and HC emissions, FFV1.*

Driving cycle; temperature, fuel	HC-FID (mg/km)	OMNMHCE (mg/km)*	(OMNMHCE/ HC-FID) x100 (%)
NEDC, +22°C, E5	72,8	72,1	>99
NEDC, -7°C, E5	m.v.#	m.v.	m.v.
NEDC, +22°C, E85	47,0	97,9	>208
NEDC, -7°C, E85	1254	2117	>169
NEDC, -7°C, E70	m.v.	m.v.	m.v.

*Underestimated due to no methanol emissions was determined. #m.v. missing value.

Table 20*. Comparison of OMNMHCE and HC emissions, FFV2.*

Driving cycle, temperature, fuel	HC-FID, (mg/km)	OMNMHCE (mg/km)*	(OMNMHCE/ HC-FID) x100 (%)
NEDC, +22°C, E5	62,8	56,1	>89
NEDC, -7°C, E5	m.v.#	mv	mv
NEDC, +22°C, E85	79,6	109	>137
NEDC, -7°C, E85	1773	2440	>138
NEDC, -7°C, E70	m.v.	m.v.	m.v.

*Underestimated due to no methanol emissions was determined. #m.v. missing value.

NO_X

Emissions of NO_X from the test vehicles are presented in **Figure 22**, **Figure 23** and **Figure 24**.

FFV1. NO_X emissions in the NEDC test cycle were lower for E85 than for E5 (**Figure 22**). Although this result was expected, the level in both cases was very low and the differences are close to the measurement scatter.

NO_X emissions are low for both tested fuels in the Artemis test cycles. The average level for E85 was somewhat higher in the Artemis MW cycle but the measurement scatter was large in this case, indicating that no firm conclusions can be drawn in this case.

At -7°C, significant differences in NO_X emissions due to fuel changes were observed. The FFV1 running on E5 has much higher NO_X emissions than the E85 and E70 fuels. The absolute level was very high for E5 in this case, i.e. almost one order of magnitude higher that the emission limit in the NEDC test cycle. No measurement error for the FFV1 vehicle has been found, indicating that the only plausible explanation for this behaviour would be that the engine is running so lean for at least part of the test cycle that NO_X conversion is hampered.

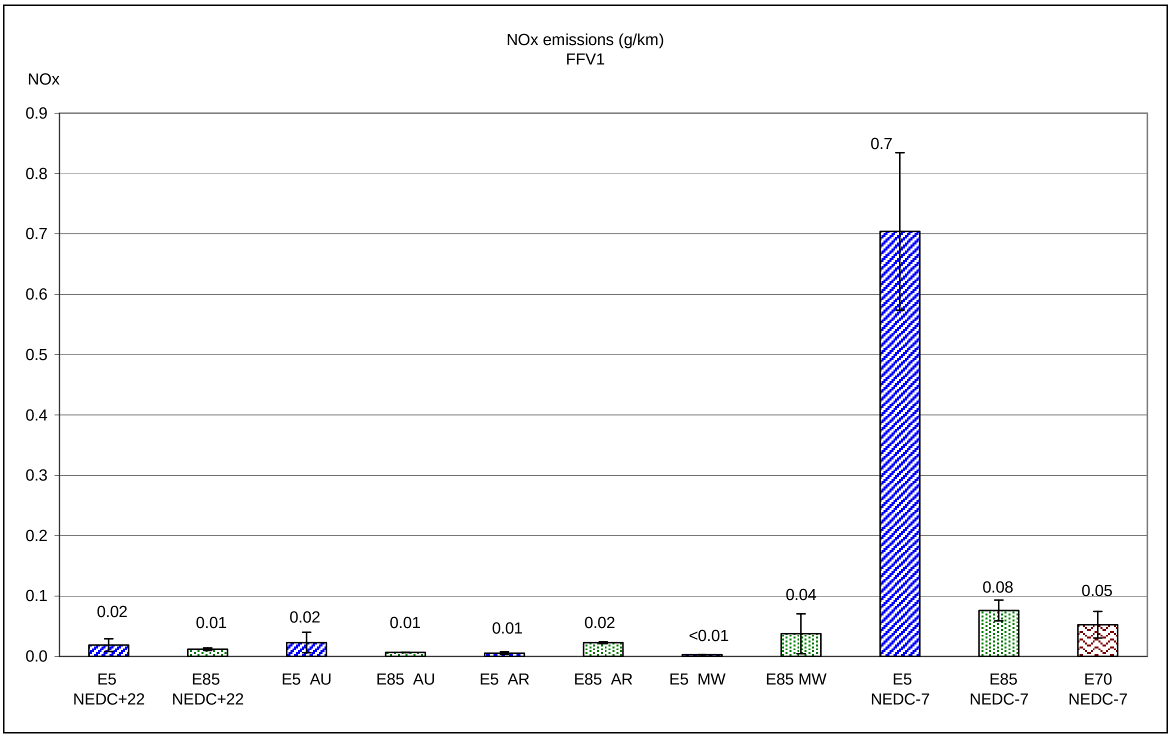

Figure 22. *NO_X emission from FFV1.*

FFV2. At +22°C, the same observation for the FFV2 vehicle as for the FFV1 can be made, i.e. that the NO_X emissions as an average for two repeated test are somewhat lower for E85 than for E5 (**Figure 23**). However, both levels are low and differences are in the same range as for the measurement scatter.

The NO_X level is higher in the Artemis AU test cycle than in the NEDC test cycle (at +22°C) but the measurement scatter is large for the individual tests with both fuels (**Figure 23**). The NO_X level in both the other Artemis test cycles is low for both fuels.

At -7C in the NEDC test cycle, the FFV2 car running on E5 fuel has somewhat lower emissions than for the E85 and E70 fuels (**Figure 23**).

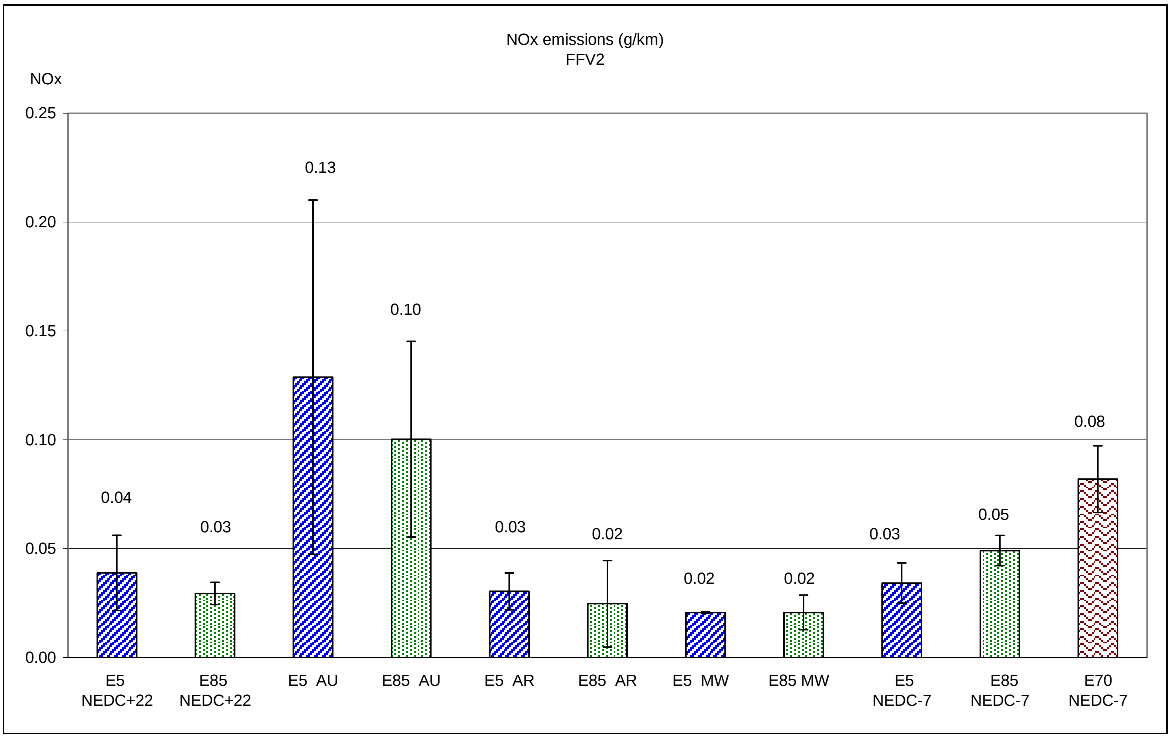

Figure 23. *NO_X emission from FFV2.*

BFV. Poor repeatability for the NO_X emission measurements was observed for the BFV car in the MW tests (**Figure 24**.). There are two potential reasons for that observation. First, there could be a breakthrough of NO_X from the catalyst due to high exhaust flow (high space velocity in the catalyst). Second, the air/fuel ratio could be on the lean side in part of the test cycle and this behaviour could also be somewhat stochastic. Fuel injection and control of air/fuel ratio is generally more difficult for gaseous fuels than for liquid fuels, due to temperature and pressure effects in the former case. Therefore, the second hypothesis is more likely than the first. In general, it was also observed that the vehicle was unable to follow the driving cycle as stated before.

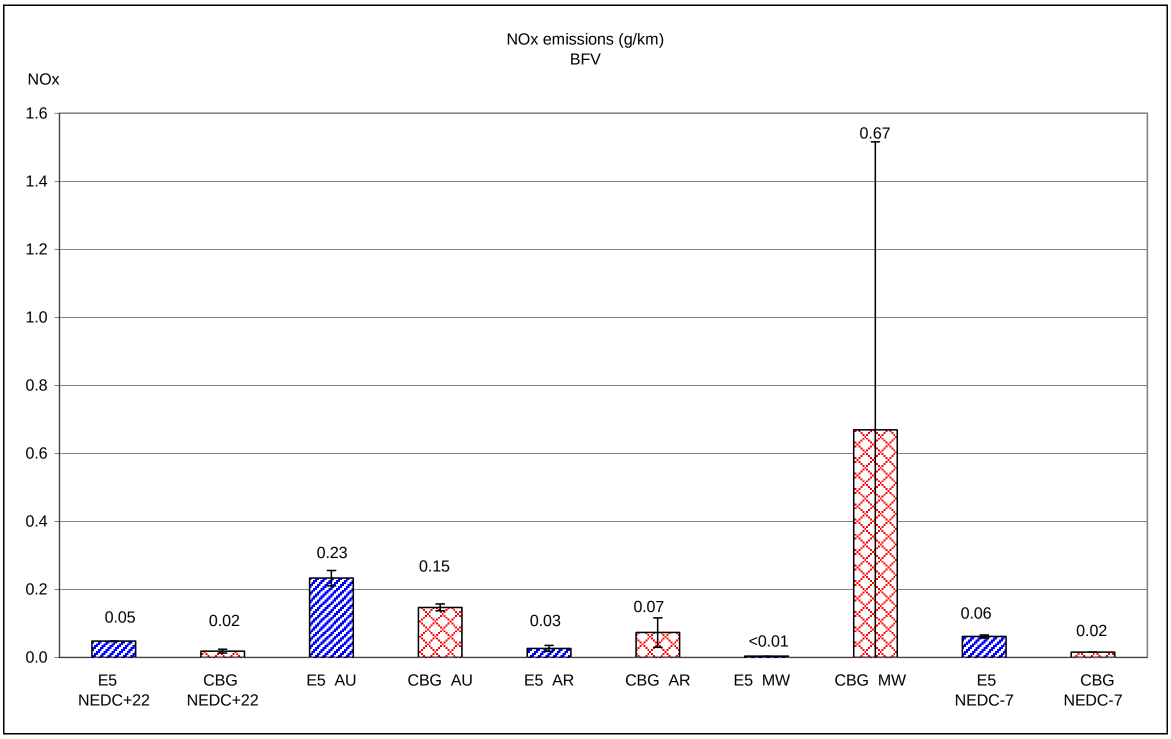

Figure 24. *NO_X emission from BFV.*

PM

Emissions of PM from the test vehicles are presented in **Figure 25**, **Figure 26** and **Figure 27**. For all vehicles, the PM emissions are generally very low except in the MW test cycle and at -7°C in the NEDC test cycle.

For the BFV car, tests on CBG fuel always give lower PM emissions than the tests running on E5 fuel.

In the +22°C tests, the FFV2 with E5 has somewhat or significant higher (MW tests) PM emissions than E85, whereas the FFV1 with E5 has similar or slightly lower emissions than the E85 except FFV1 MW tests, in which E5 has higher emissions than the E85. In the cold climate, the ethanol dominated fuels have similar or somewhat higher PM emissions than the E5 for both vehicles.

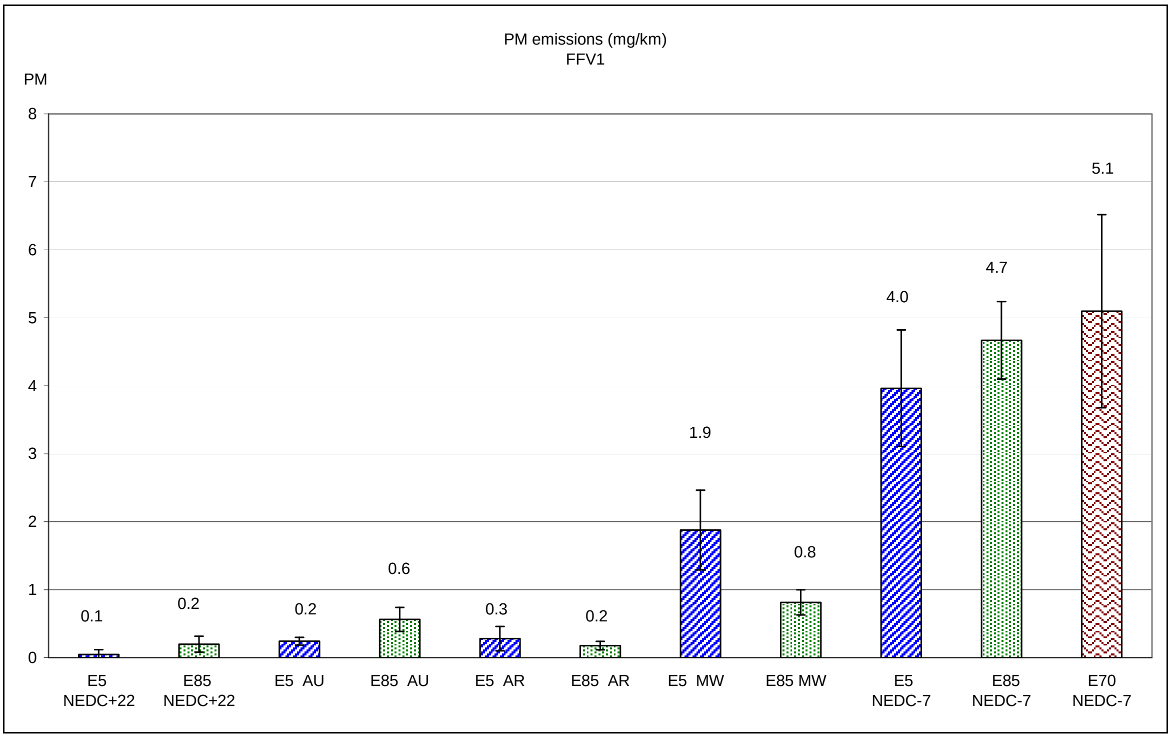

Figure 25. *PM emission from FFV1.*

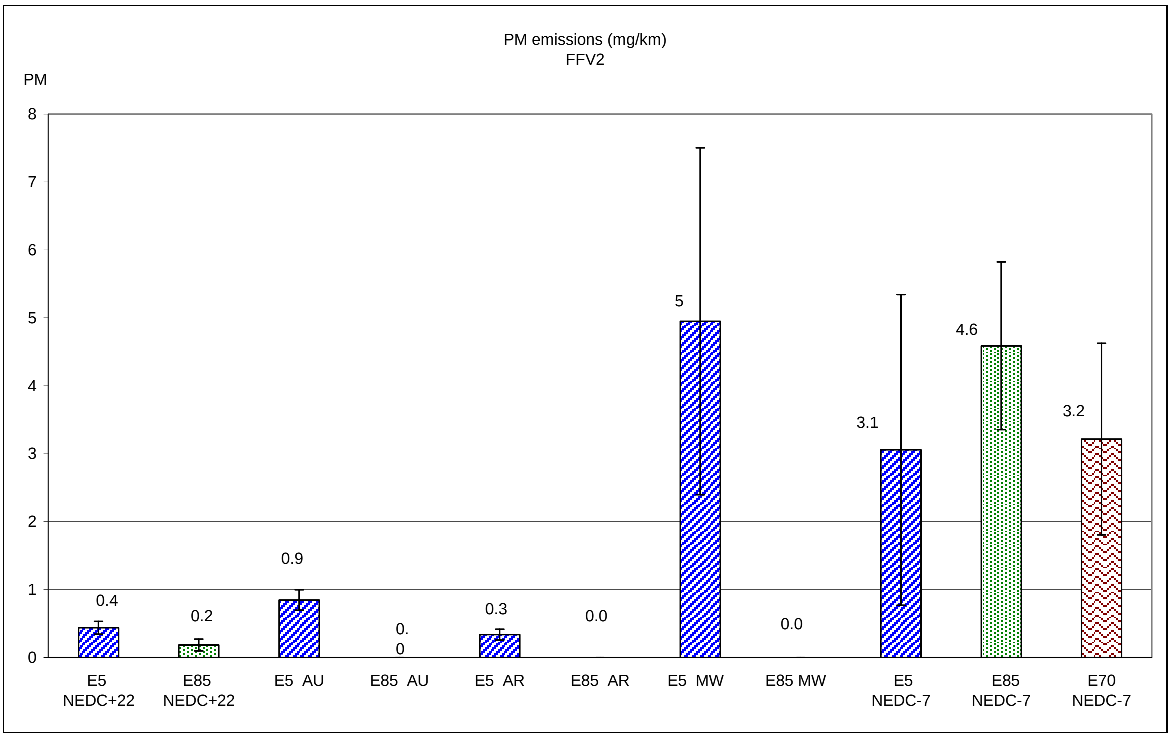

Figure 26. *PM emission from FFV2.*

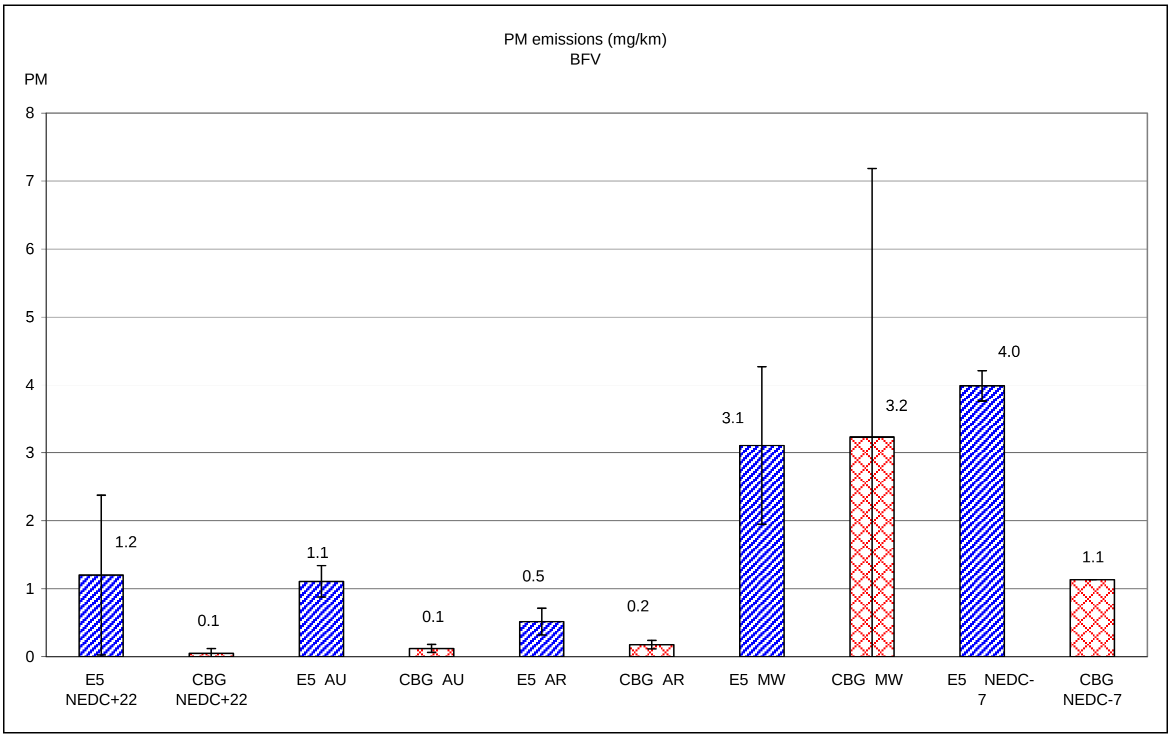

Figure 27. *PM emission from BFV.*

3.2.2 Unregulated emissions

Methane

Methane emissions from the test vehicles are presented in **Figure 28** to **Figure 30**. Note that methane values are calculated as the measured HC values minus the measured non-methane HC for the repeated tests. All vehicles have low methane emissions in the tests. BFV with CBG has always higher methane emissions comparing to the E5 fuel. The cold climate tests show that the flex fuel vehicles with E85/E70 have significant higher methane emissions comparing to E5.

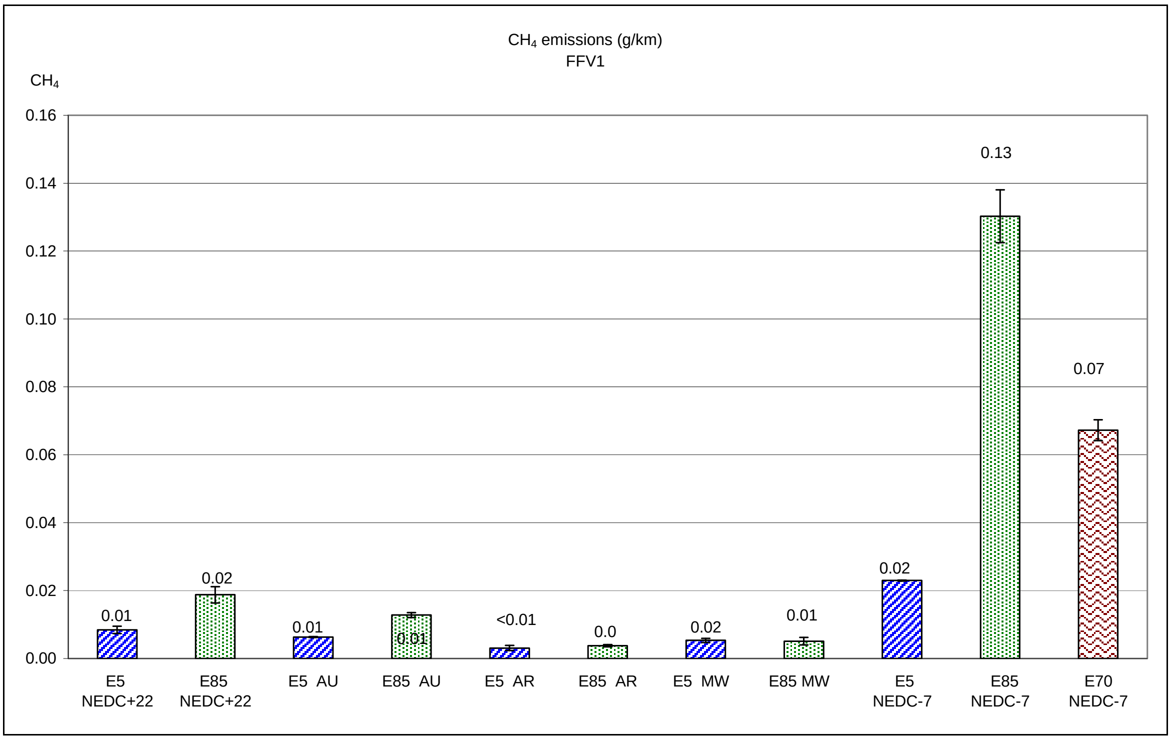

Figure 28. *Methane emission from FFV1.*

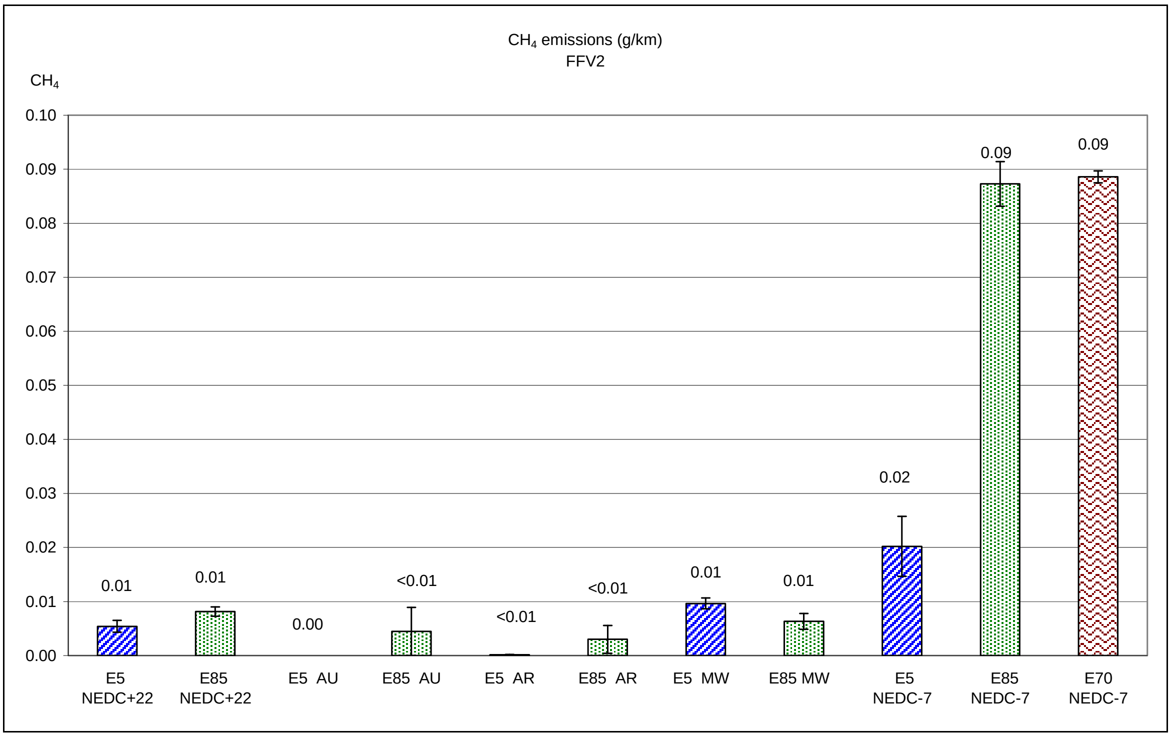

Figure 29. *Methane emission from FFV2.*

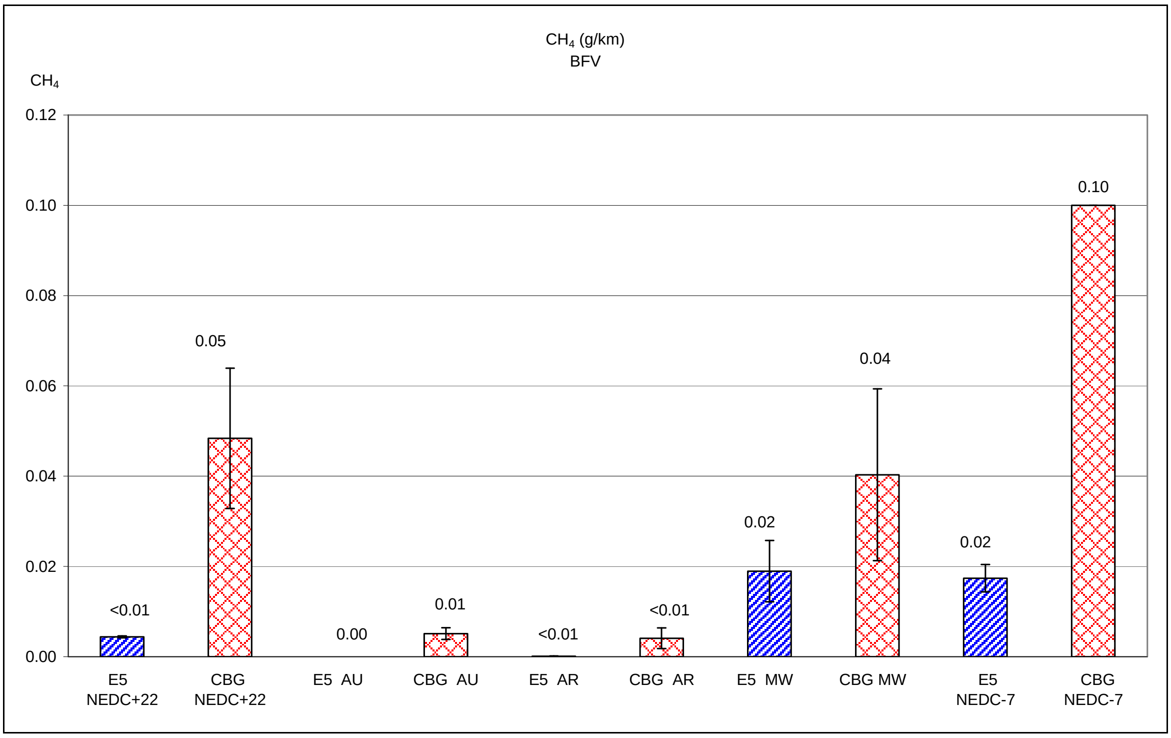

Figure 30. *Methane emission from BFV.*

NO_2 emissions

NO_2 emissions from the test vehicles are not presented in any diagrams, since only a few tests gave results above the detection limit. Note that NO_2 emissions are calculated as the measured NO_X values minus the measured NO values (NO_X-NO).

For the flex fuel vehicles cold climate tests, FFV1 with E5 has significant higher NO_2 emissions than the E85 and E70 whereas FFV2 with E5 has much lower NO_2 emissions than E85 and E70, which are correlated with the NO_X emission results. The NO_2 emissions from all +22°C tests are very low corresponding to low NO_X emissions in respective tests.

For the BFV car, NO_2 emissions are very low in all tests except CBG MW tests, in which correspondingly, highest the NO_X emissions are also detected.

Aldehyde emissions

Formaldehyde (HCHO) and acetaldehyde (CH_3CHO) emissions from the test vehicles are presented in **Figure 31** to **Figure 36**.

For the flex fuel vehicle Artemis tests, aldehyde emissions are very low for both E5 and E85 fuels. For NEDC tests, the ethanol dominated fuel has higher formaldehyde and acetaldehyde emissions than the E5 fuel, and the cold climate tests lead to significant increase in the emissions of the two aldehyde species comparing to the +22°C tests. Comparing E85 and E70 to E5, the increase in aldehyde emissions are much more profound in the cold climate tests than the +22°C tests.

For the BFV, the aldehyde emissions are always higher with E5 comparing to CBG fuel except the -7°C tests, in which CBG leads to higher formaldehyde emissions than E5.

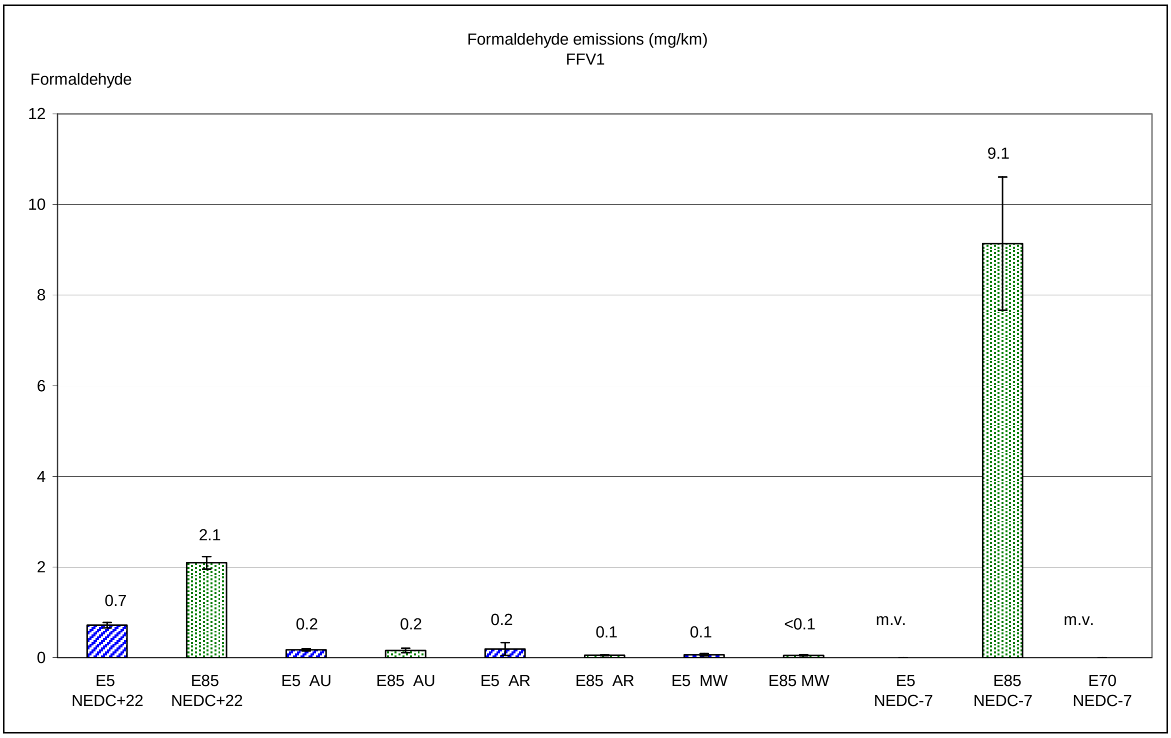

Figure 31. *Formaldehyde emission from FFV1.*

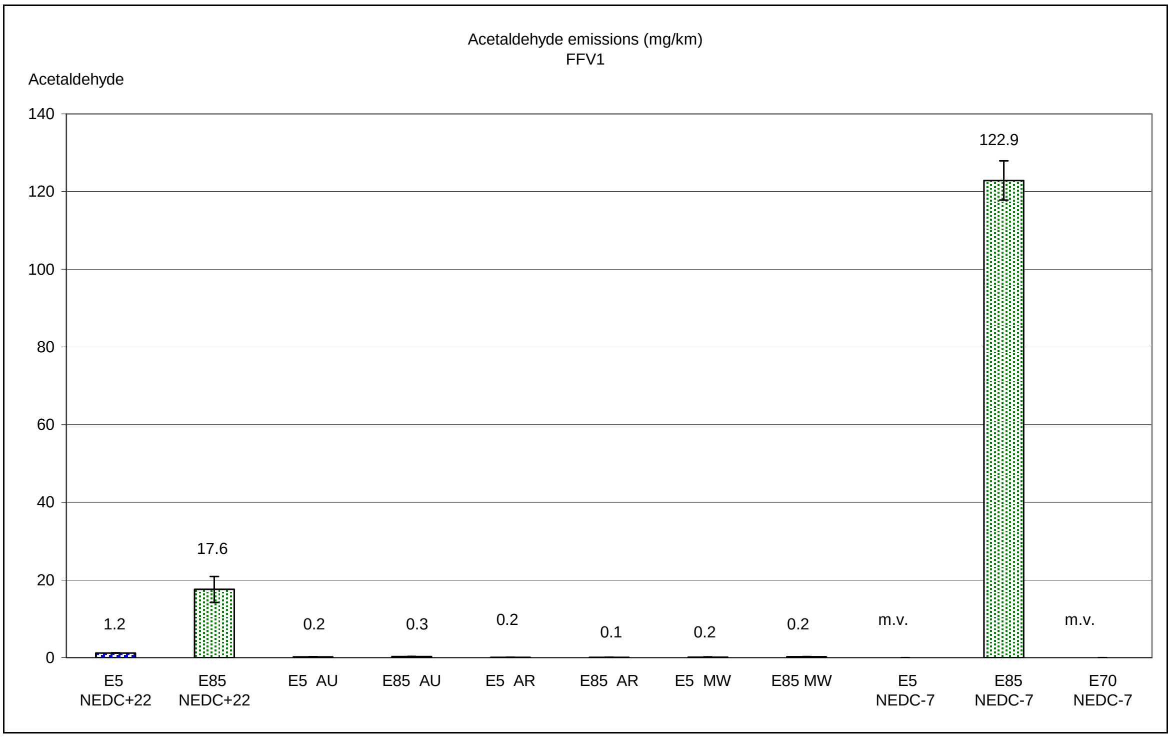

Figure 32. *Acetaldehyde emission from FFV1.*

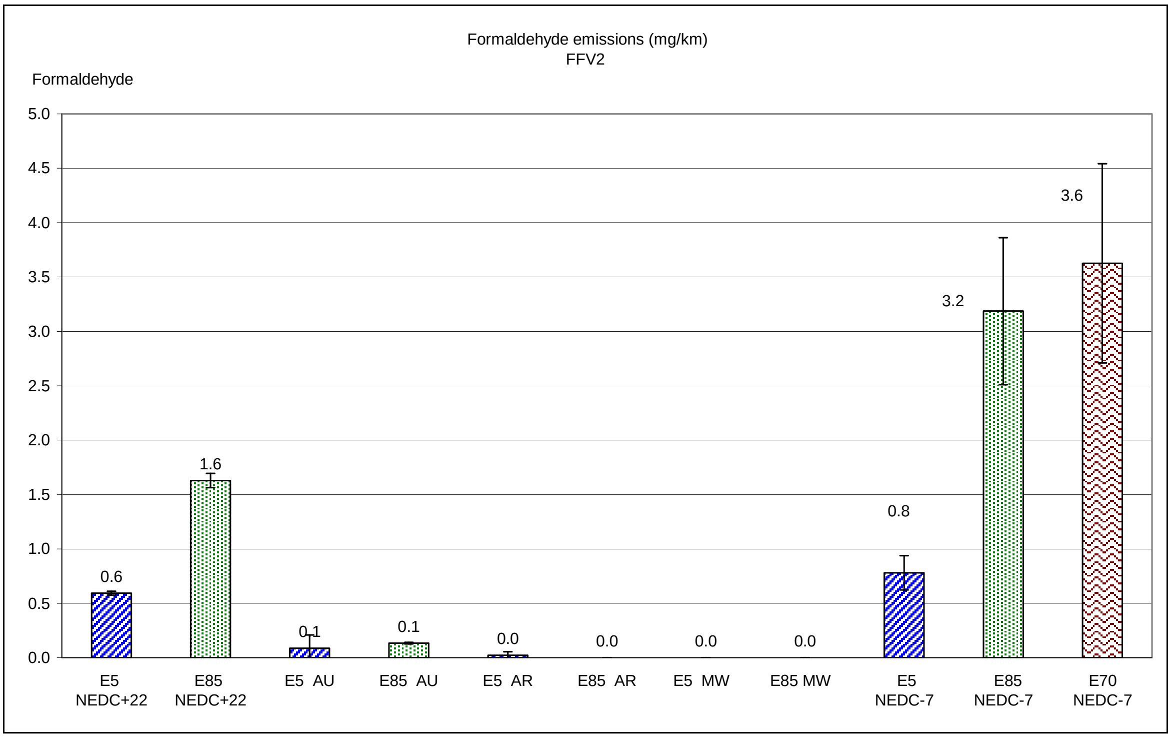

Figure 33. *Formaldehyde emission from FFV2.*

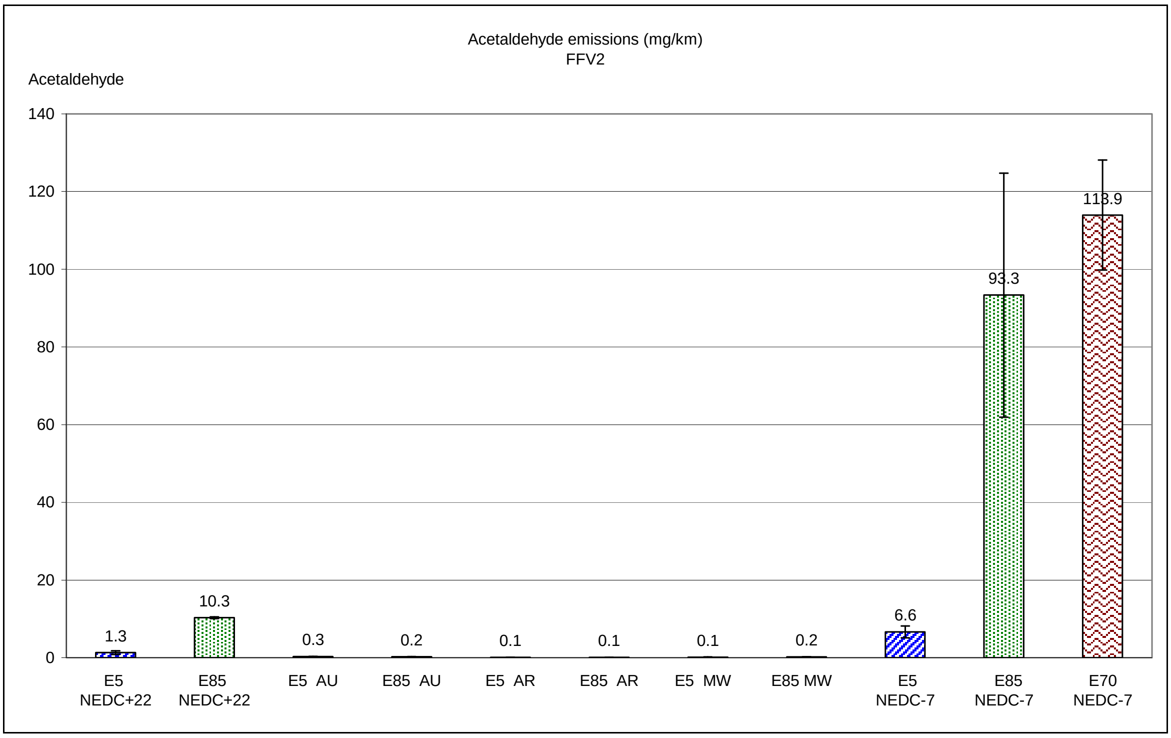

Figure 34. *Acetaldehyde emission from FFV2.*

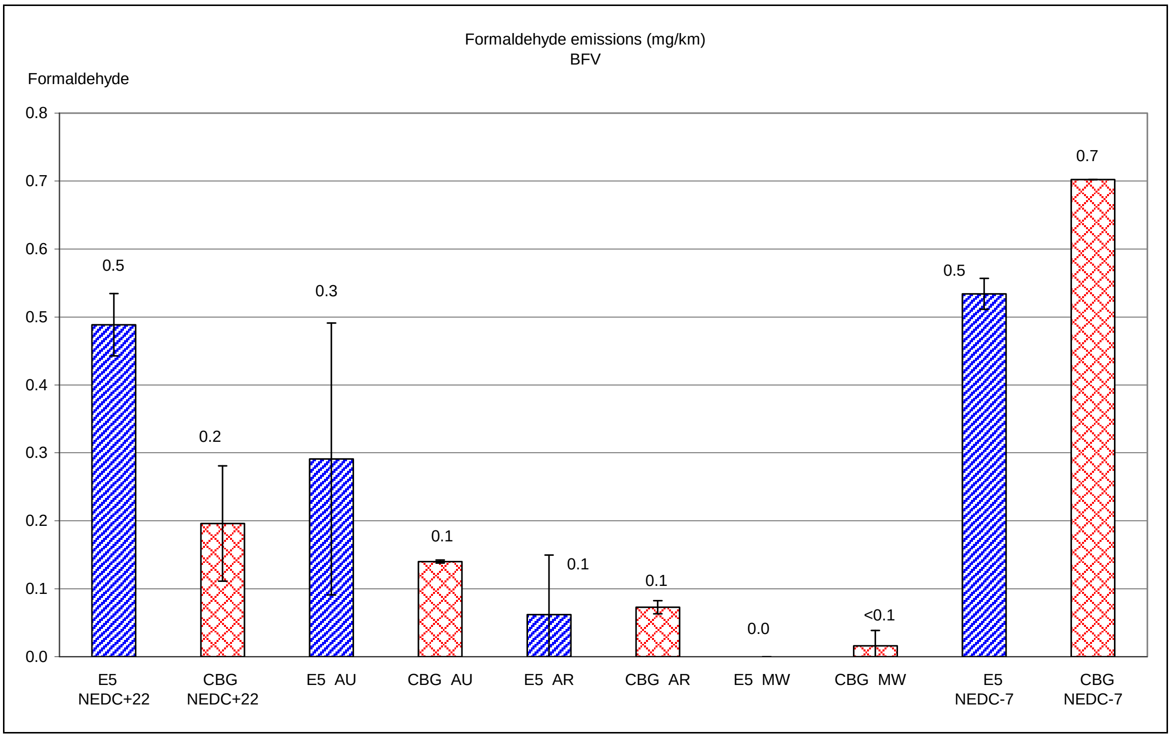

Figure 35. *Formaldehyde emission from BFV.*

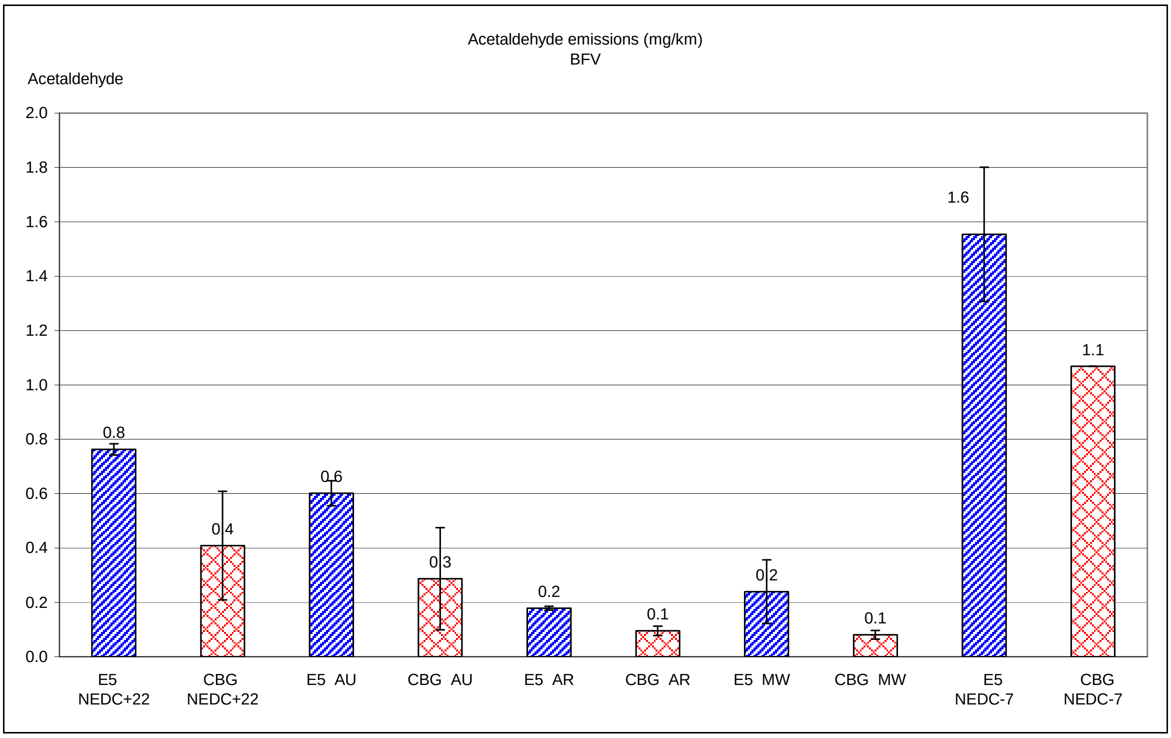

Figure 36. *Acetaldehyde emission from BFV.*

Ethanol

Ethanol (CH_3CH_2OH) emissions from the test vehicles are presented in **Figure 37** to **Figure 39**. Ethanol emissions are only detected at NEDC tests. For the BFV the ethanol emissions were very low. For the flex fuel vehicles, ethanol dominated fuels have significantly higher emissions than the E5.

Note that different Y-axis scale is used in **Figure 39** compared to the figures on the FFVs, since the latter category has significantly higher ethanol emissions when running on ethanol fuels. Although CBG does not contain any ethanol, there seems to be some formation of ethanol anyway in the engine.

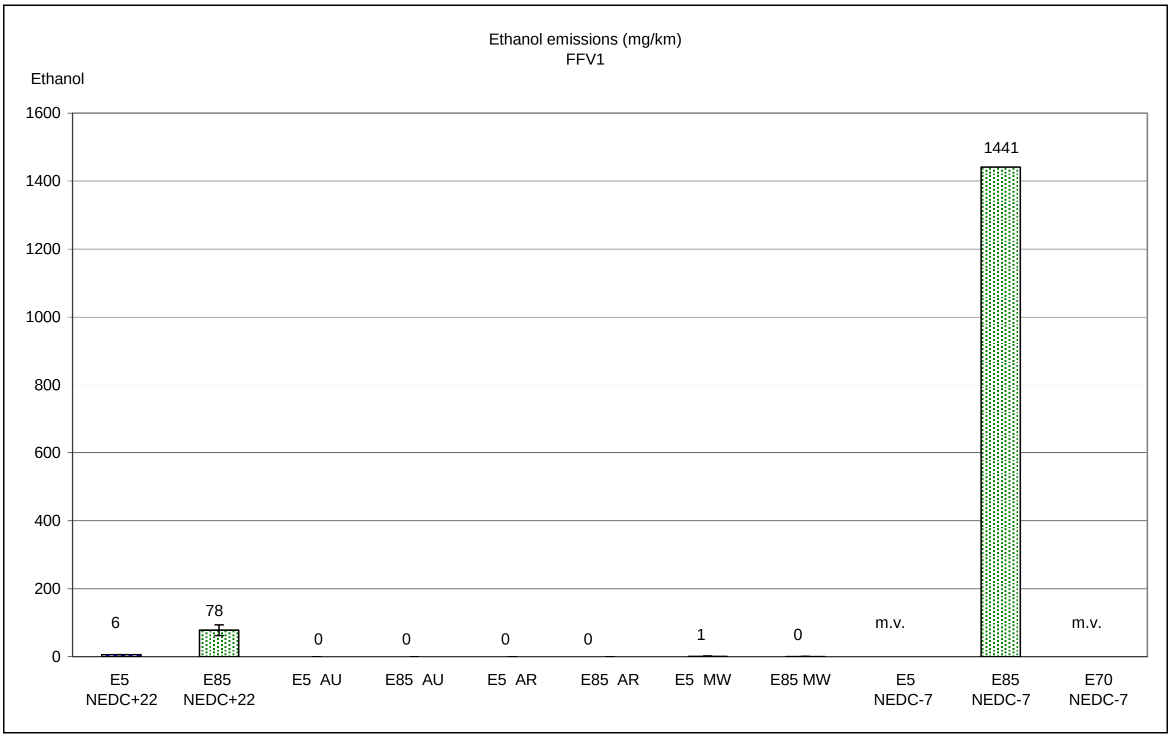

Figure 37. *Ethanol emission from FFV1.*

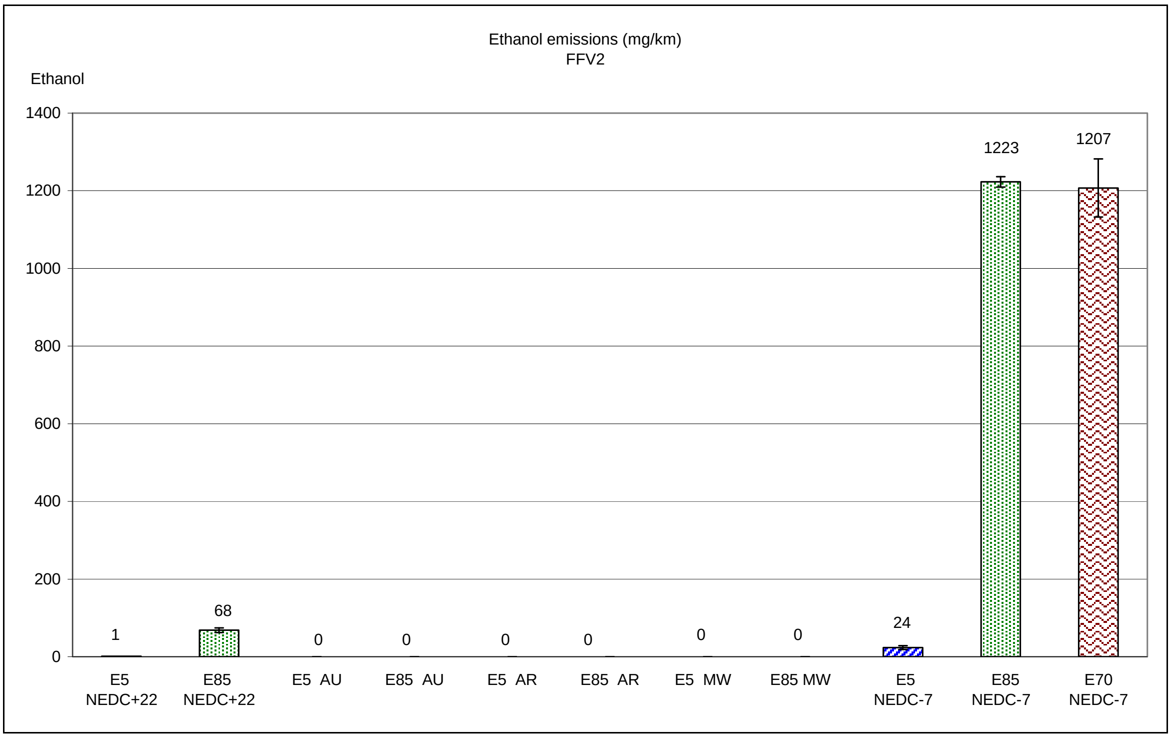

Figure 38. *Ethanol emission from FFV2.*

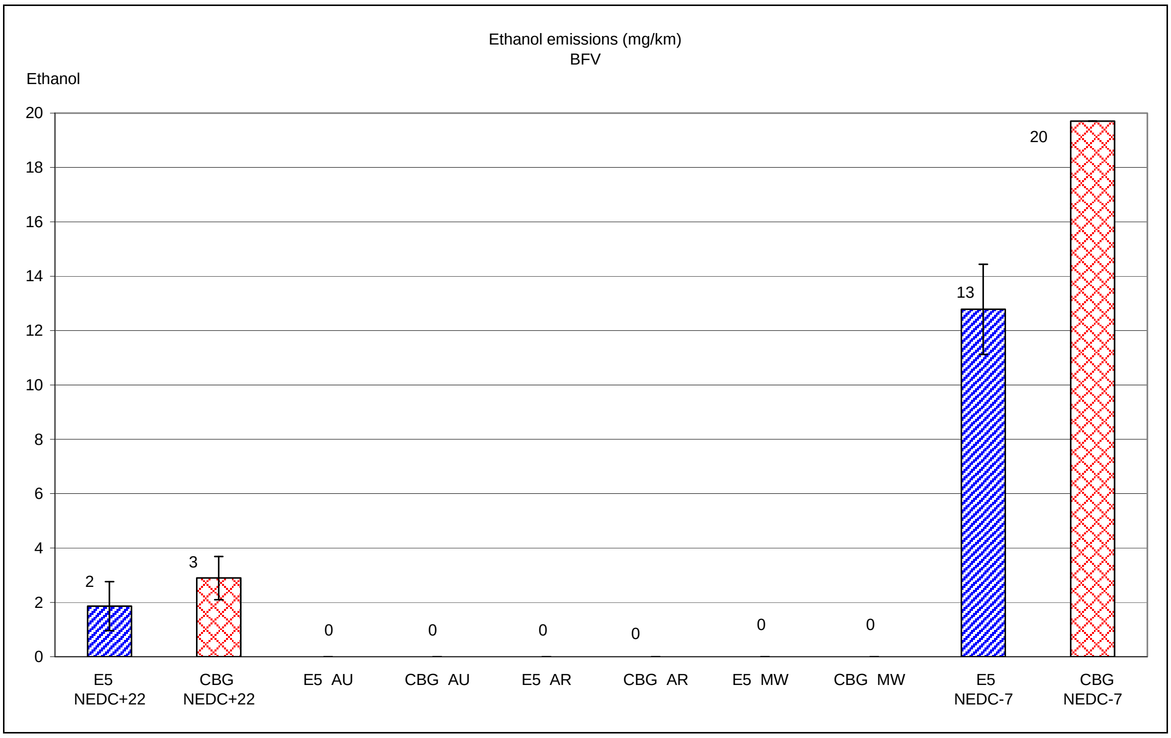

Figure 39. *Ethanol emission from BFV.*

Ammonia

Ammonia (NH_3) emissions from the test vehicles are presented in **Figure 40** to **Figure 42**. Ammonia is only detected at MW tests and -7° NEDC tests of FFV2. At +22°C, the E5 ammonia emissions were higher than CBG or E85.

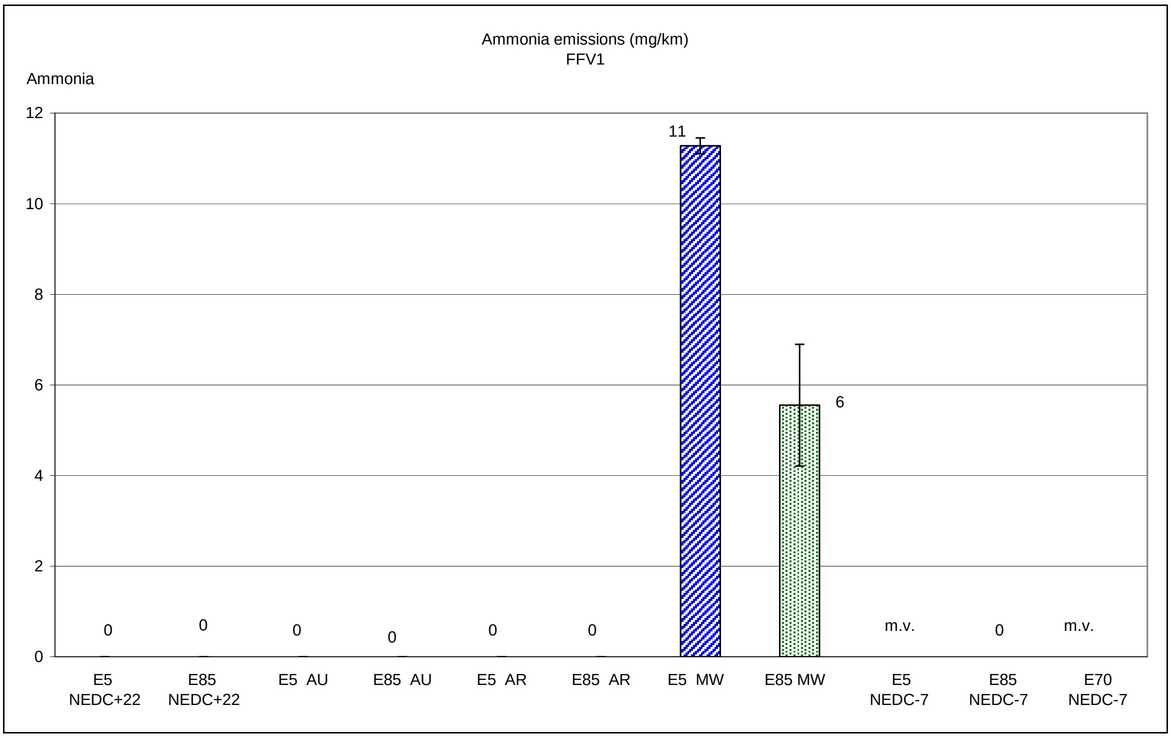

Figure 40. *Ammonia emission from FFV1.*

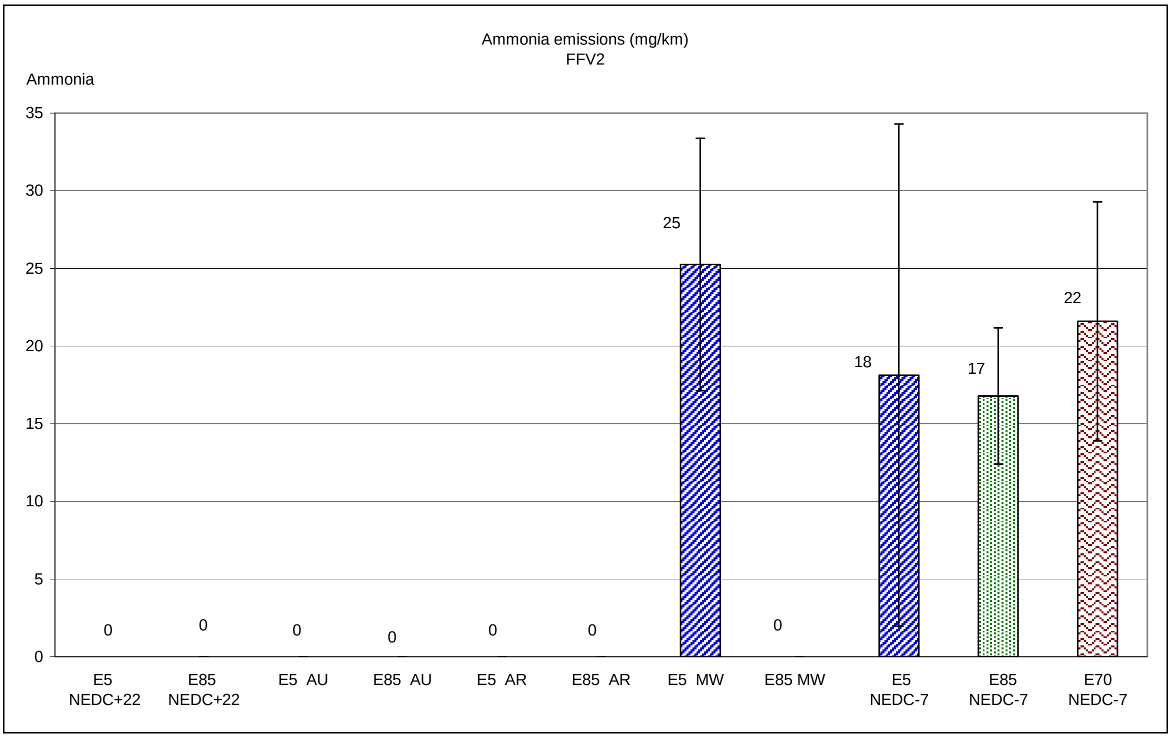

Figure 41. *Ammonia emission from FFV2.*

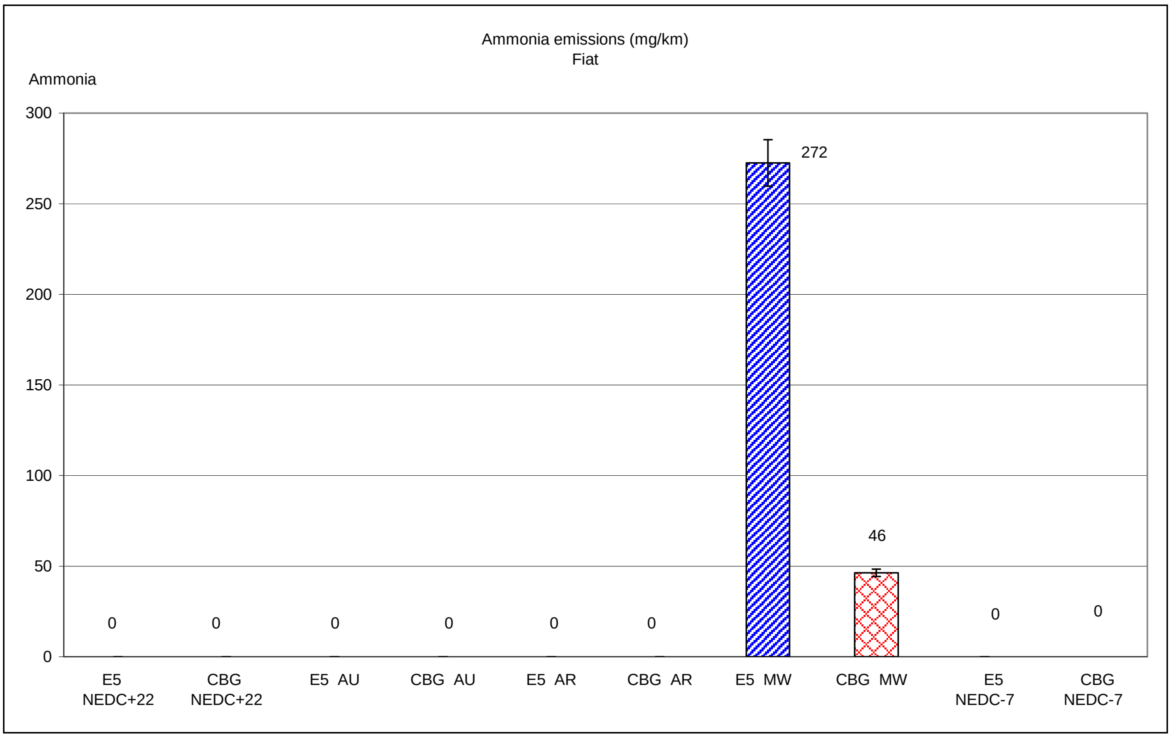

Figure 42. *Ammonia emission from BFV.*

HC speciation

Non-regulated emissions of different HC species from the test vehicles are presented in **Figure 43** to **Figure 57**. The monitored HC species are only detected at MW tests and NEDC tests, and the emissions increase with the -7°C NEDC tests comparing to +22°C tests.

For ethene E85 and E70 have significant higher emissions than E5 at the -7°C NEDC tests of FFV2, whereas the BFV has higher ethene emissions with E5 than CBG at +22°C tests, but the emissions differences between the two fuels are trivial at cold climate tests.

At +22°C tests, E5 has higher propene, benzene and toluene emissions comparing to E70, E85 or CBG. The emissions differences due to different fuel are less significant at -7°C NEDC tests.

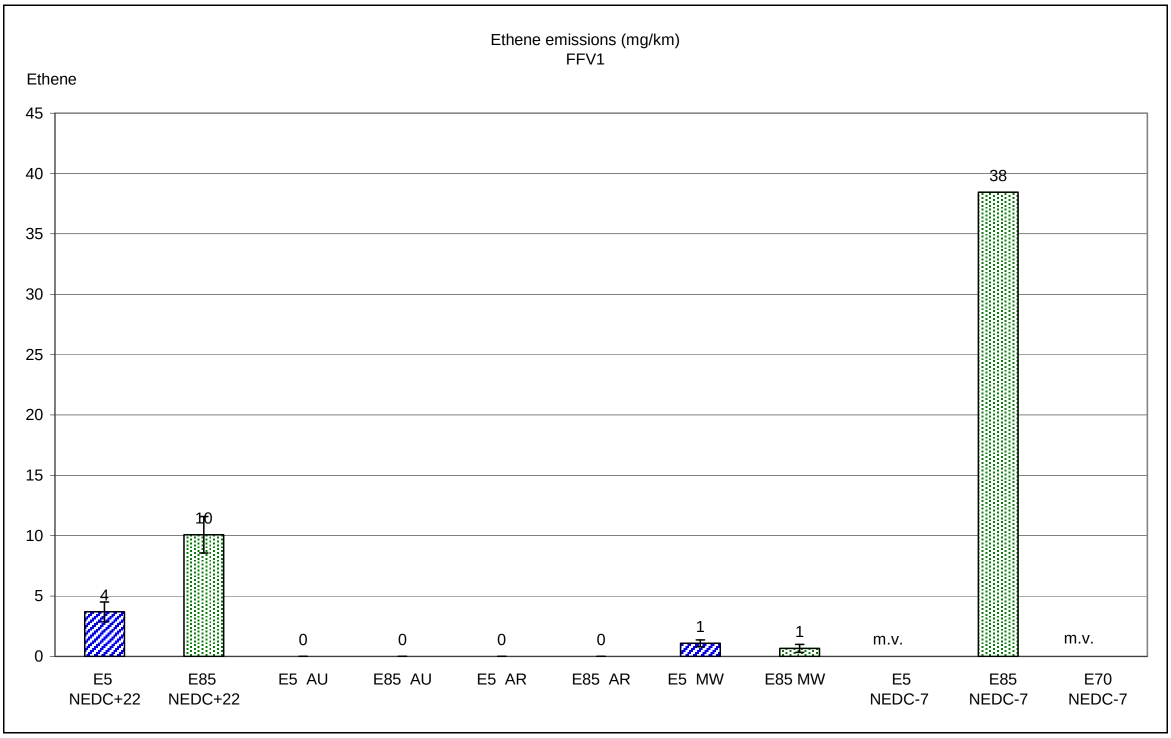

Figure 43. *Ethene emission from FFV1.*

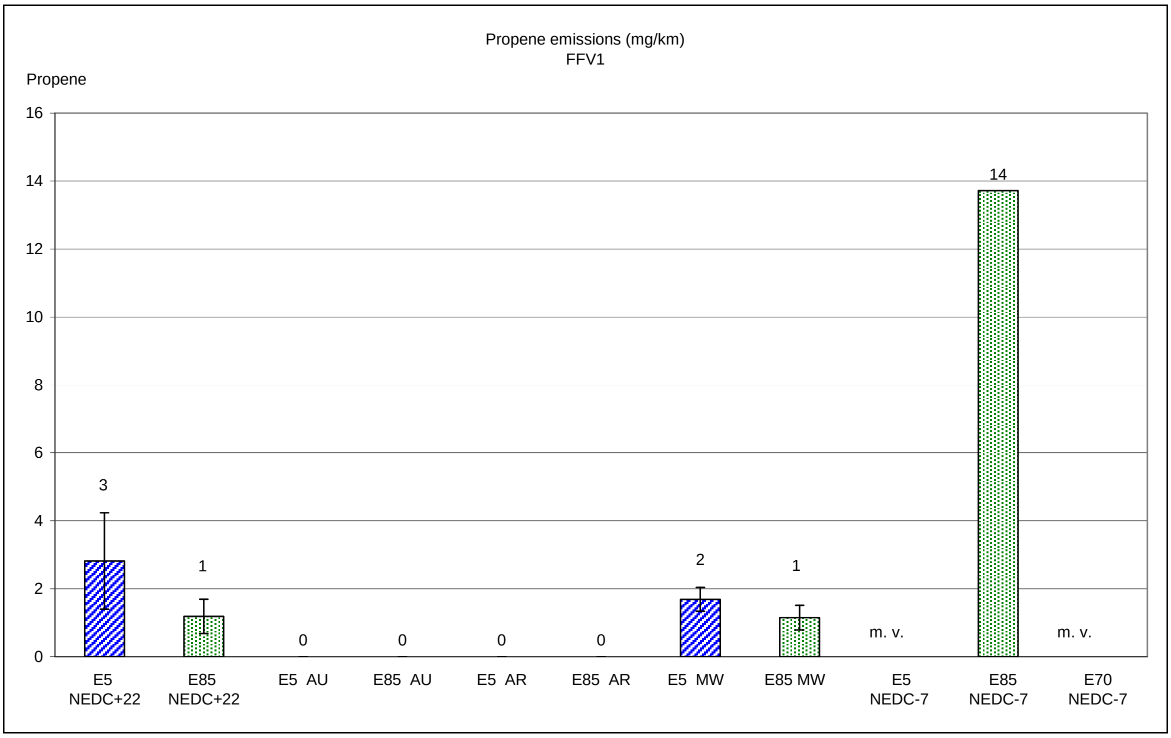

Figure 44. *Propene emission from FFV1.*

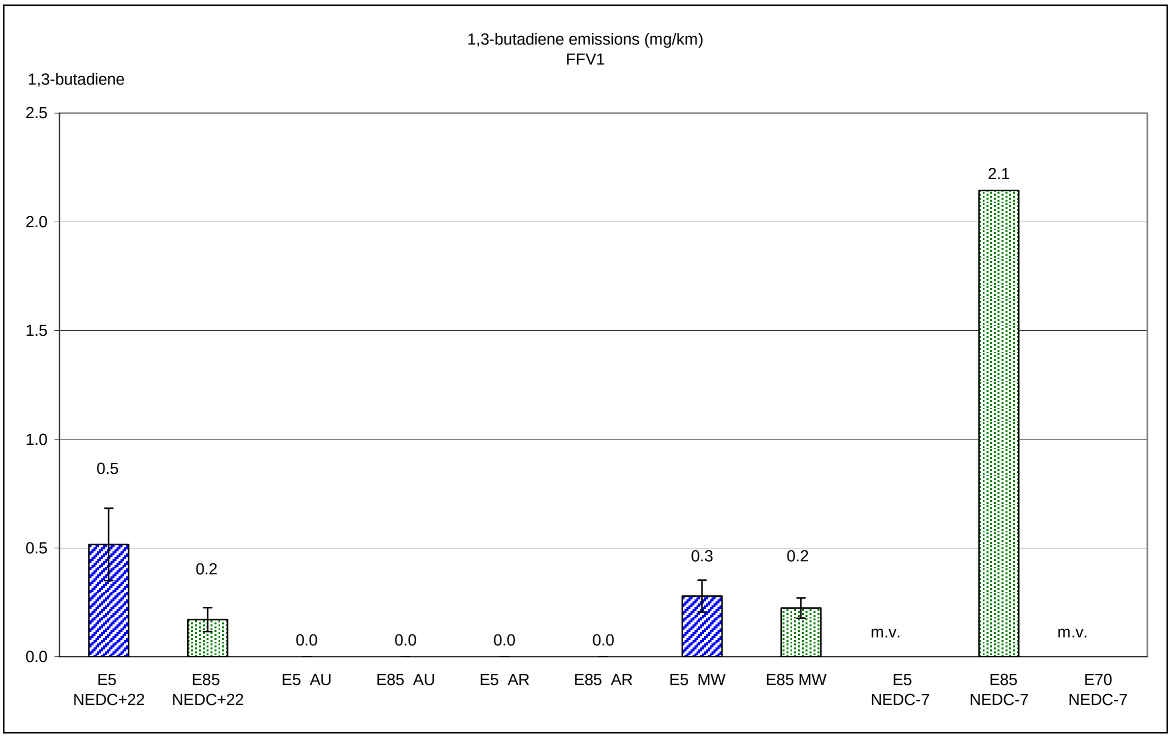

Figure 45. *1,3-butadiene emission from FFV1.*

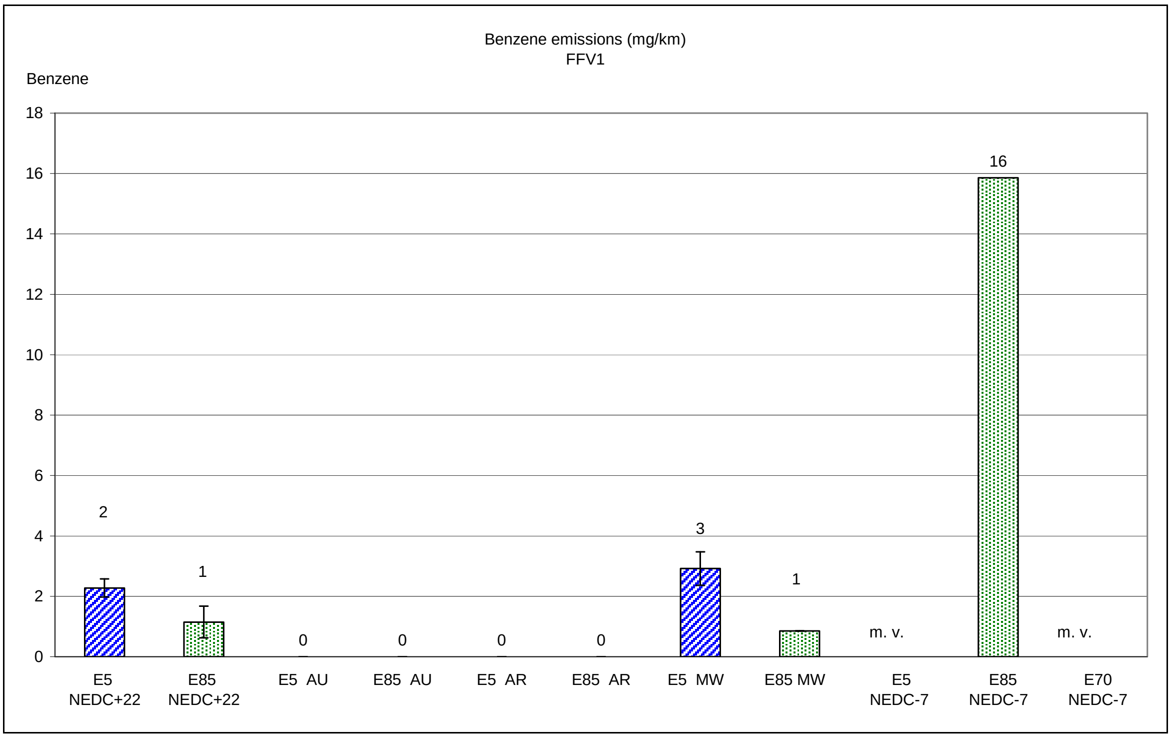

Figure 46. *Benzene emission from FFV1.*

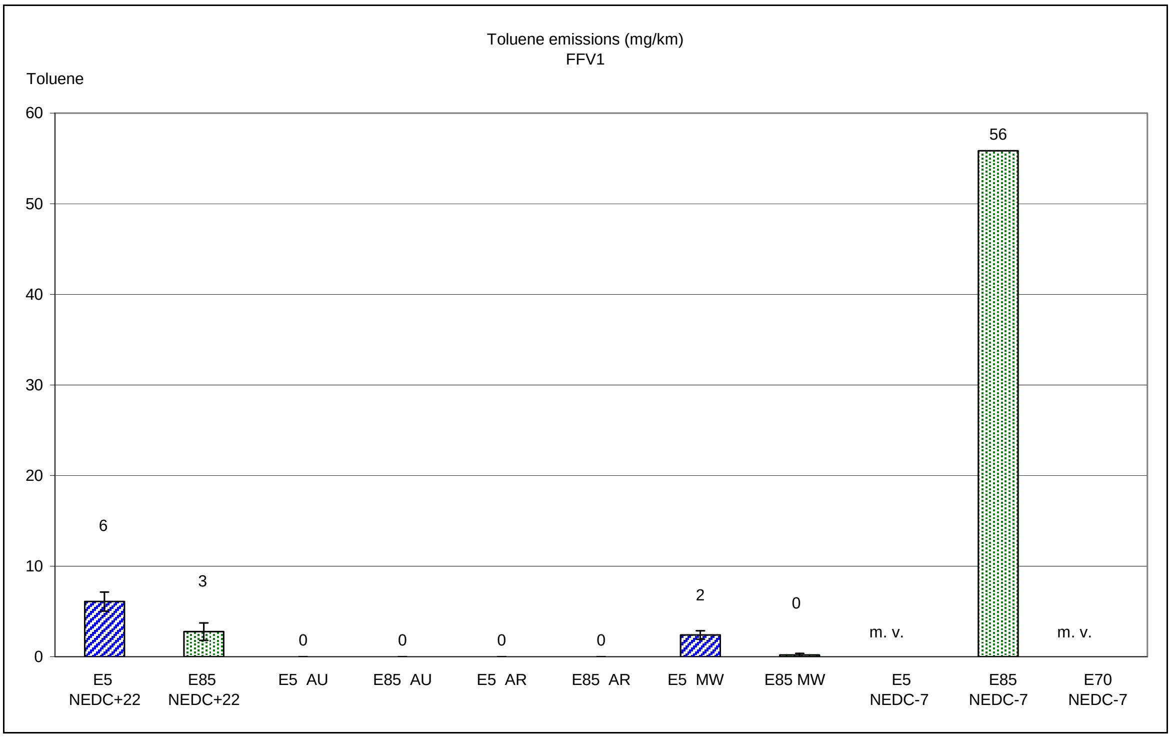

Figure 47. *Toluene emission from FFV1.*

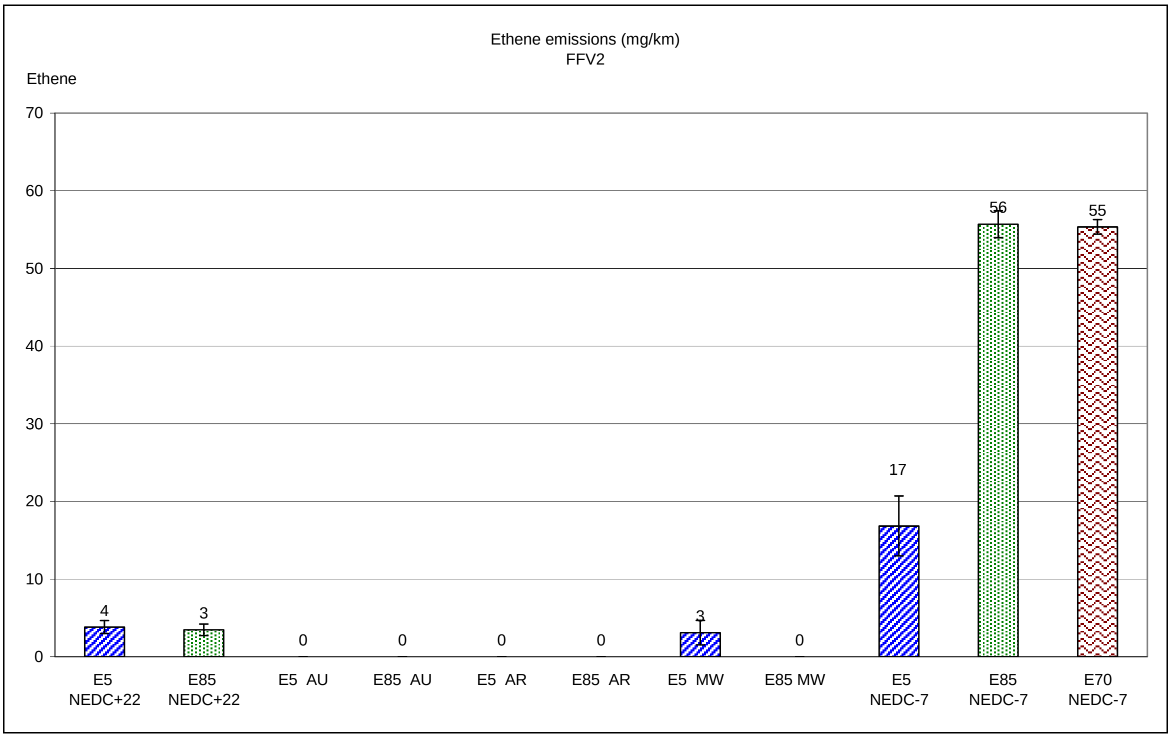

Figure 48. *Ethene emission from FFV2.*

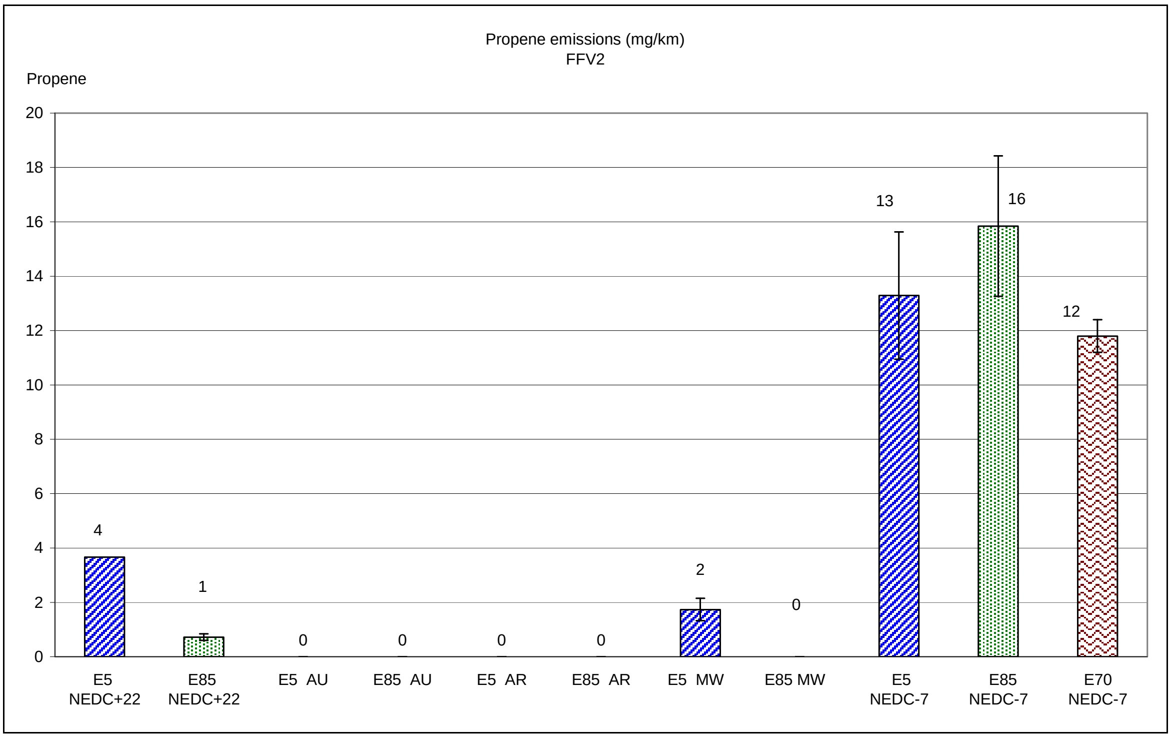

Figure 49. *Propene emission from FFV2.*

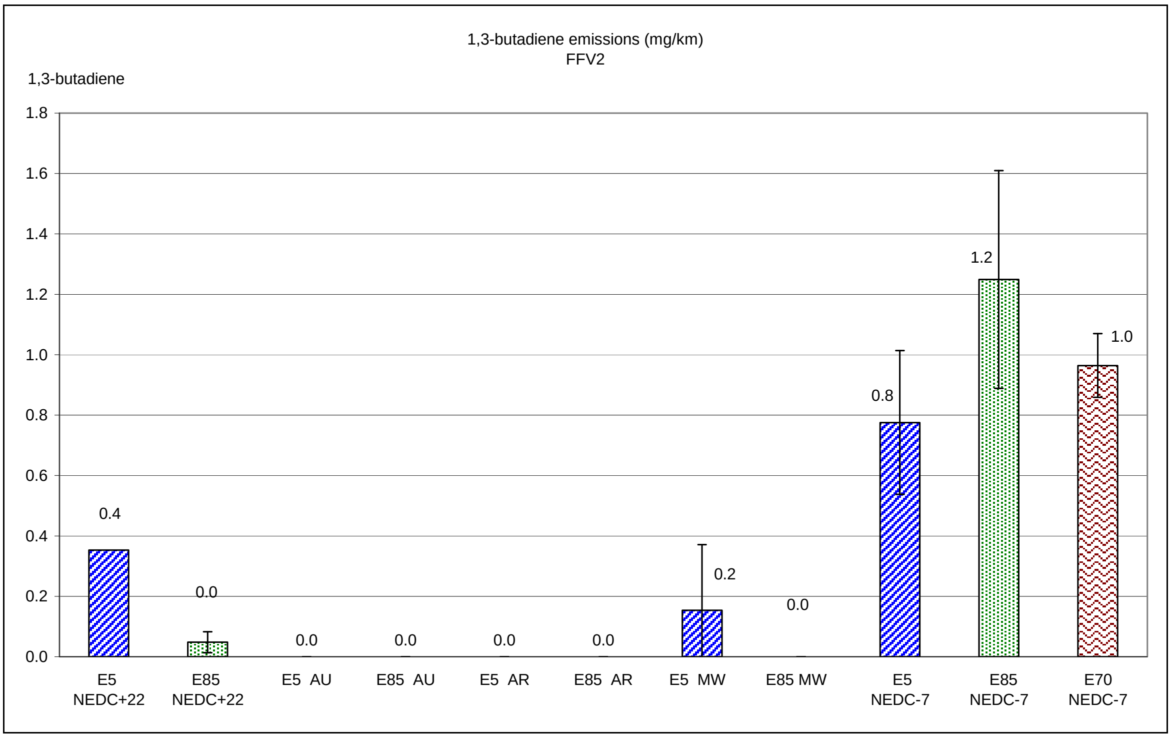

Figure 50. *1,3-butadiene emission from FFV2.*

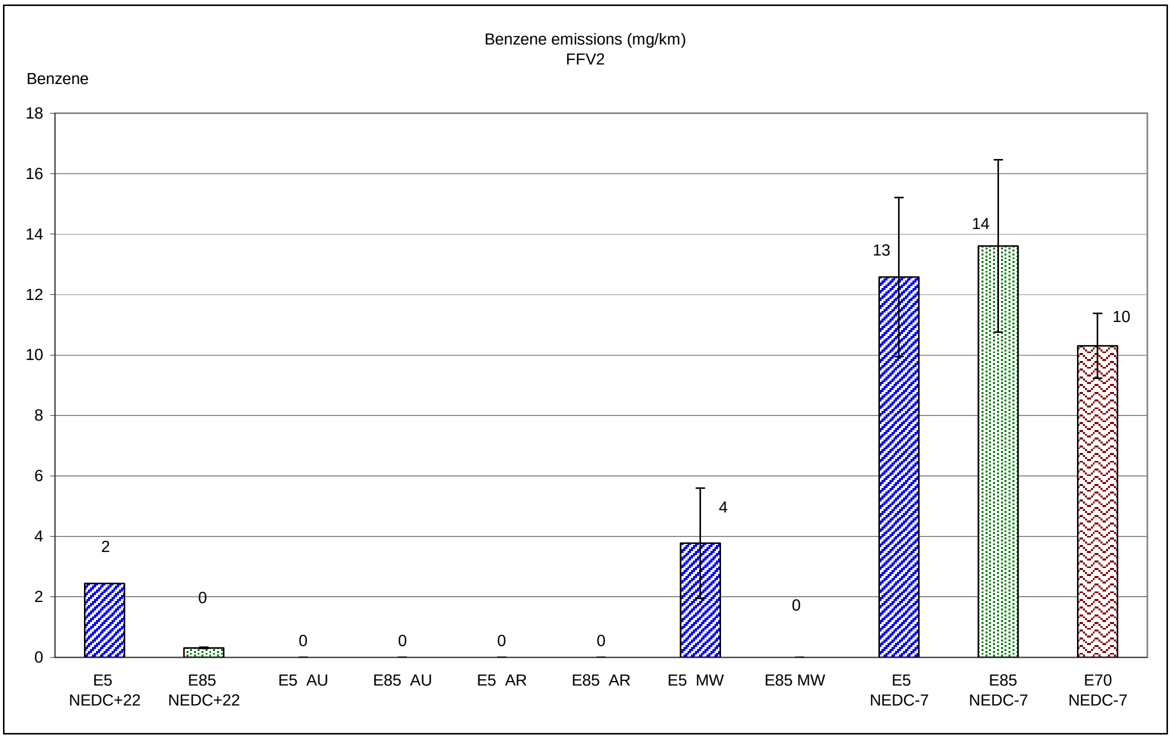

Figure 51. *Benzene emission from FFV2.*

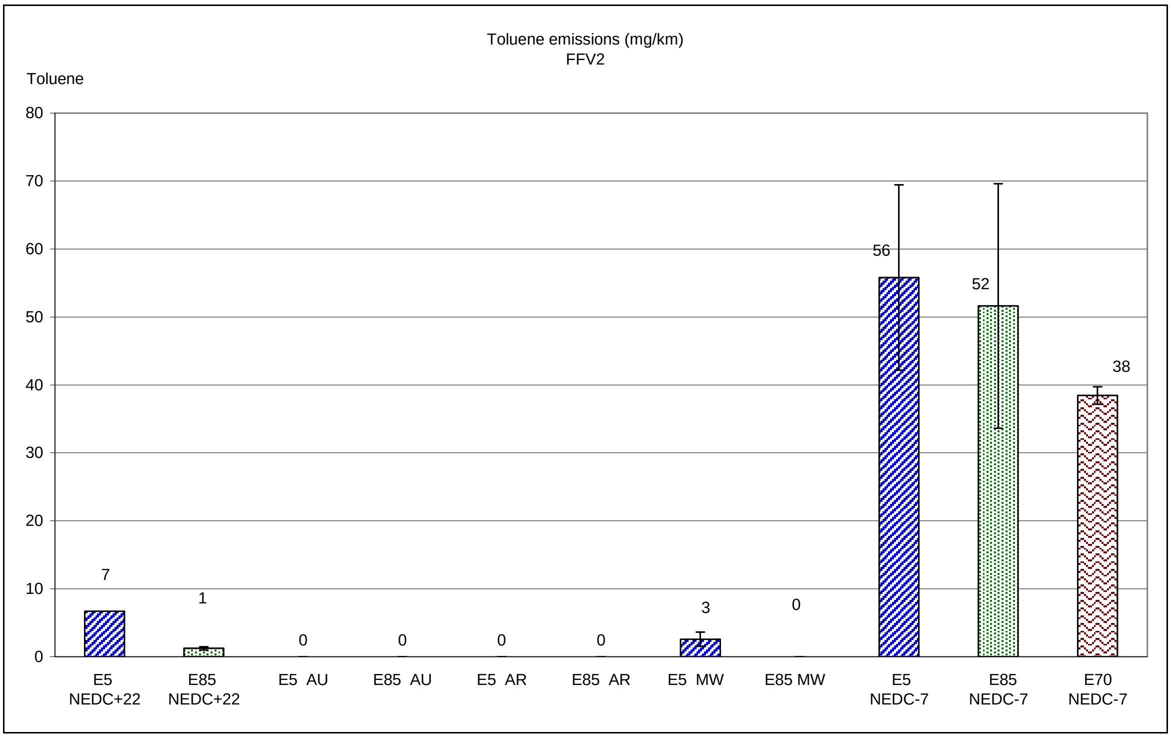

Figure 52. *Toluene emission from FFV2.*

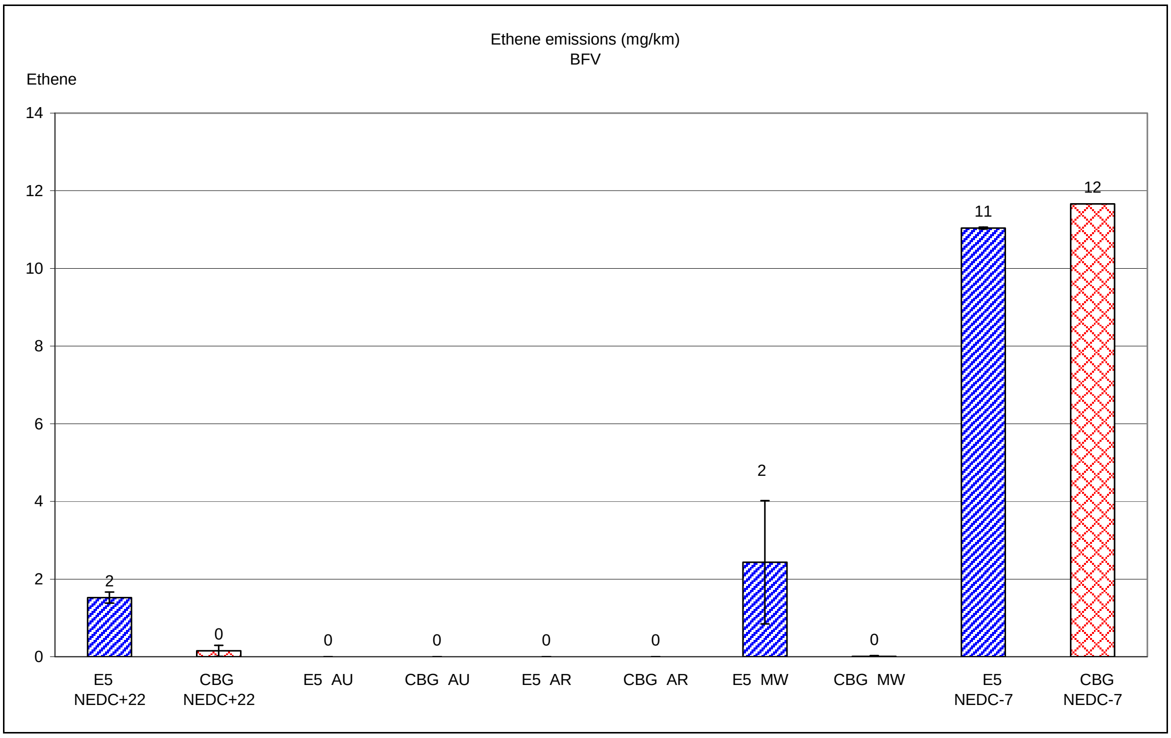

Figure 53. *Ethene emission from BFV.*

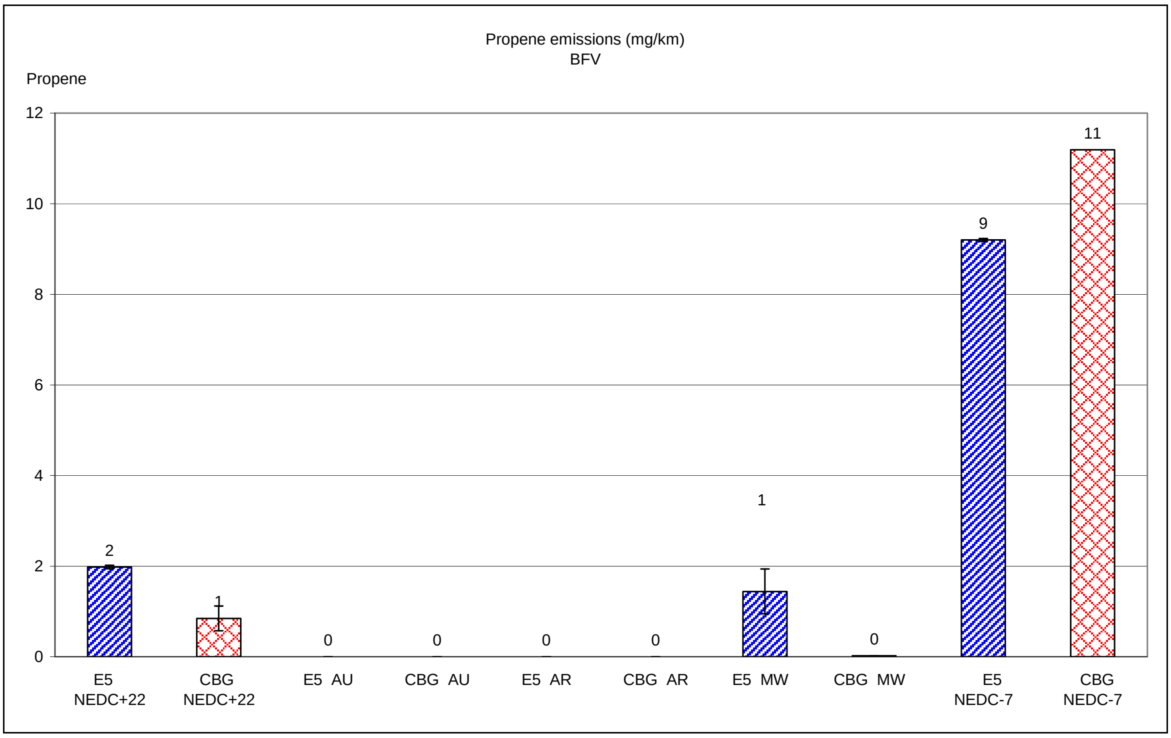

Figure 54. *Propene emission from BFV.*

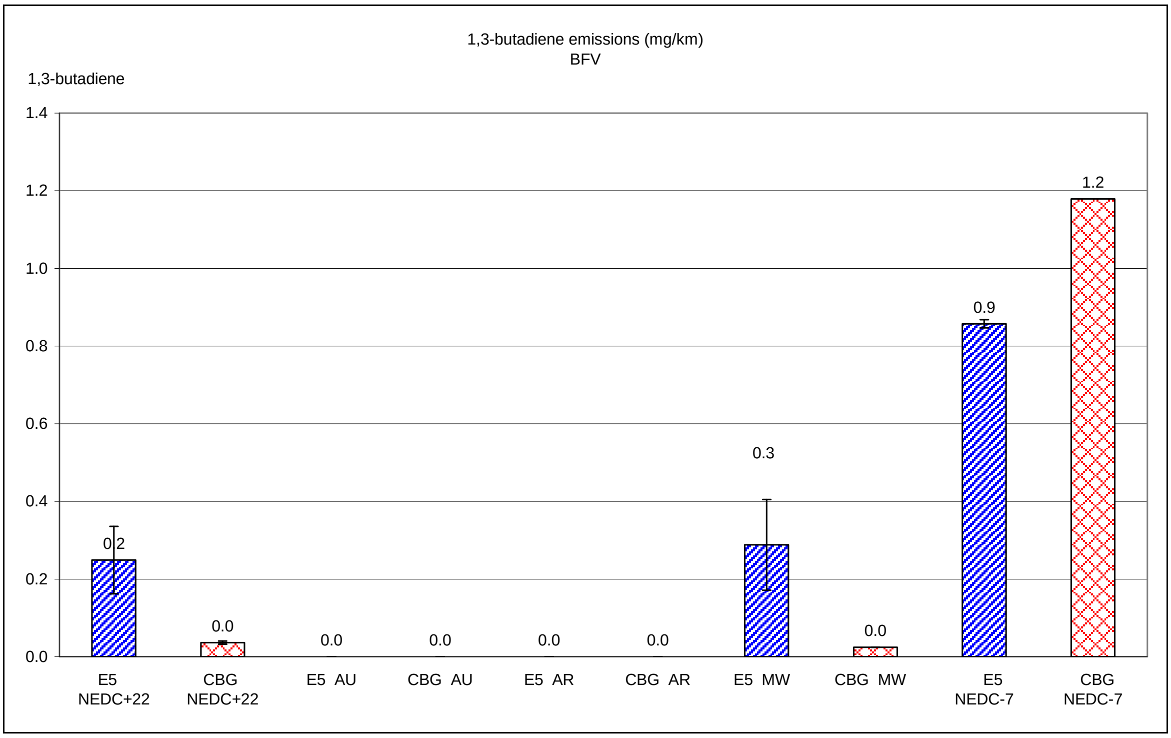

Figure 55. *1,3-butadiene emission from BFV.*

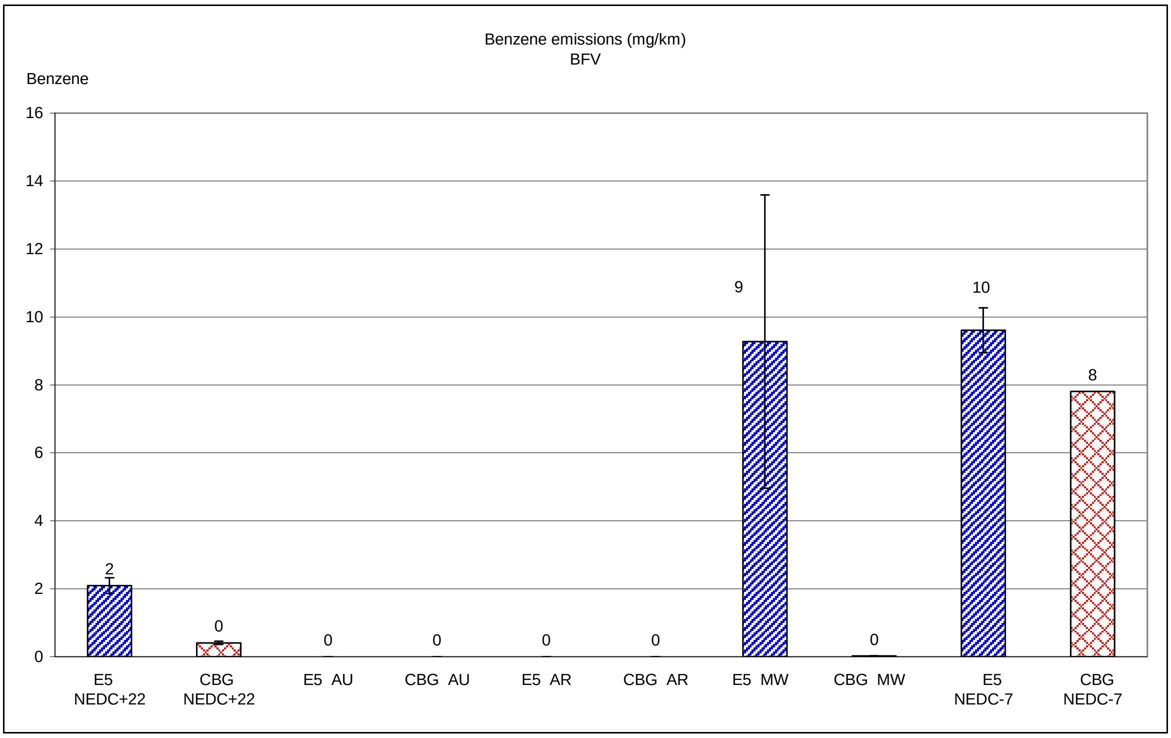

__Figure 56.__ Benzene emission from BFV.

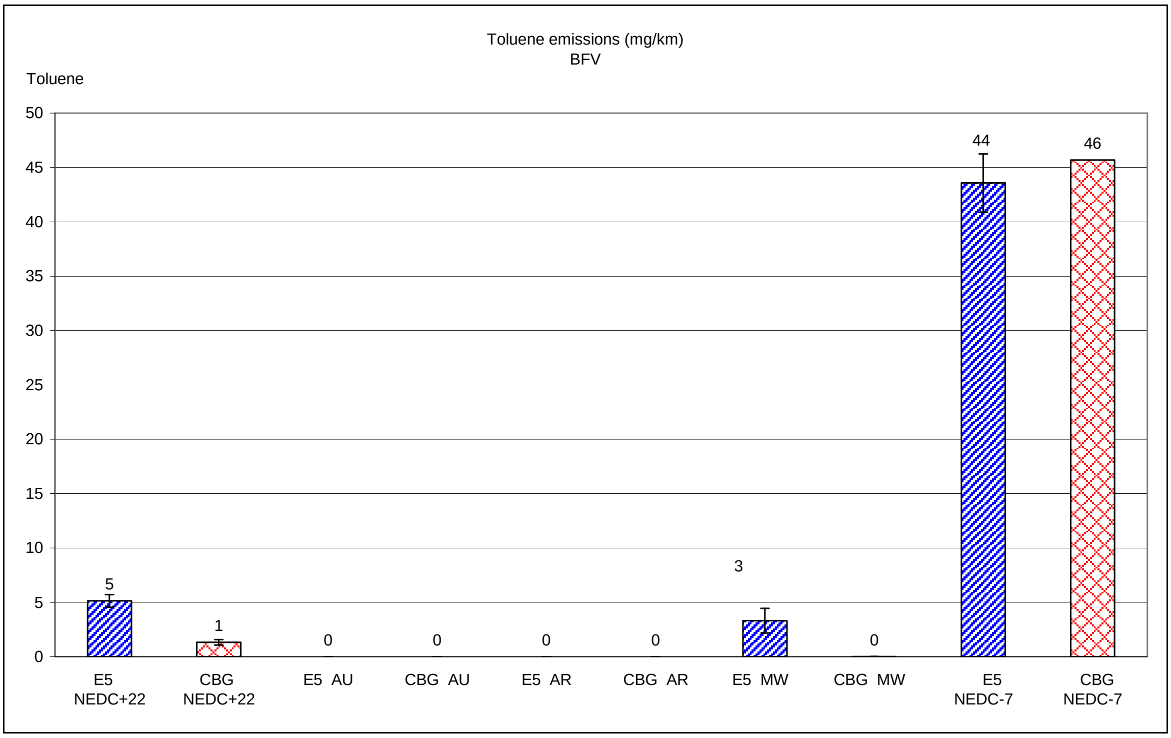

__Figure 57.__ Toluene emission from BFV.

PN emissions

PN emission results measured using PMP methodology and ELPI are presented in **Figure 58** to **Figure 63**. Good correlations between PN_{PMP} measurement and PN_{ELPI} measurement, in most cases the PN_{ELPI} emissions are somewhat higher than the PN_{PMP} emissions.

Comparing to the +22°C NEDC tests, clearly the -7°C tests lead to higher PN_{ELPI} and PN_{PMP} emissions. The CBG PN emissions are always lower than the E5 PN. The FFV2 E85 PN emissions are lower than E5 at +22°C tests except the MW tests, but the differences in PN emissions caused by fuels become trivial at -7°C tests. However the PN emissions from the FFV1 show no clear fuel dependence. Interestingly the PN emissions in related to fuels are in some agreement with the PM emissions in related to fuels.

Figure 64 and **Figure 65** illustrates the PN_{PMP} and PN_{ELPI} emissions from +22°C NEDC tests of the FFV1 and FFV using E5 and E85 fuels. Clearly the emissions are mostly from the cold start and the high way part of the tests cycles, and ELPI and PMP measurements correlate to each other.

In some cases, for example the FFV2 car running on E5 fuel (**Figure 65**), there is a notable difference between the results from ELPI and CPC instruments at the low-load parts of the NEDC test cycle. No detailed investigation of this phenomenon has been made but a possible cause might be that the particle number in these parts of the test cycle is dominated by very small particles. Since ELPI has a cut-point far lower than the CPC, this could explain the difference between the two instruments under the conditions mentioned. The total number of particles in the whole test cycle is dominated by other parts of the test cycle so this difference would is not seen in the total results.

Figure 66 shows that the PN_{PMP} emissions decrease much faster after the cold start with CBF fuel compared to E5 fuel. The rapid switch from E5 fuel to CBG just after the start of the engine is the cause of the observed trend. The PN_{ELPI} emissions are approximately similar during the cold start phase of the NEDC test cycle for both fuels. However, the PN_{ELPI} emissions are significantly higher for CBG compared to E5 during the low load part of the NEDC cycle when the engine is warm. This trend is not visible in the data from the CPC instrument. The most likely explanation for this discrepancy is that the particles in this phase of the driving cycle are significantly smaller for CBG than for E5. The CPC instrument does not measure as small particles as the ELPI instrument.

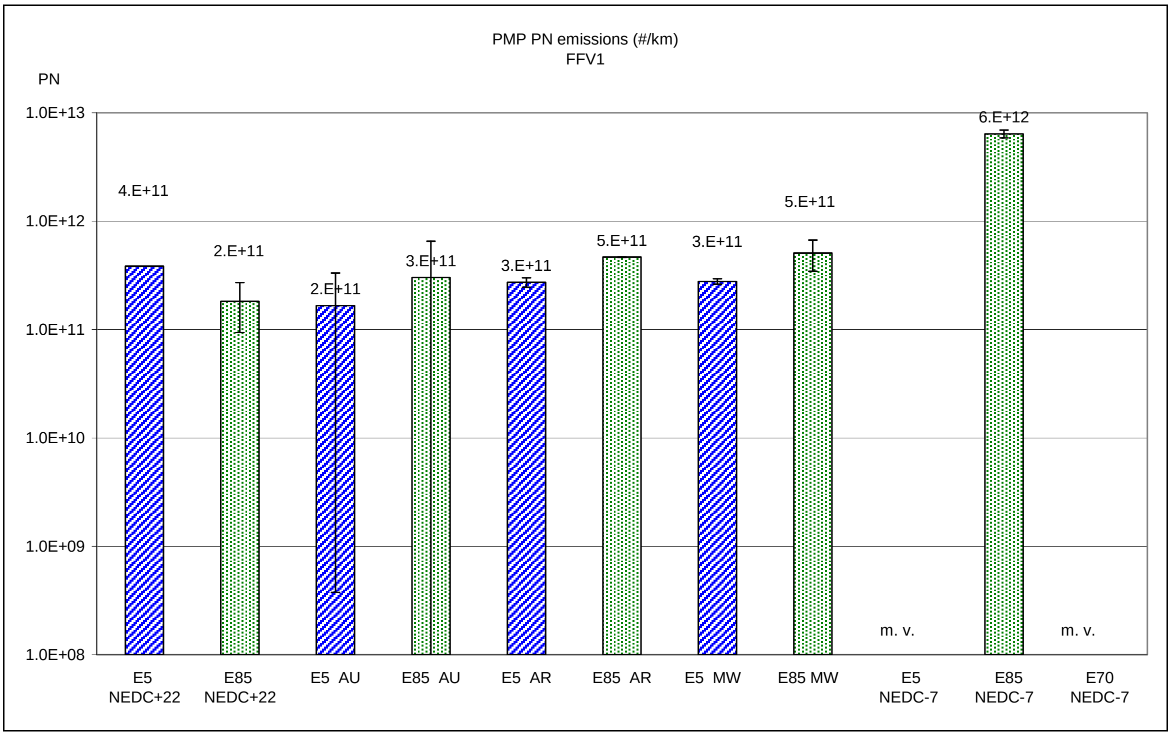

Figure 58. *PMP PN emission from FFV1.*

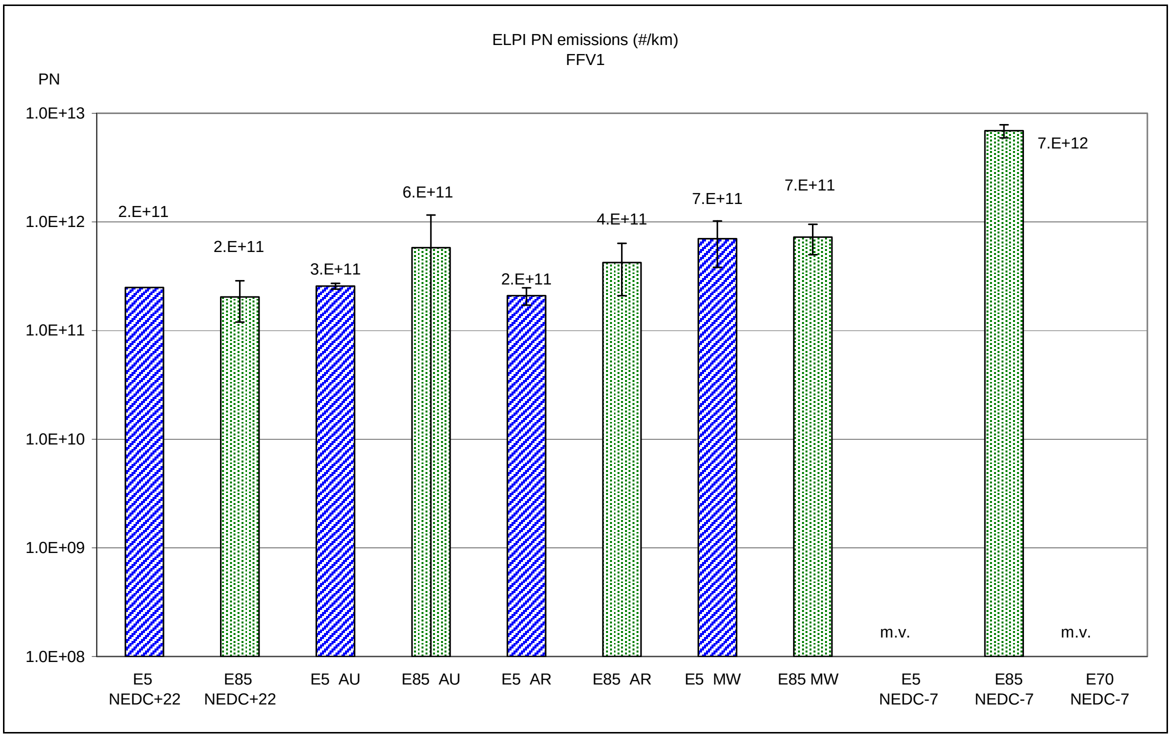

Figure 59. *ELPI PN emission from FFV1.*

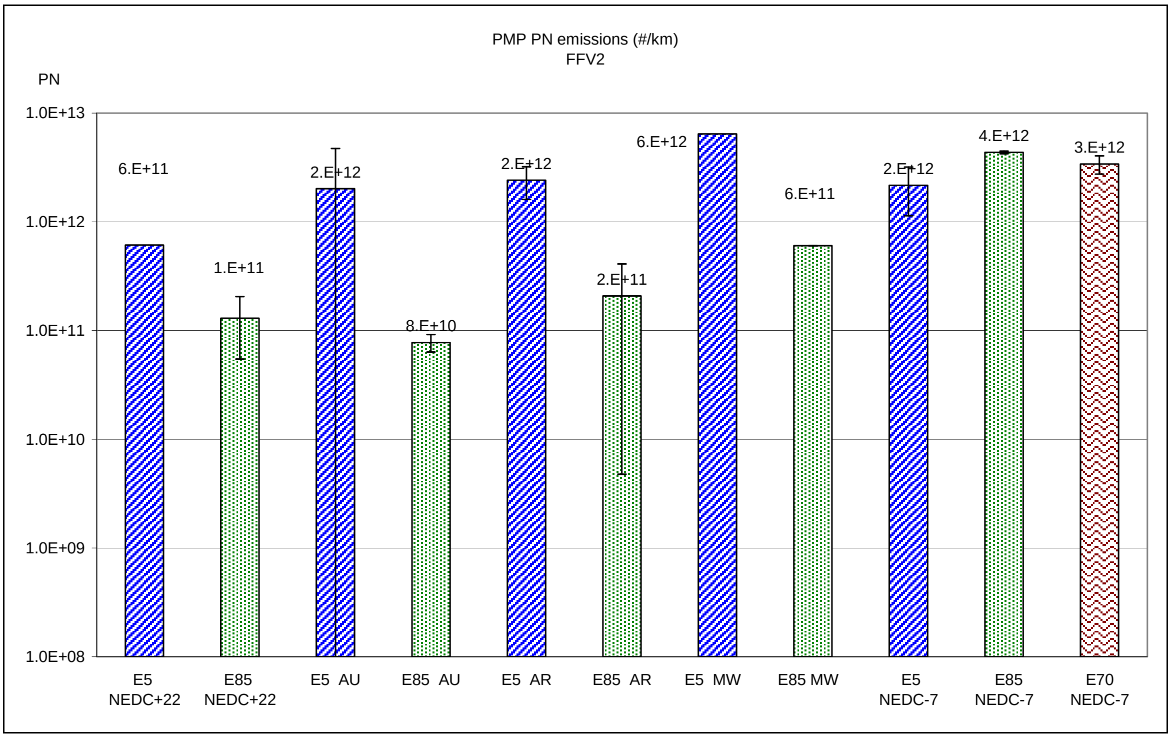

Figure 60. *PMP PN emission from FFV2.*

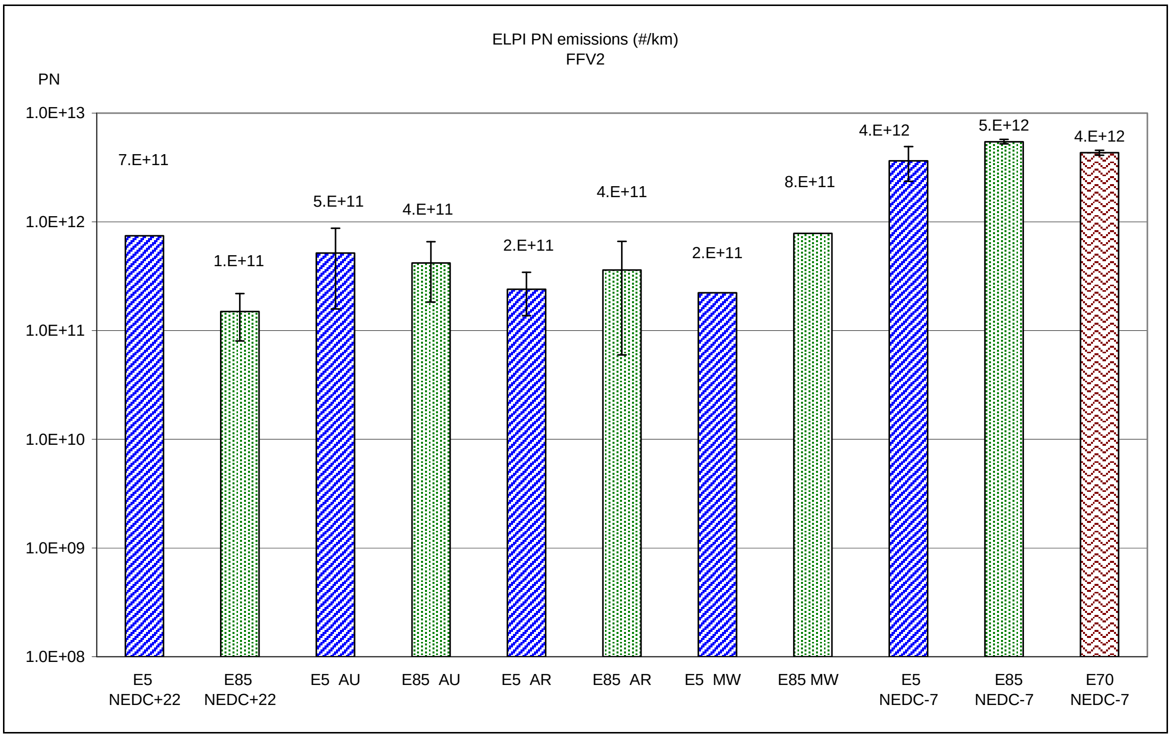

Figure 61. *ELPI PN emission from FFV2.*

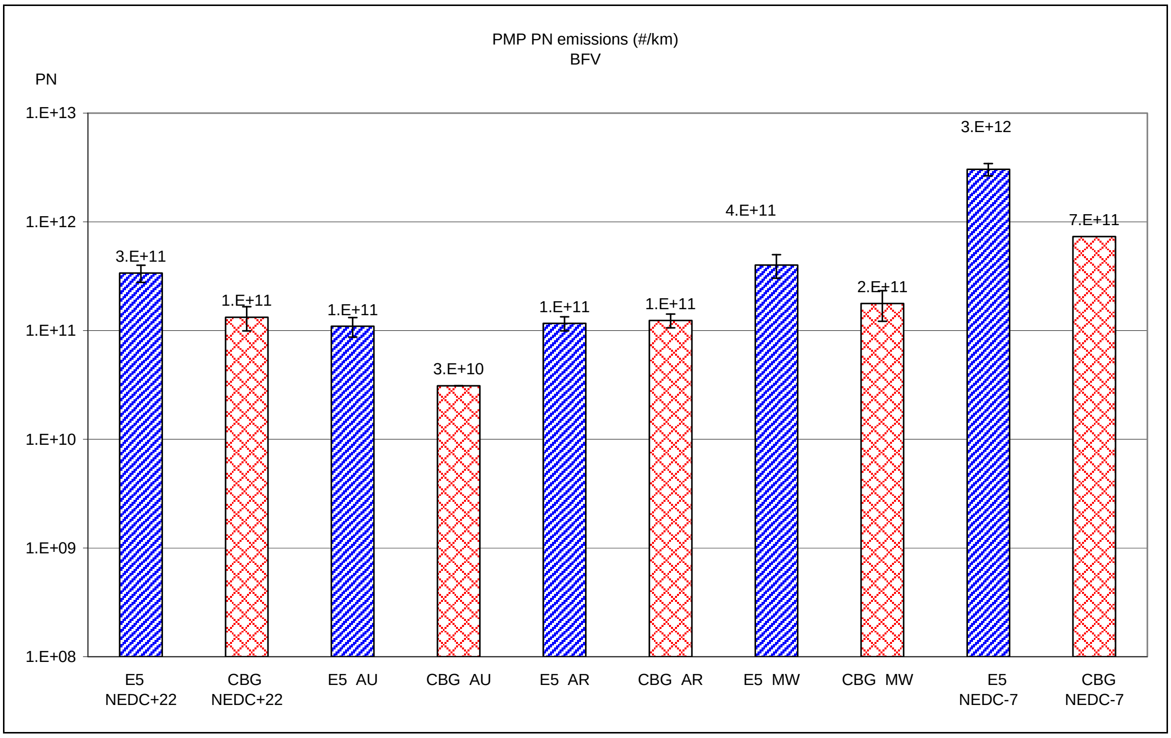

Figure 62. *PMP PN emission from BFV.*

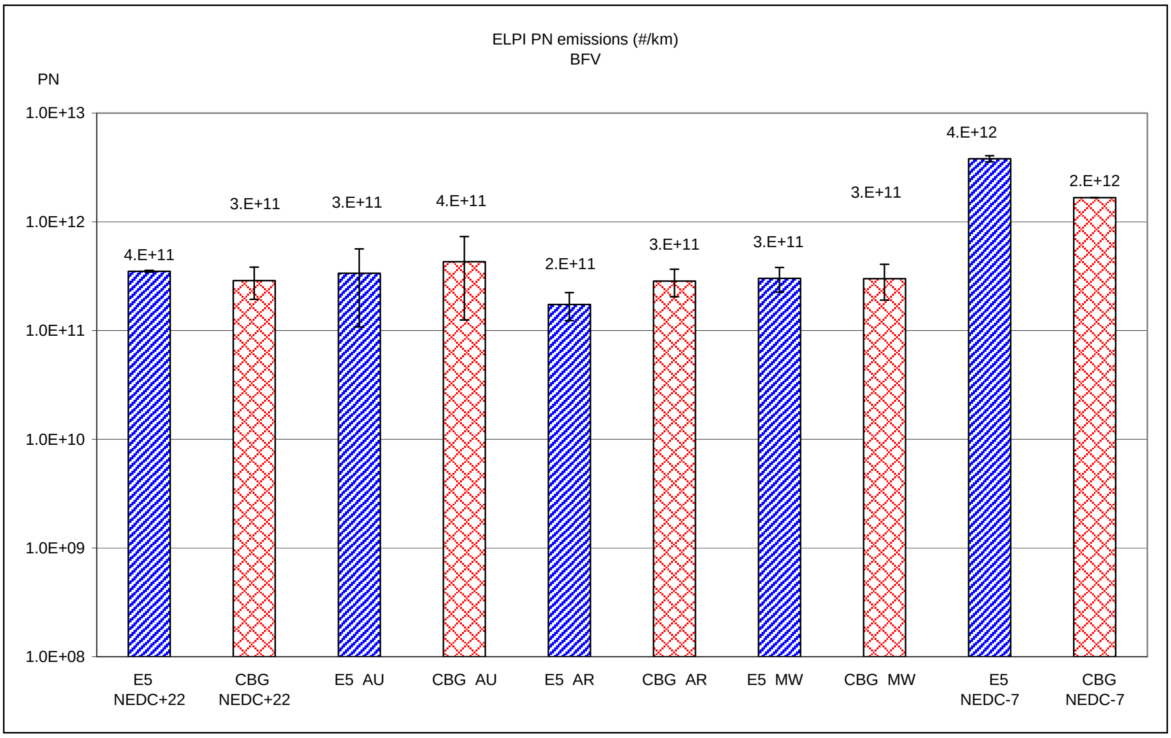

Figure 63. *ELPI PN emission from BFV.*

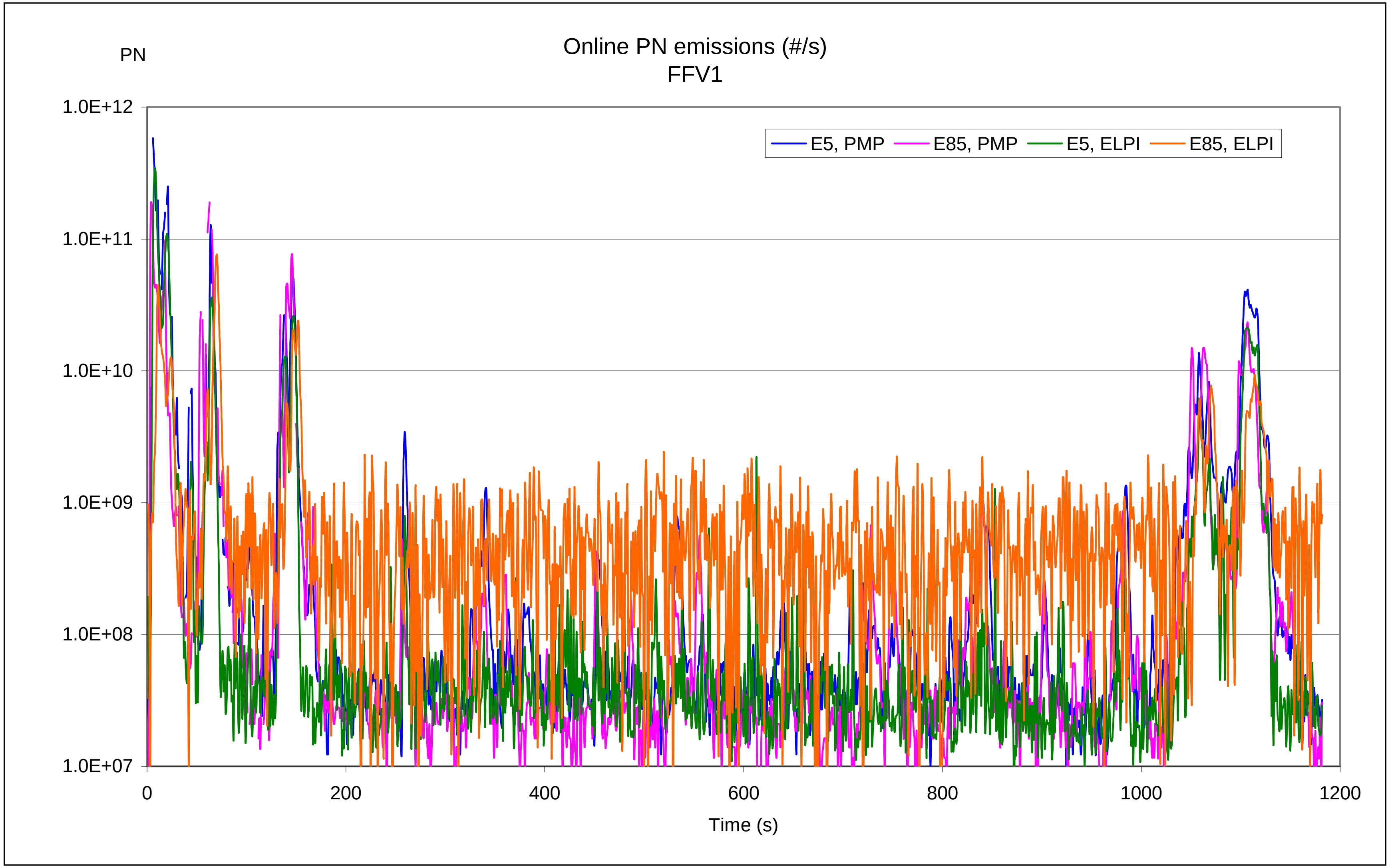

Figure 64. *PN emission from FFV1 NEDC tests at +22°C.*

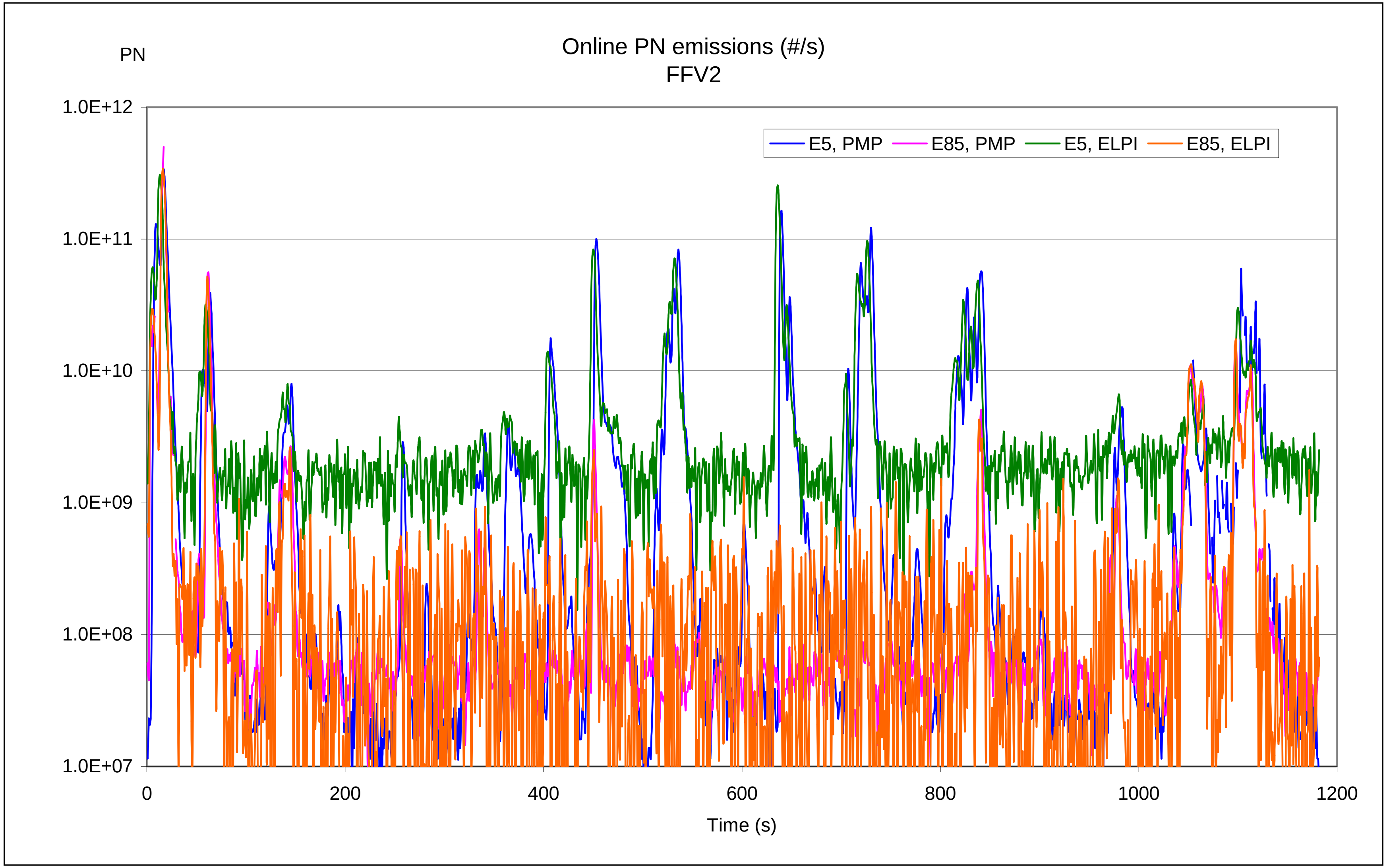

Figure 65. *PN emission from FFV2 NEDC tests at +22°C.*

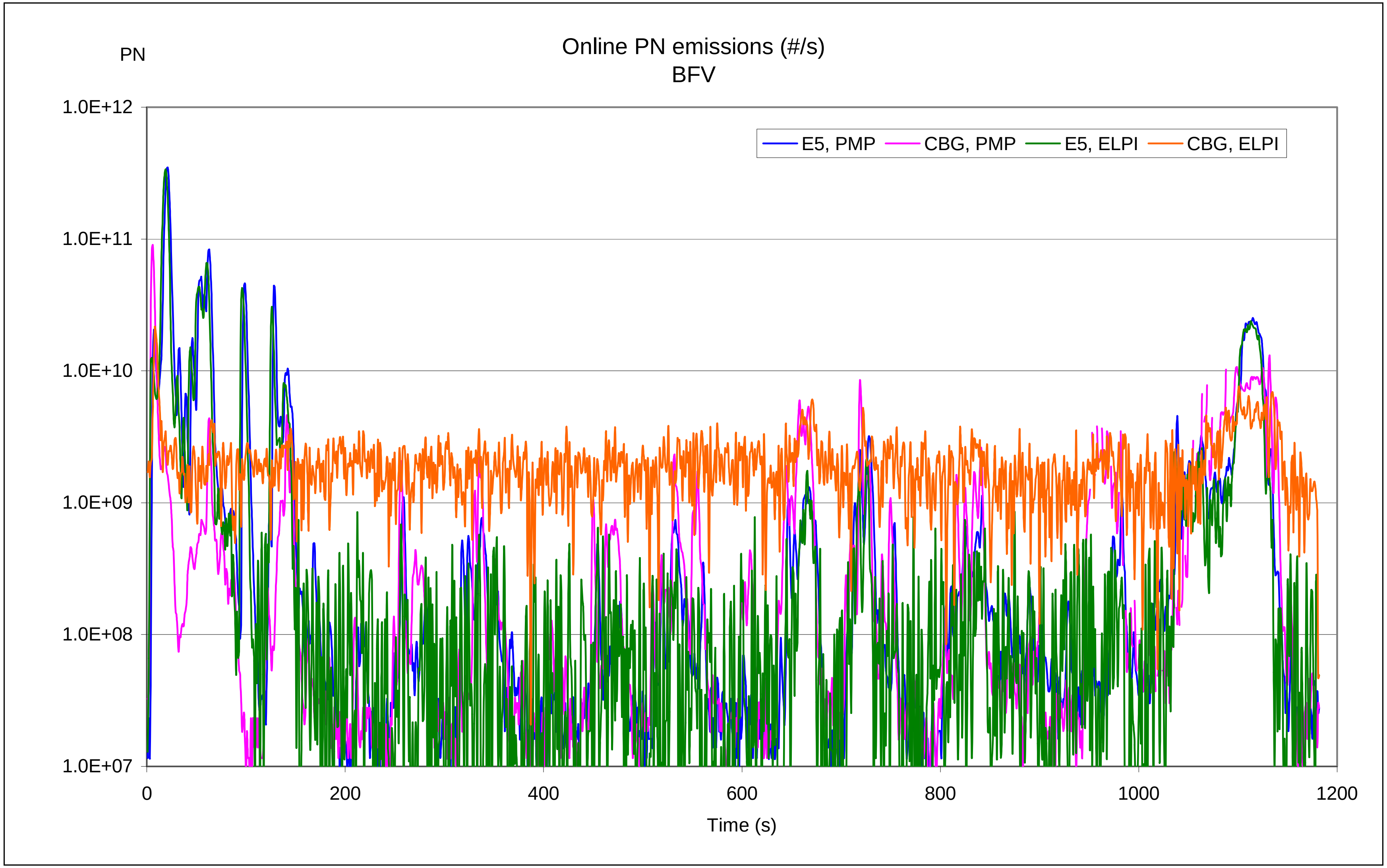

Figure 66. *PN emission from BFV NEDC tests at +22°C.*

Figure 67, **Figure 68** and **Figure 69** show the particle size distribution as measured by the ELPI instrument in the NEDC test cycle.

Figure 67 illustrates that the particle size distribution in the NEDC tests of the FFV1 has a similar pattern with a maximum at slightly below 100 nm for all fuels. However, the level at -7°C is significantly higher than at +22°C for all sizes. By comparing the two fuels at +22°C it can be seen that the level for E85 is lower than for E5, except for the smallest size class of particles (7-30 nm), where E85 has a higher level.

The size distribution curves for the FFV2 vehicle, as shown in **Figure 68**, have relatively similar shape for all fuels and test temperatures. E85 at +22°C has generally the lowest level, i.e. lower than E5 at the same temperature. The level at -7°C is relatively similar for all three tested fuels.

Figure 69 shows a higher number of particles for the lower test temperature compared to the higher temperature. This conclusion is valid for both fuels. The relative difference between the test temperatures is approximately one order of magnitude in each case. CBG has a lower level than E5 for all sizes above 30 nm, whereas the level is higher for CBG in the smallest size class (7-30 nm).

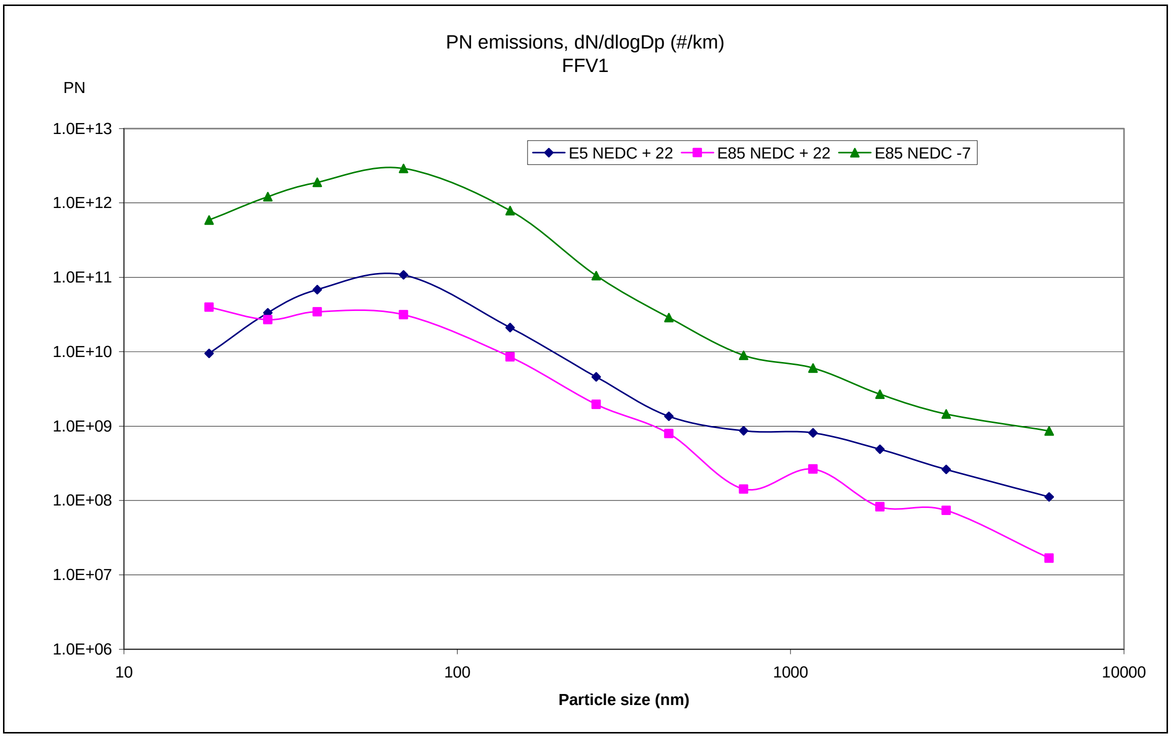

Figure 67. *Particle size distribution of FFV1 NEDC tests.*

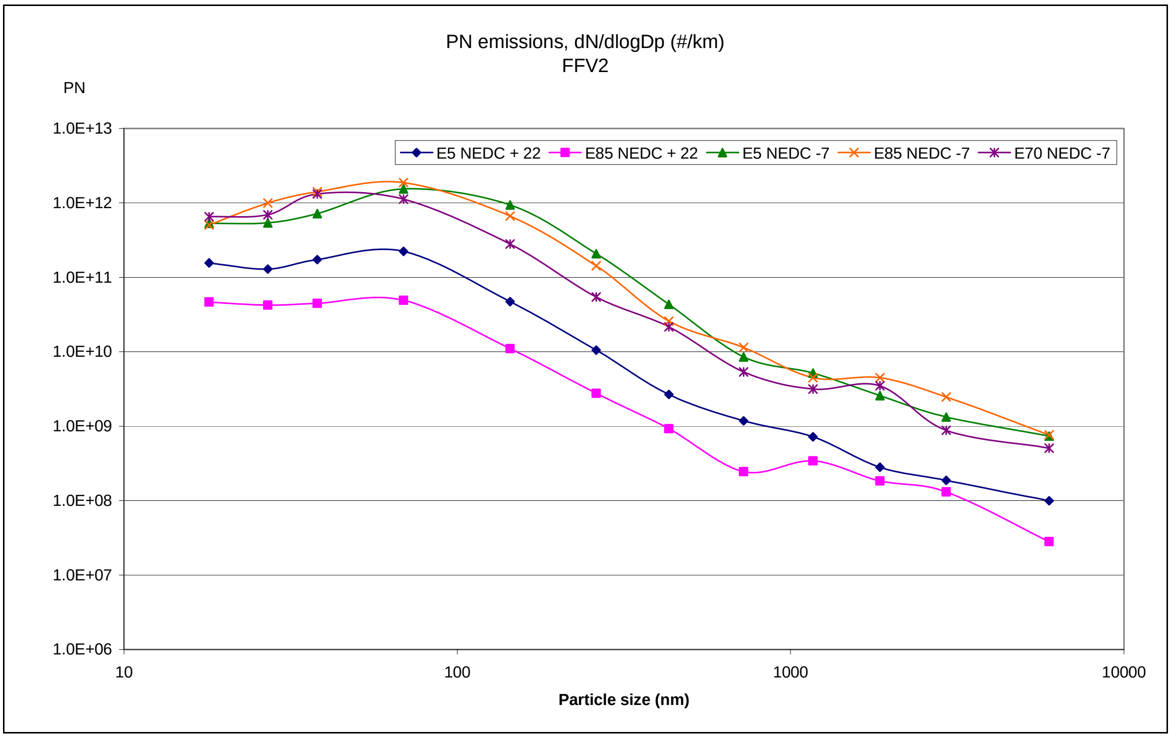

Figure 68. *Particle size distribution of FFV2 NEDC tests.*

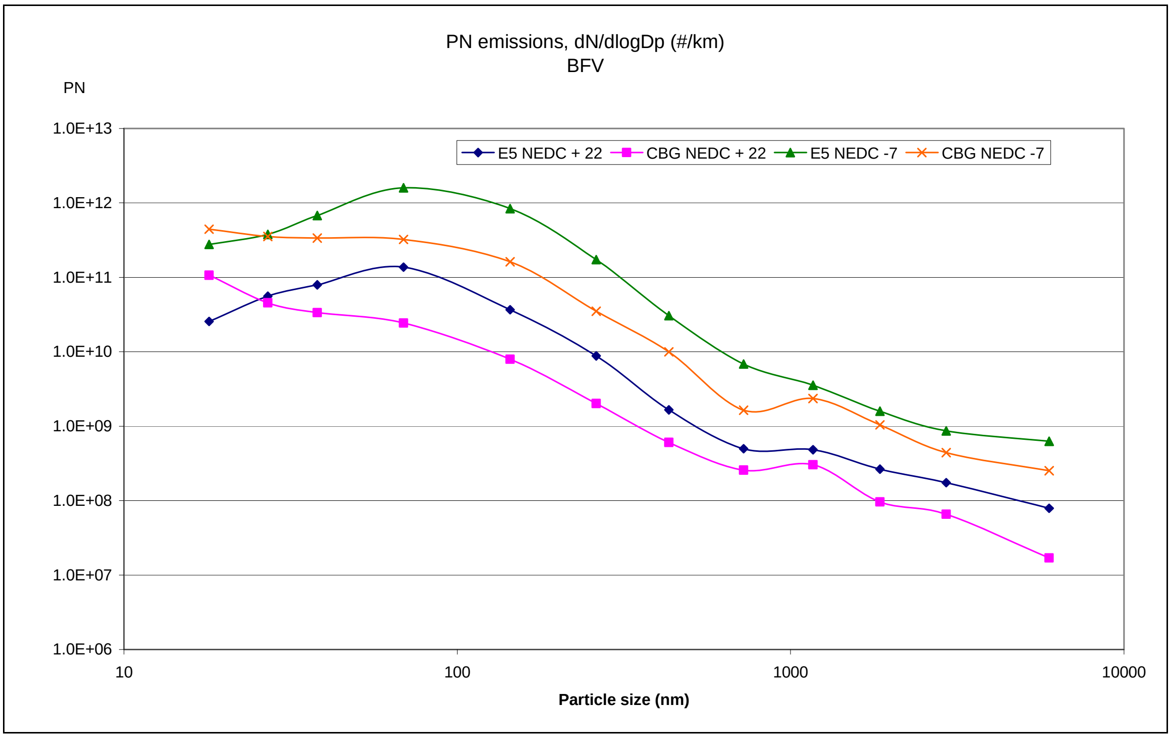

Figure 69. *Particle size distribution of BFV NEDC tests.*

Particle mass emissions measured with DMM

As previously mentioned, particle mass emissions were measured using the DMM instrument as a complementary method to the gravimetric measurements. The main advantage of real-time measurement is obviously that much more information can be obtained than by using the conventional gravimetric method.

During the measurements, some problems were experienced that significantly reduced the data collected. The problems encountered with the FFV1 car regarding its adaptation in changing fuel resulted in that several of these tests had to be repeated. When these tests were repeated couple of weeks later, it was unfortunate there was no access to the DMM instrument and the FPS dilution system during that time. Thus, no data from the DMM instrument are available from these repeat tests. Furthermore, during the initial part of the test series, a problem with the DMM instrument was experienced. A dirty BNC connector caused creeping currents, which corrupted the data. Although cleaning with acetone and subsequent drying of the connector solved this problem, data from a couple of tests are probably not reliable. In the figures below, missing data can be noted in two ways. First, there is no measurement scatter bar (highest and lowest value), i.e. there is only one measurement and no duplicate test. Second, there is a note “i.d.” (“invalid data”) or, in some cases, “m.v.” (“missing value”), indicating that data are not valid or missing.

In all the figures below showing bar diagrams of data from the whole test cycles, the unit mg/km has been used in all cases, except for the overtaking tests. Since the overtaking distance is different from car to car and also from fuel to fuel, it not meaningful to express the emissions in mg/km. Instead, the unit mg/test has been used. Therefore, no direct comparisons between overtaking and the other test cycles should be made. For example, the NEDC has a total distance of about 11 km but it is hardly likely – however not completely impossible – that a driver could overtake 11 lorries during this distance. Thus, in a direct comparison between bars in those diagrams, the importance of overtaking could be exaggerated.

In **Figure 70**, the DMM PM results from the FFV1 car are shown. In general, the PM levels are very low, i.e. below 1 mg/km in all cases where representative data have been obtained. The scatter in some cases is rather high due to this reason.

There is no noticeable advantage in PM emissions for E85 over petrol at the tests run at +22°C. Much higher levels were recorded for the FFV1 car when the fuel adaptation was not correct. However, these data have been omitted, since they are not considered representative of a well-functioning car.

It can be seen in **Figure 70**, that there is a tendency to increased levels in the Artemis Urban and Motorway test cycles compared to the NEDC cycle at +22°C. This is remarkable, since the Artemis test cycles do not contain a cold start, as the NEDC tests do. The higher accelerations and speed (Motorway) compared to the NEDC test cycle are likely explanations for the higher level in the Artemis Motorway tests.

In general, the PM level is much higher at -7°C compared to +22°C, as expected. However, due to the reasons explained above, no data are available for the E5 fuel at the lower temperature.

Bearing in mind that the overtaking test is expressed in the unit mg/test in contrast to the other tests, the level has to be considered relatively high for the FFV 1 car. Presumably this test should be the most severe of all operating conditions regarding the engine load. In the direct comparison between the two fuels, the level for E85 is about 4 times higher in the overtaking test. This does not necessarily have to be a feature of the fuel itself but rather it could be a result of different engine calibration for the two fuels. The FFV1 car uses a turbocharger. It has been shown in other tests, e.g. by the Swedish company Rototest, that turbocharged cars often have very high particle number emissions at high engine loads (Färnlund et al. 2001). Rototest was using a chassis dynamometer of their own design mounted on the wheel hubs and a specific test cycle comprising a number of steady-state load and speed points. Particle number measurements were conducted with an ELPI instrument.

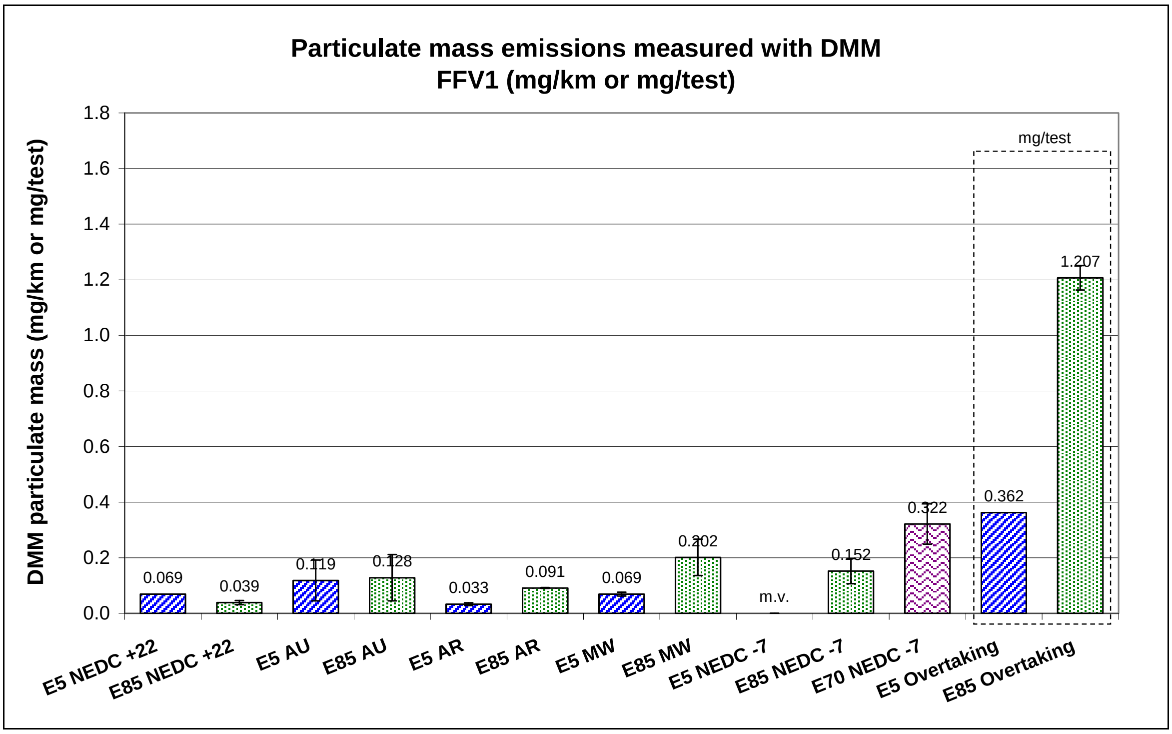

Figure 70. *DMM PM, FFV1.*

In **Figure 71**, the results from the measurements with the DMM instrument are shown on the FFV2 car. Many of the trends shown already for the FFV1 car are visible also here, but not all of these trends are similar.

The PM level is higher for E85 compared to E5 in NEDC at -7°C. In contrast, the PM level is lower for the E70 fuel than for E85, indicating that the PM level increases by increasing ethanol content in the fuel.

In comparison to the previously discussed results on the FFV1 car, the PM level during overtaking is much lower for both fuels investigated on the FFV2 car. In this case, E85 fuel showed a lower level than E5. However, since only one test of each fuel was valid, the influence of test-to-test variation could not be estimated and therefore, the conclusions in this case are less reliable.

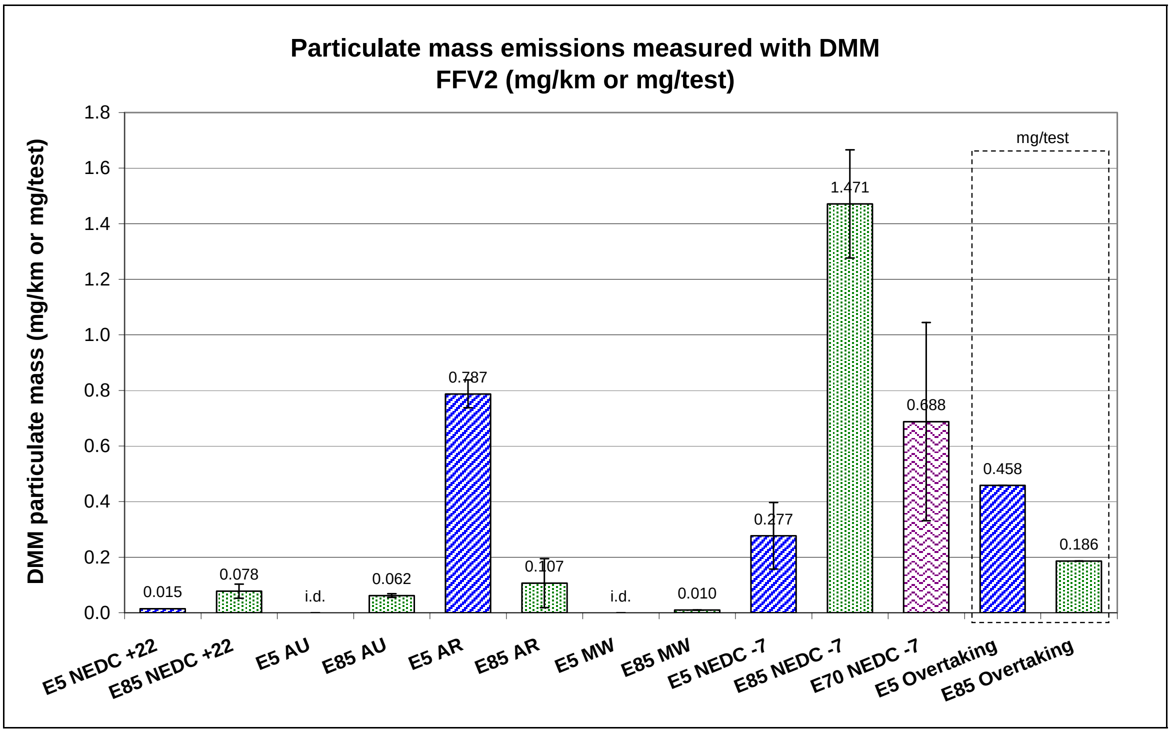

Figure 71. *DMM PM, FFV2.*

In **Figure 72**, the results for PM emissions measured with the DMM instrument on the BFV car are shown. As for the two previous cars, the absolute level is very low in most of the tests carried out.

There is an indication that the level is lower for CBG in the Artemis Motorway test cycle compared to E5. Unfortunately, missing or invalid data prevents a comparison between results from the other Artemis test cycles.

There is a remarkable difference for the results in the NEDC test cycle at -7°C. First, the level is as for E5 higher than for the other two cars running on the same fuel. Second, the level for CBG is lower than for the two other cars with any fuel. Consequently, the relative difference between the two fuels is more than one order of magnitude for the BFV car. The reason for this result should be commented on. By looking at the second-by-second real-time data (see also discussion below), it is obvious that the cold start emissions in the inital phase of the test cycle are generally dominating over emissions generated later in the test cycle. The length of the period with increased PM emissions varies somewhat from car to car and from fuel to fuel. In the CBG case, the car is started on petrol but it is switched from petrol to CBG operation as quickly as possible. Thus, the PM emissions in this initial phase of the test cycle are generally reduced although the engine is started on petrol. It is plausible that lower PM emissions could have been achieved if the engine had started on CBG instead of on petrol, as discussed previously in chapter 1.

The results from the overtaking test with E5 fuel in the BFV car shows a level roughly similar to the FFV2 car. Also in this case, CBG has a lower level than E5 although there is only one valid test on each fuel.

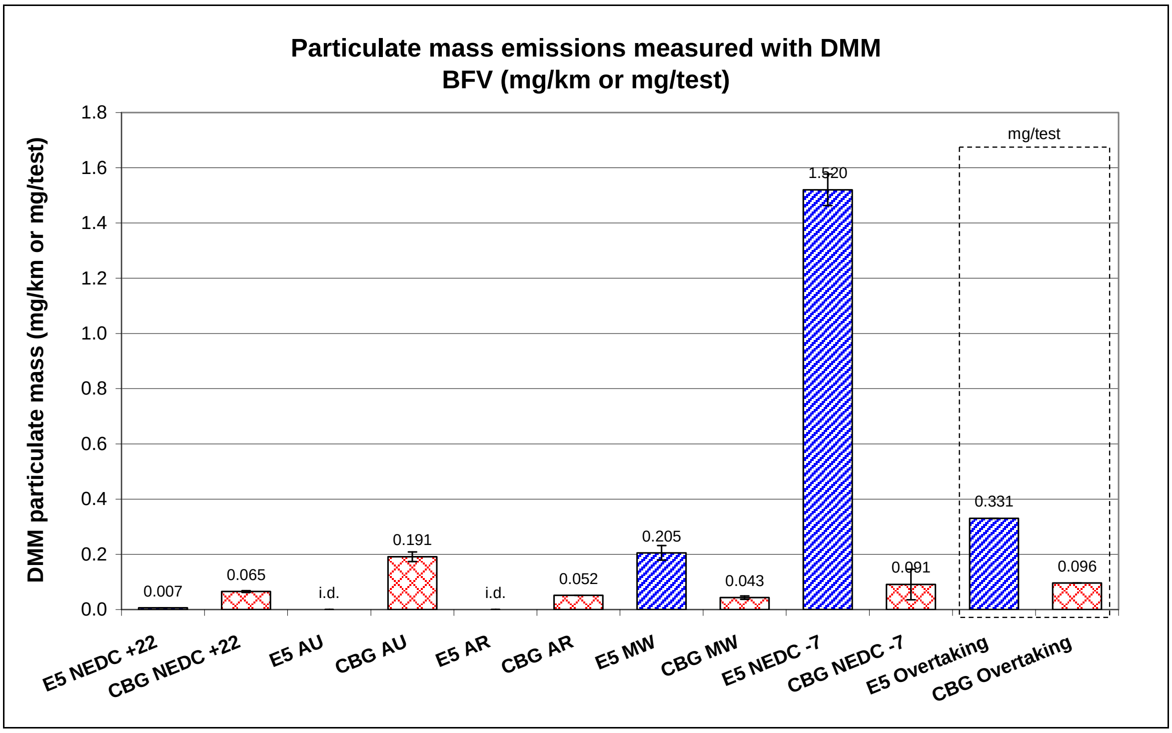

Figure 72. *DMM PM, BFV.*

No direct comparison between the PM emissions obtained by the conventional gravimetric method and by the DMM instrument is made here. The PM level is generally often one order of magnitude or more lower by the DMM instrument than the conventional method. This is due to the so-called filter artefact that plagues the conventional gravimetric filter test method. This problem has been noted in several previous studies, e.g. by Chase et al. (Chase et al. 2004). Not only solid particles and droplets are collected on the filter media but also hydrocarbons in gas-phase and possibly also other volatile material. For vehicles with very low particle emissions, the filter artefact can give a substantial contribution to the total measured particulate mass. For example, in the final report from the light-duty PMP programme, it was concluded that this could comprise more than >95 % of the particulate mass determined by the filter method (Andersson et al. 2007). It is plausible that a similar artefact could also apply for petrol-fuelled vehicles, such as those in this project. By using the PMP dilution system for the DMM instrument, only solid particles will be measured. Thus, it is conceivable that the emissions measured by this instrument could be one magnitude or more lower than the level measured by the gravimetric filter method.

The main advantage of real-time instrument such as the DMM over the conventional gravimetric filter method is the ability to follow transient emissions in detail. Due to space limitations, not all data depicted as second-by-second traces are shown here. Just a selection of the most interesting figures has been made in the following.

All figures below showing PM emissions traces versus time have similar layout. A curve for cumulative mass is shown, which yields the total specific PM emission (g/km) in the test at the end of the driving cycle. Similarly, the PM mass flow is also expressed in grams per km and per second so that the integral of this curve yields the cumulative specific PM emissions, as defined above. The authors realize that this is not the most common way of presenting data but it adds to the intuitive understanding of the emissions in the test cycle to be able to show a cumulative mass in the same units as for the whole test and likewise, a mass flow that corresponds to this number. The alternative of showing PM concentrations in the exhaust was not considered.

The detection limit for the DMM given by the instrument manufacturer is at a mass concentration of 1 µg/m^3. The detection limit shown in the figures below has been calculated using that data and the total exhaust dilution. However, the experience from the instrument distributor ExIS in own measurements (unpublished data) is that the "real" detection limit is well below this level. An indication that this is a valid conclusion is also seen below in that some typical peaks in PM emissions, such as, e.g. at the end of the NEDC cycle, are seen in each test, albeit often at a level below the detection limit specified by the instrument manufacturer. Note that the absolute detection limit shown in the figures appear to vary from case to case. This is due to that the dilution ratio is not necessary similar from test to test.

In general, real-time data varies from test to test. The causes for this variation are not clear, it can only be concluded that this is the case. Due to this variation, reporting averaged data from several tests might be somewhat misleading. Therefore, only single tests are shown in the diagrams below.

In **Figure 73**, a typical mass emission trace from the DMM in the NEDC cycle is shown. Initially in the test cycle, there are some peaks in PM emissions due to the cold start effect. However, for most of the remaining part of the test cycle, the emissions are very low, i.e. at or below the detection limit. Only at the greatest accelerations, e.g. at the end of the test cycle, there are emission "spikes" approaching the nominal detection limit. With the detection limit in mind, the accumulated emission level might be overestimated at this low emission level.

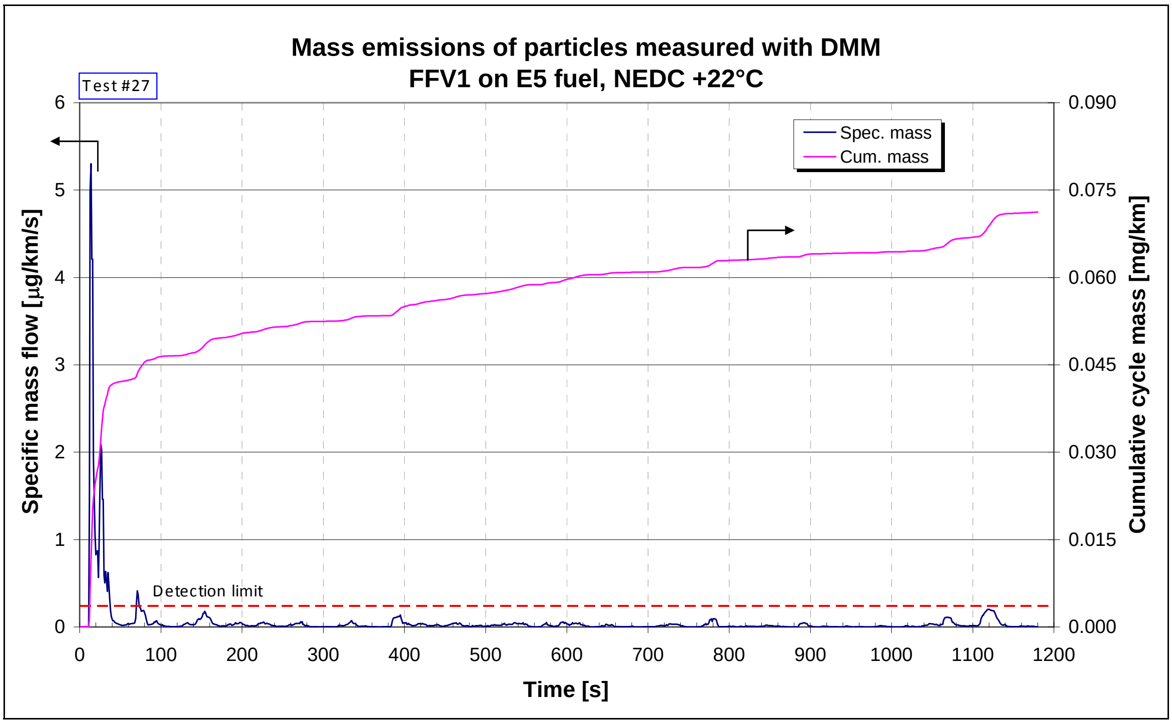

__Figure 73.__ DMM particle mass emission trace in NEDC, FFV1 on E5 fuel.

In **Figure 74**, the corresponding PM emission trace as in the figure above is shown for the FFV1 car running on E85 fuel. In this case, the initial peak just after the start in the test cycle is considerably smaller. Keeping in mind that the scales in both figures are different, there is no difference for the rest of the test cycle and the level is constantly below the detection limit. The difference between the two fuels shown here indicates that E85 might have a small advantage over E5 under these operating conditions. However, this hypothesis is contradicted by the fact that that the results on the FFV2 car were the opposite. In this case (no graph shown here) the very first peak on E5 fuel is smaller than the second peak and significantly smaller than the corresponding first peak on E85 fuel.

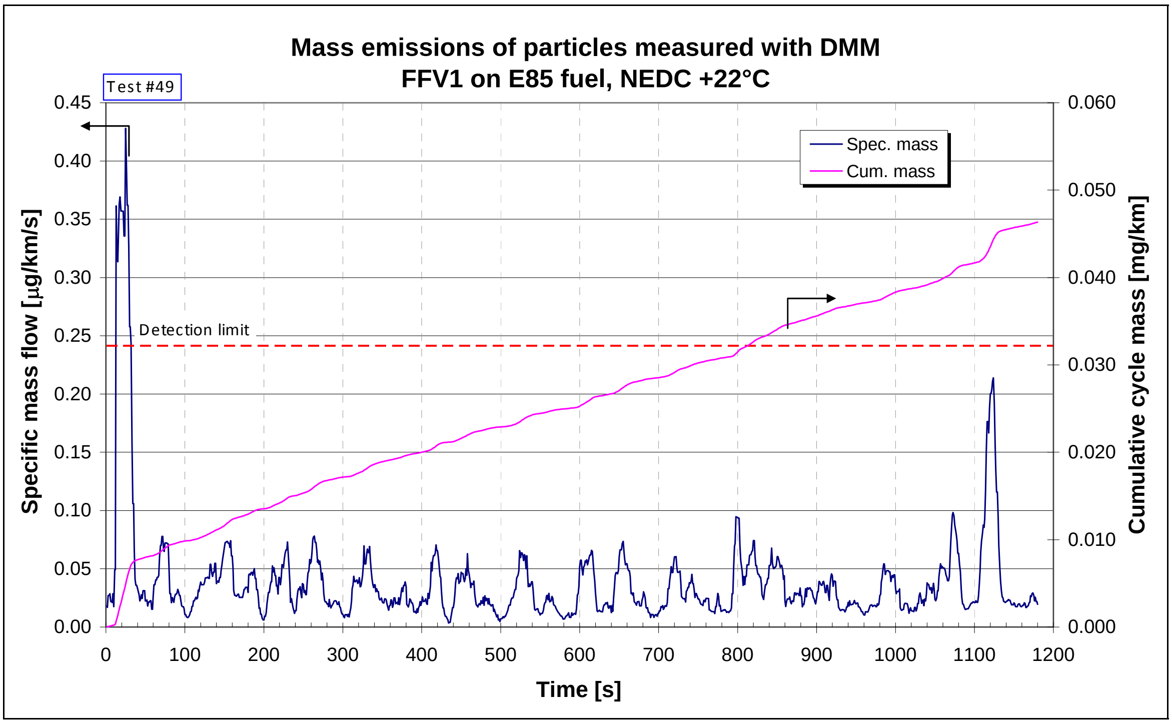

Figure 74. DMM particle mass emission trace in NEDC, FFV1 on E85 fuel.

As mentioned above, the emission level for the FFV2 car was very low in the NEDC test regardless of fuel used. At -7°C, the emission level is generally higher for all fuels. Since the scatter between the two tests on each fuel was relatively high, the test with the highest level is shown below for each fuel.

Figure 75 shows the PM emissions at -7°C for the FFV2 car running on E5 fuel. Most of the emissions are generated in the initial part of the test cycle, i.e. the 3 first minutes. The contribution from the latter part of the test cycle might be discussed with regard to the detection limit.

In general, a lower temperature prolongs the period with higher emissions in the initial part of the test cycle. This is a general conclusion valid for both FFV cars and for all fuel used in these cars.

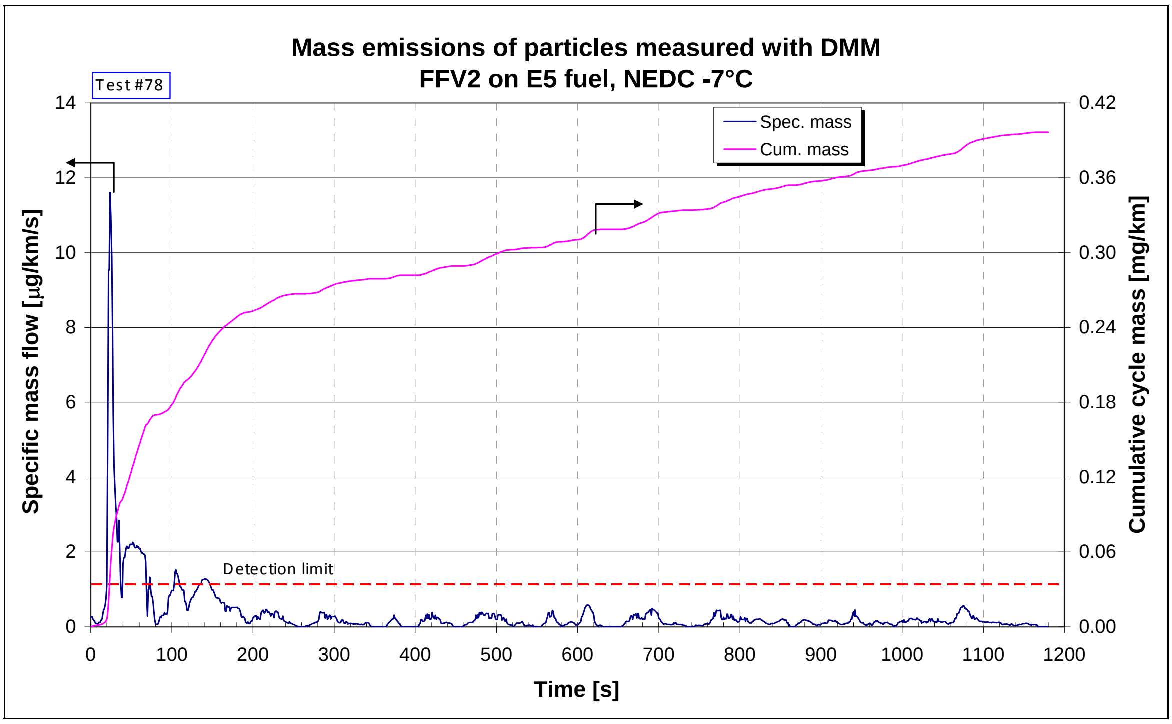

Figure 75. *DMM particle mass emission trace in the NEDC test at -7°C, FFV2 on E5 fuel.*

Figure 76 shows the emission trace from the FFV2 car at -7°C running on E85 fuel. Note that the scale on the left y-axis is almost one order of magnitude higher than in **Figure 75** (E5 fuel). All the initial peaks are higher for E85 in comparison to E5 but there are also peaks later in the test cycle that are higher than for E5, although it is somewhat difficult to distinguish that in the figure, due to the change in scale factor.

As previously mentioned, the PM level is lower for the FFV2 car running on E70 fuel compared to E85 fuel. This PM trace is not shown here.

In **Figure 77**, the PM emissions for the BFV car running on E5 fuel is shown. This curve is rather similar to the curve from the FFV2 car , as shown above (**Figure 76** to **Figure 82**). After approximately 2,5 minutes, the cold start effect is over. Only at the end of the test cycle, a level significantly over the detection limit is recorded.

In contrast to the results on E5 fuel shown above (**Figure 77**), the level running on CBG is significantly lower, i.e. more than one order of magnitude in difference (**Figure 78**). In the tests on CBG, the car was switched over from petrol operation immediately after the start by the driver. In the second of the tests on CBG, the switching could not be made properly, so there is only one valid test result on CBG operation available for comparison. In the E5 case, the test-to-test scatter between the two tests was very low. Apparently, the first emission peak during cold start does not come during the initial idling period of 11 s but first after the driving starts. Therefore, switching immediately to CBG operation reduces the particulate emissions significantly. Whether the normal driver does this in daily operation has not been studied here. If not, the particulate emissions will approach the level of petrol operation and the potential benefit of a “clean” fuel is more or less lost.

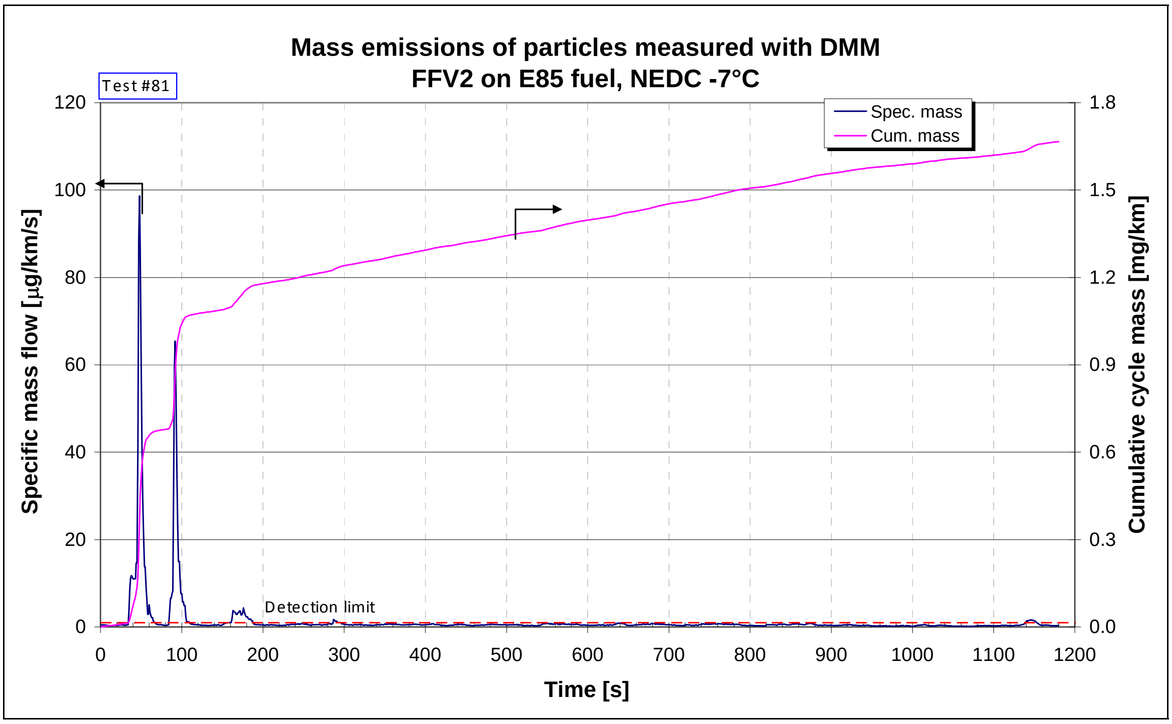

Figure 76. *DMM particle mass emission trace in the NEDC test at -7°C, FFV2 on E85 fuel.*

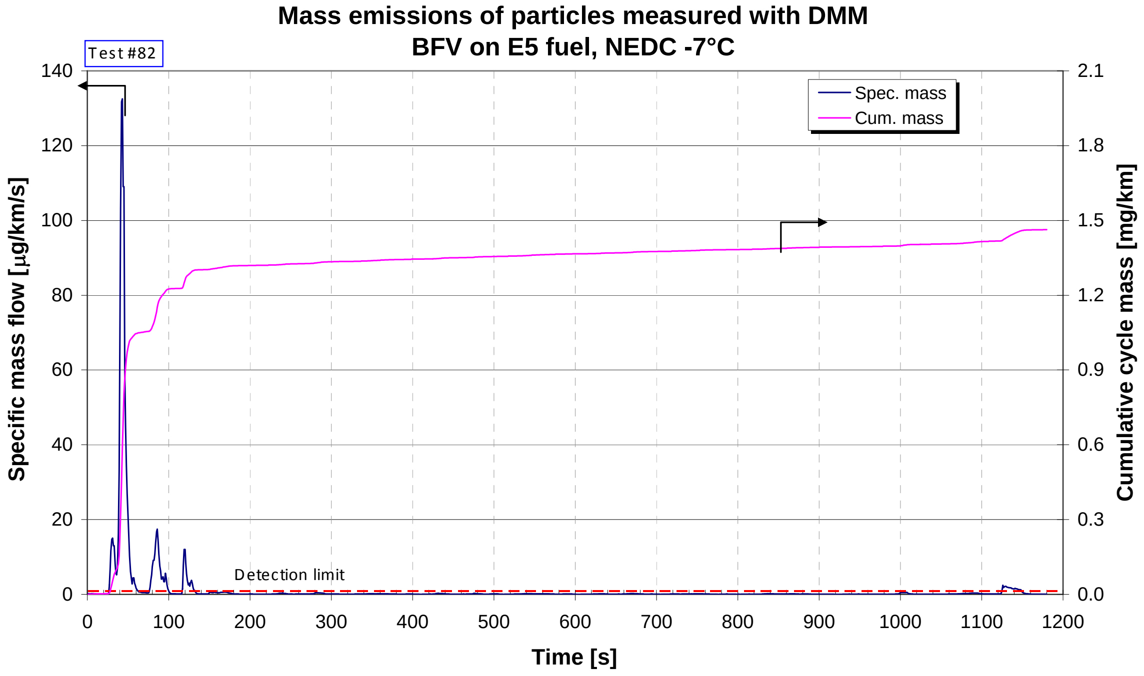

Figure 77. *DMM particle mass emission trace in the NEDC test at -7°C, BFV on E5 fuel.*

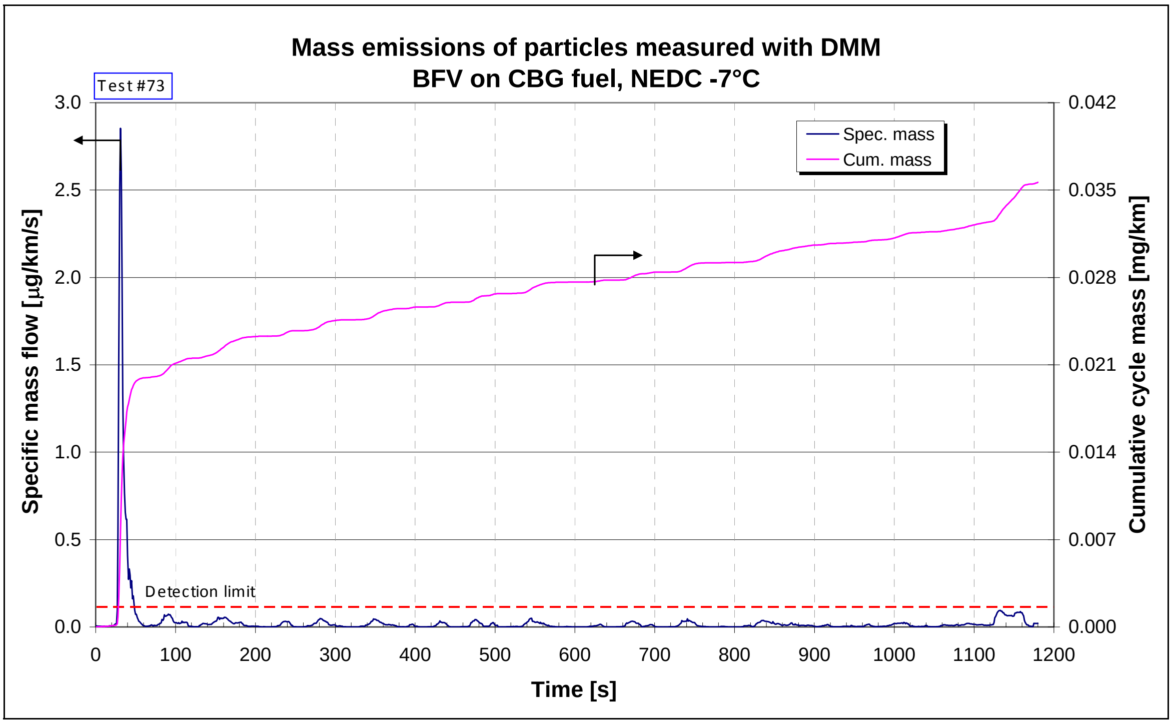

Figure 78. *DMM particle mass emission trace in the NEDC test at -7°C, BFV on CBG fuel.*

Results for regulated emissions and particle number emissions in the overtaking tests

Table 21 shows the total overtaking time (t_{tot}) and total driven distance (d_{tot}) of the three tested cars with different fuels. As can be seen in **Table 21**, there is a considerable difference in overtaking time and distance between the tested cars. FFV1, which is turbocharged, is fastest and the BFV car, which has the lowest power, is slowest.

Table 21. *Total overtaking time and total driven distance per test.*

Vehicle	**Fuel**	t_{tot} (s)	d_{tot} (m)
FFV1	E5	12	406
FFV1	E85	11	388
FFV2	E5	14	454
FFV2	E85	13	429
BFV	E5	21	570
BFV	CBG	25	660

Emissions of CO, HC NO_X, PN according to PMP and ELPI (PN_{PMP} PN_{ELPI}) from the overtaking tests are presented in **Figure 79** to **Figure 83**.

The E5 has significantly higher CO, PN_{PMP} and PN_{ELPI} emissions comparing to E85 or CBG. The HC emissions are very low, and showing no conclusive fuel dependence.

The NO_X emissions are also very low for all cars, except for the BFV car running on CBG fuel. No measurement error has been found in this case. There are two possible explanations for this result. First, the engine control of air/fuel ratio could be shifted to lean conditions (understoichiometric). Second, there could be a breakthrough in the catalyst due to the high exhaust flow. A combination of both problems could also be possible.

Again, there is a relatively good agreement between the ELPI and the PMP measurements. ELPI always show somewhat higher PN emissions than the PMP method.

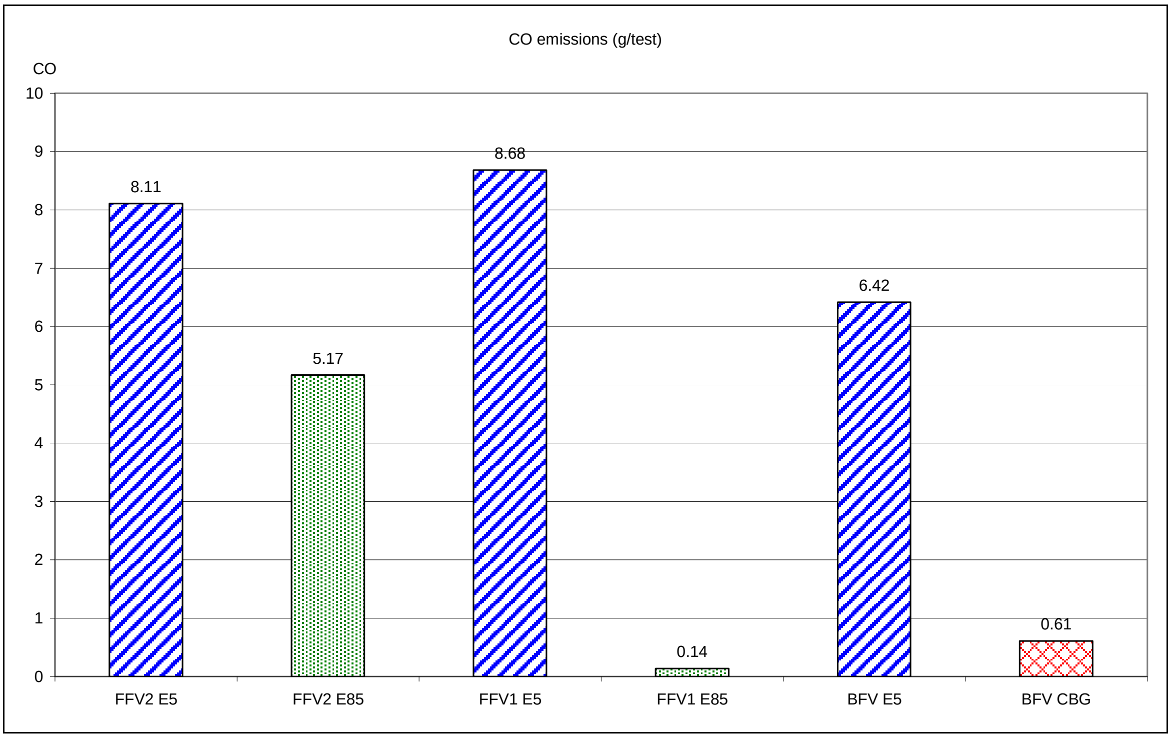

Figure 79. *CO emission from the overtaking cycle.*

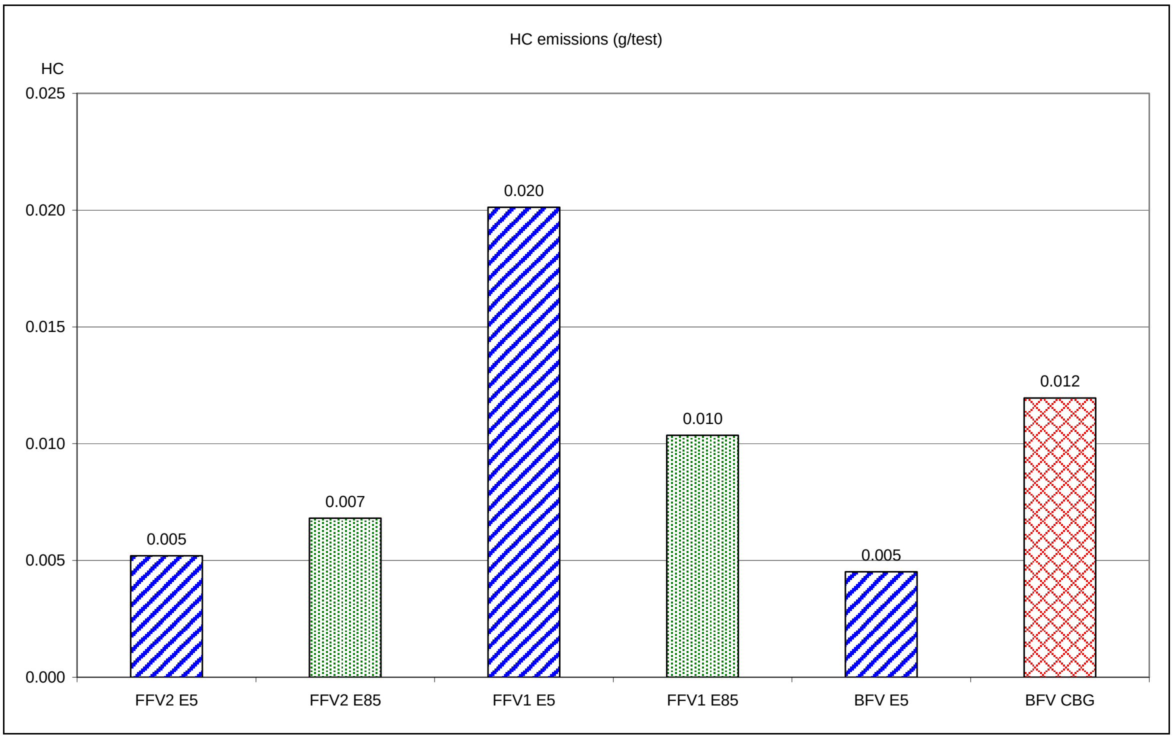

Figure 80. *HC emission from the overtaking cycle.*

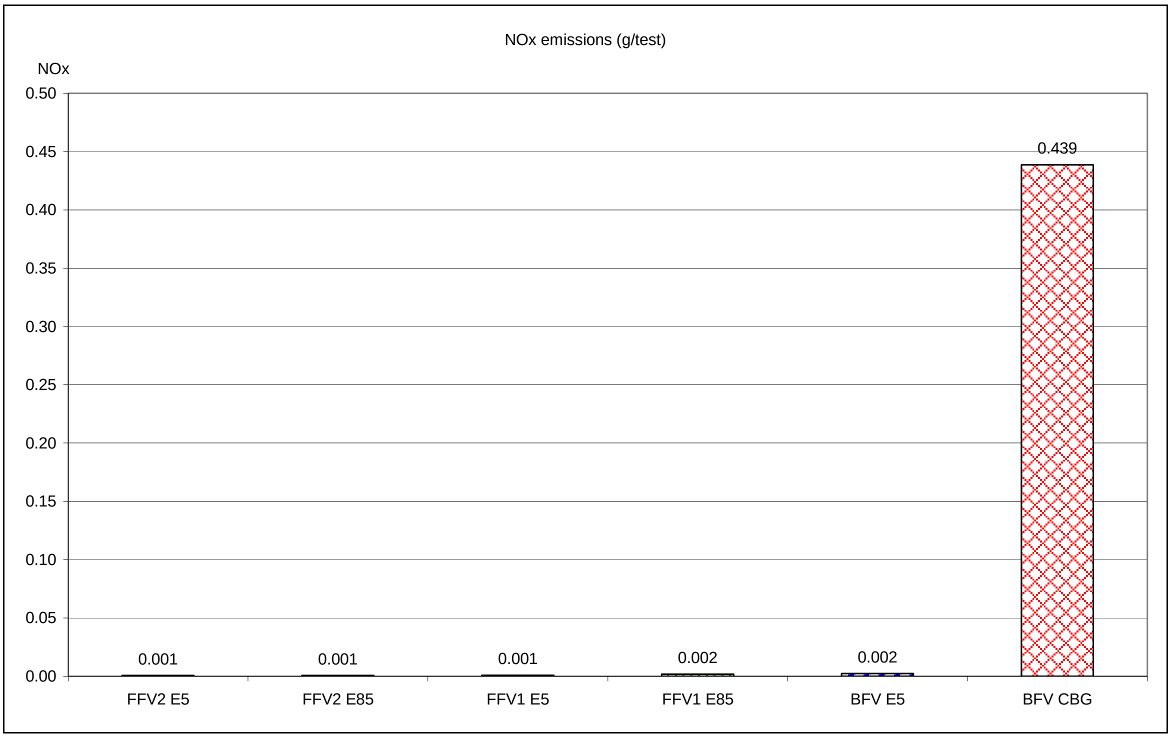

Figure 81. *NO_X emission from the overtaking cycle.*

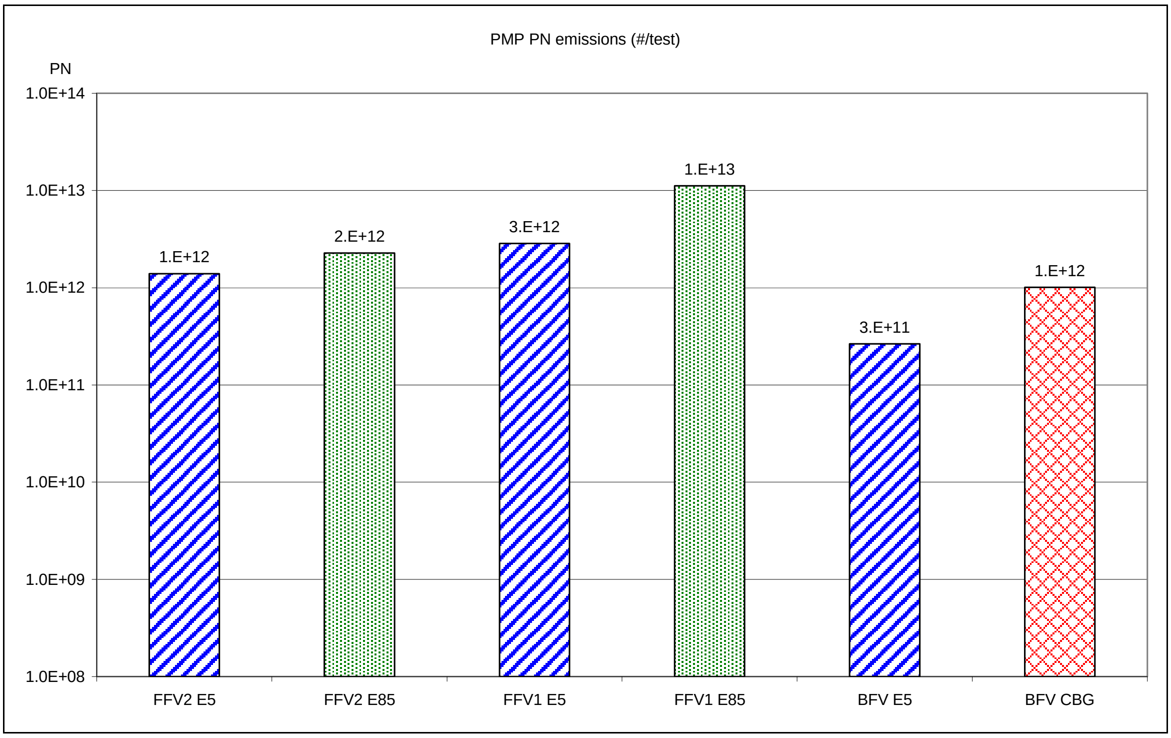

Figure 82. *PMP PN emission from the overtaking cycle.*

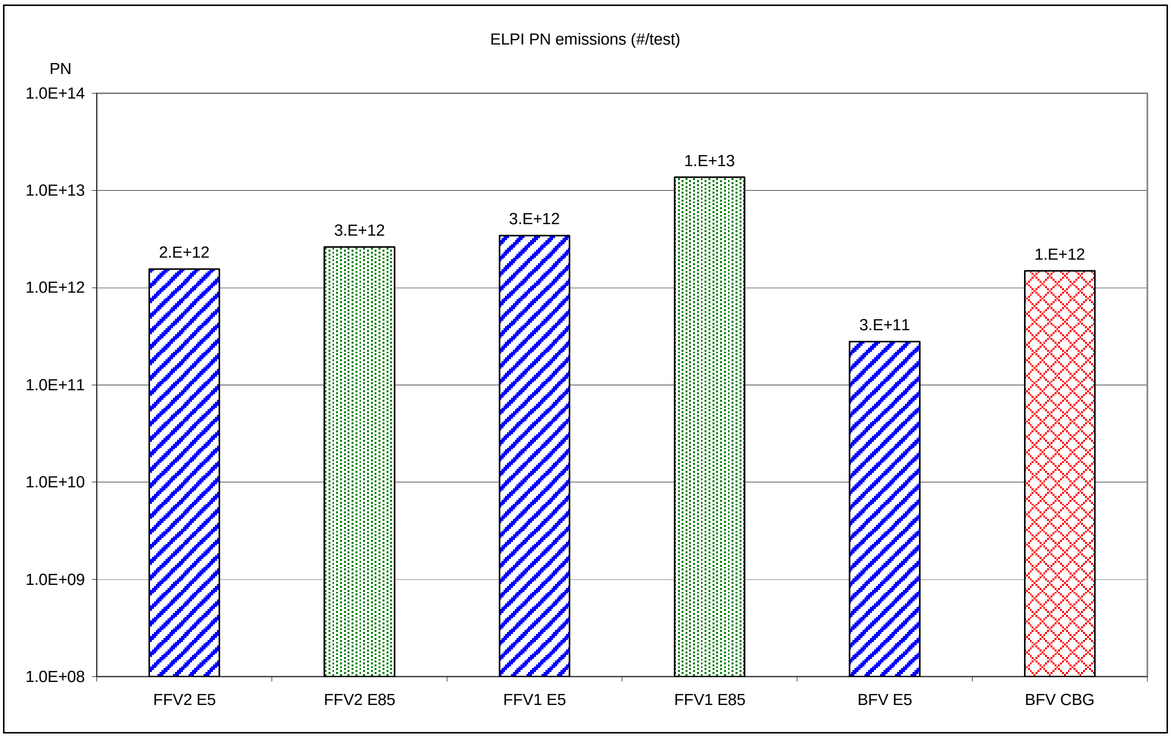

Figure 83. *ELPI PN emission from the overtaking cycle.*

As noted above, overtaking was an operating condition with relatively high particulate mass emissions, as measured by the DMM instrument. The level for the FFV1 car was higher than for the other cars. Therefore, emissions on this car are depicted in two graphs below for operation on both fuels. No specific adjustment of the start and stop of the test cycle has made other than that the peak is adjusted to be in the approximate centre of the picture. The duration shown is 100 s. The cumulative mass emissions per test (mg/test) have been calculated in addition to the mass flow (µg/s).

In **Figure 84**, the result for the particle trace on E85 fuel is shown for the FFV1 car. The peak is very high although the duration is relatively limited in time. In spite of the great total dilution ratio, the level is much higher than the detection limit in this case. The total cumulative mass, at about 1,2 mg/test, is relatively low after all, due to the limited time period of the peak.

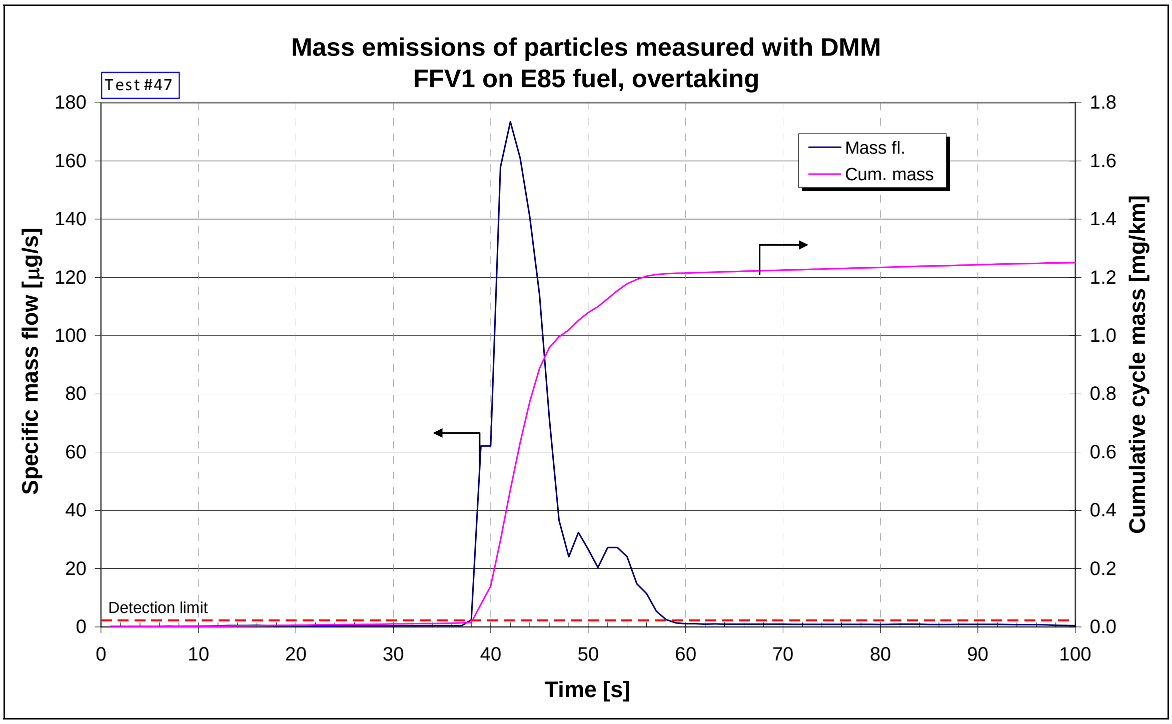

Figure 84. DMM particle mass emission trace during overtaking, FFV1 on E85 fuel.

Figure 85 shows the particle trace with operation on E5 fuel for the FFV1 car. In this case, the level is significantly lower than for E85. The relative magnitude for both the peak and the cumulative mass is about a factor of 4 lower than on E85 fuel.

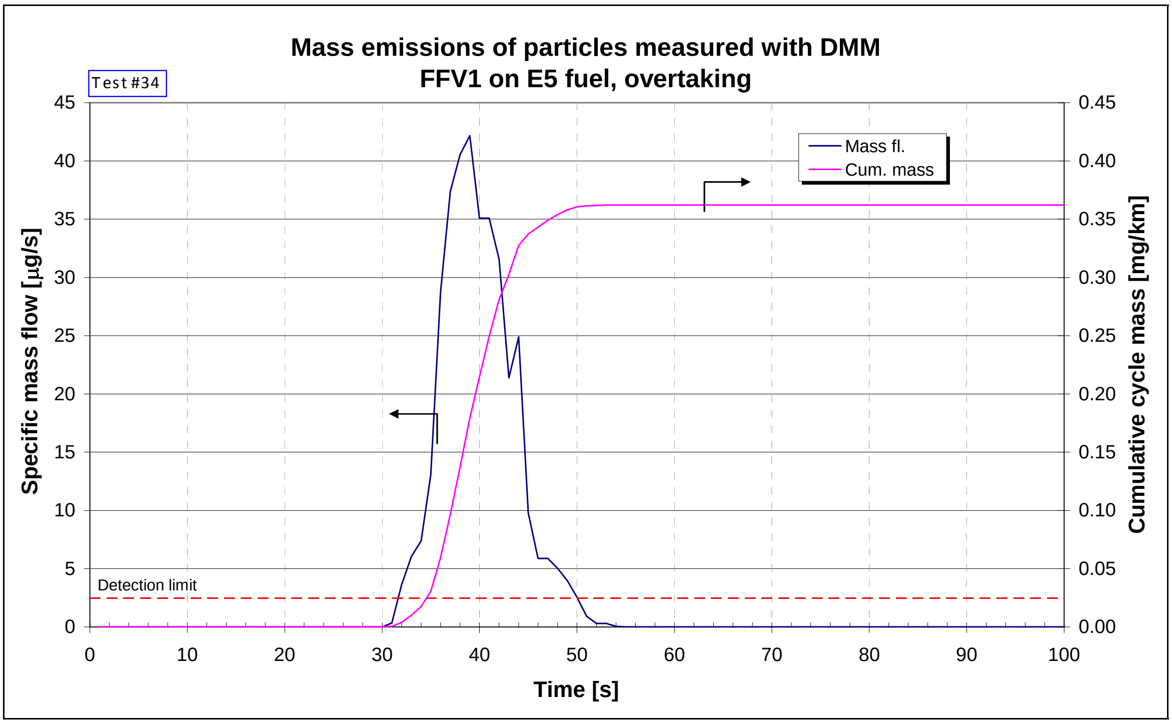

Figure 85. *DMM particle mass emission trace during overtaking, FFV1 on E5 fuel.*

PAH emissions

PAH emissions are divided into two parts i. e. particulate-associated and semivolatile-associated PAH emissions in figures shown. PAHs determined present in the particulate emissions are added together into total particulate-associated PAH emissions in the figures shown. Furthermore, PAHs determined present in the gaseous emissions are added together into total semivolatile-associated PAH emissions in the figures shown. The semivolatile concept addresses that certain PAHs determined and quantified in the present project are associated both to the particles and in the gaseous state, i.e. semivolatile.

Particulate-associated polycyclic aromatic hydrocarbons

In **Figure 86** is total particulate-associated PAH emissions shown from the FFV1 and in **Figure 87** corresponding from FFV2 and in **Figure 88** corresponding from BFV, respectively.

FFV1: Total particulate-associated PAH emissions ranges from 0,7 µg/km to 112 µg/km, **Figure 86**. The PAH emissions are similar emanating from tests performed at +22°C and also relatively independent on fuel used. However, at –7°C the PAH emissions increases substantially and are fuel dependant. The PAH emission increases with increasing ethanol content of the petrol blend tested that is E5 (36 µg/km) <E70 (84 µg/km) <E85 (112 µg/km), respectively.

Valid for all the three vehicles tested is that total particulate-associated PAH emissions increases substantially at decreased ambient temperature.

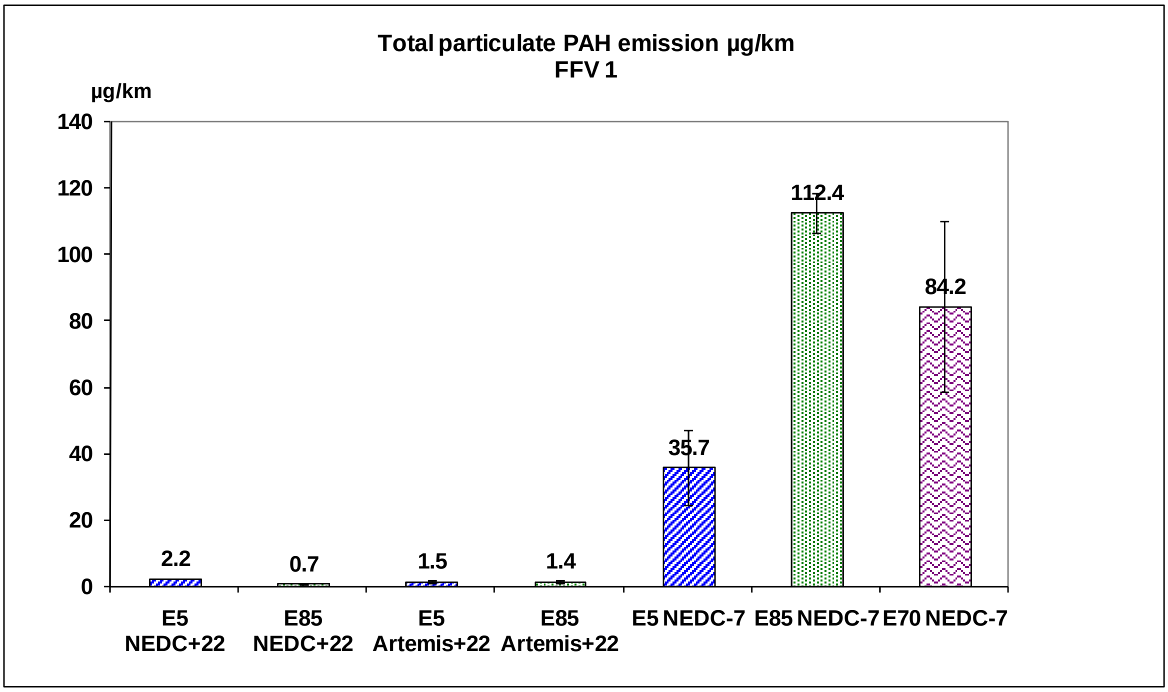

Figure 86. *Total particulate-associated PAH emissions (µg/km), FFV1.*

FFV2: Total particulate-associated PAH emissions ranges from 0,3 µg/km to 106 µg/km, **Figure 87**. The PAH emissions are similar emanating from tests performed at +22°C and also relatively independent on fuel used. However, at –7°C the PAH emissions increases substantially and are fuel dependent. The PAH emission increases with increasing ethanol content of the petrol blend tested that E5 (41 µg/km) <E70 (100 µg/km) <E85 (106 µg/km), respectively.

BFV: Total particulate-associated PAH emissions ranges from 0,6 µg/km to 65 µg/km, **Figure 88**. The PAH emissions are similar emanating from tests performed at +22°C, however, PAH emissions from CBG fuel is somewhat lower compared to corresponding test with the E5 fuel. At –7°C, the PAH emissions increases substantially and are fuel dependent. The lowest PAH emission emanates from the CBG fuel at –7°C.

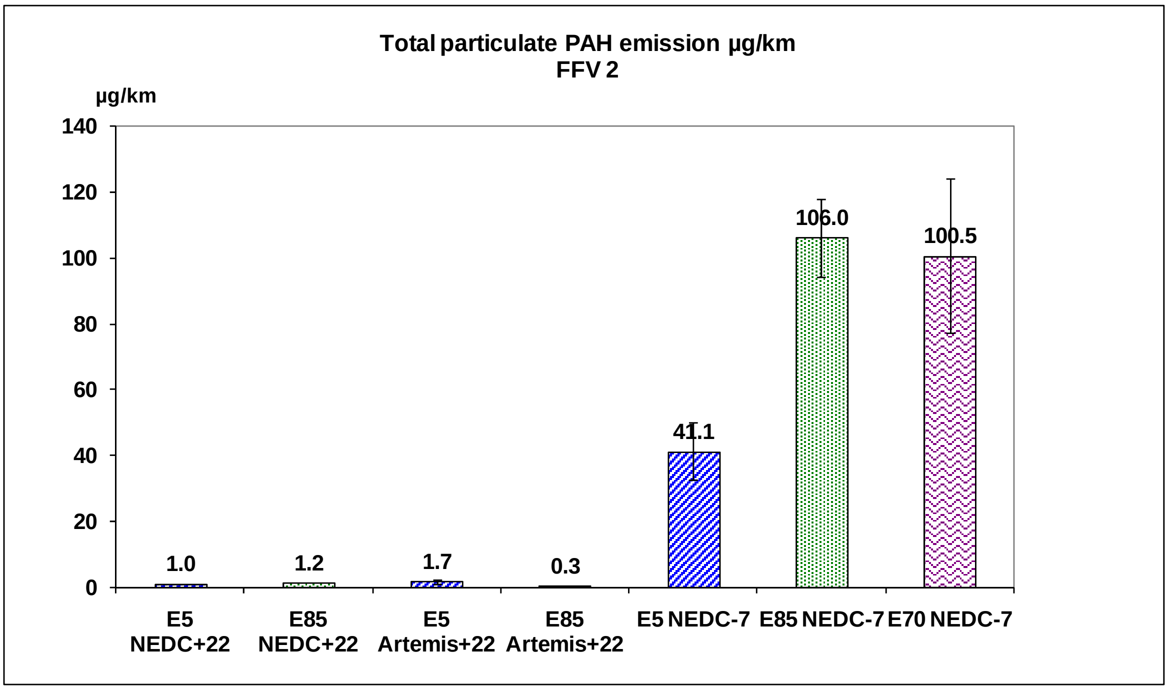

Figure 87. *Total particulate-associated PAH emissions (µg/km), FFV2.*

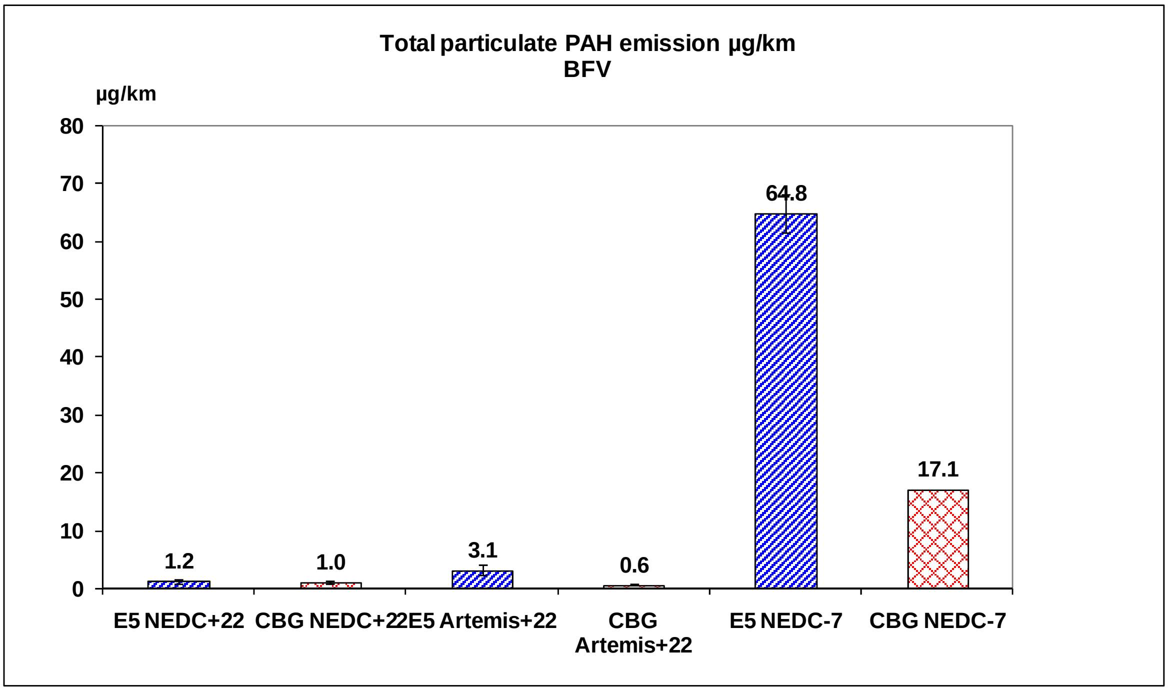

Figure 88. *Total particulate-associated PAH emissions (µg/km), BFV.*

Semivolatile-associated polycyclic aromatic hydrocarbons

In **Figure 89**, the total semivolatile-associated PAH emissions is shown from FFV1, in **Figure 90** from FFV2 and in **Figure 91** from BFV, respectively

FFV1: Total semivolatile-associated PAH emissions ranges from 6 µg/km to 864 µg/km, **Figure 89**. The PAH emissions are similar emanating from tests performed at +22°C and are also relatively independent on fuel tested. However, at –7°C, the PAH emissions increases substantially and are fuel dependent. The PAH emission increases with increasing ethanol contents of the petrol blend tested that is E5 (255 µg/km) < E70 (637 µg/km) <E85 (634 µg/km), respectively.

FFV2: Total semivolatile-associated PAH emissions ranges from 2,3 µg/km to 2 700 mg/km, **Figure 90**. The PAH emissions are relatively low emanating from tests performed at +22°C however, a driving cycle and fuel dependence can be seen. At –7°C the PAH emissions increases substantially compared to tests at +22°C and are fuel dependent. The PAH emission increases with increasing ethanol content of the petrol blend tested that is E5 (497 µg/km) < E70 (1 411 µg/km) <E85 (2 711 µg/km), respectively.

BFV: Total semivolatile-associated PAH emissions range from 6 µg/km to 231 µg/km, **Figure 91**. The PAH emissions emanating from tests performed at +22°C shows a driving cycle dependence and a fuel dependence i.e. PAH emissions from the CBG fuel is somewhat lower for the NEDC driving cycle. Corresponding PAH emissions from the CBG fuel and the Artemis driving cycle is approximately a factor 5 lower compared to corresponding test with the E5 fuel. At –7°C the PAH emissions increases substantially and are fuel dependent. The lowest PAH emission (145 µg/km) emanates from the CBG fuel.

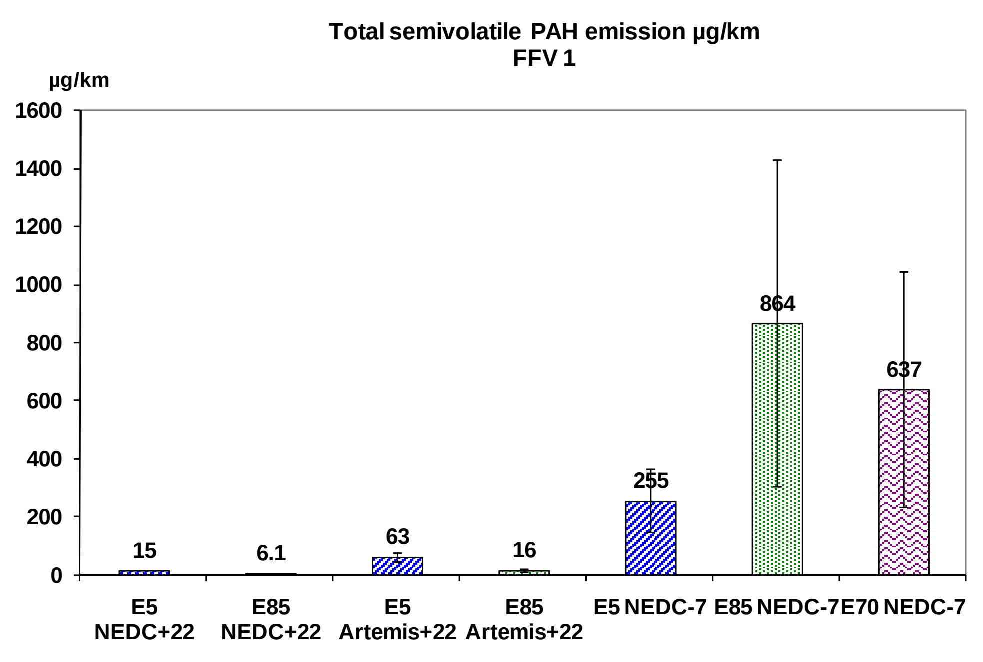

Figure 89. Total semivolatile-associated PAH emissions (µg/km), FFV1.

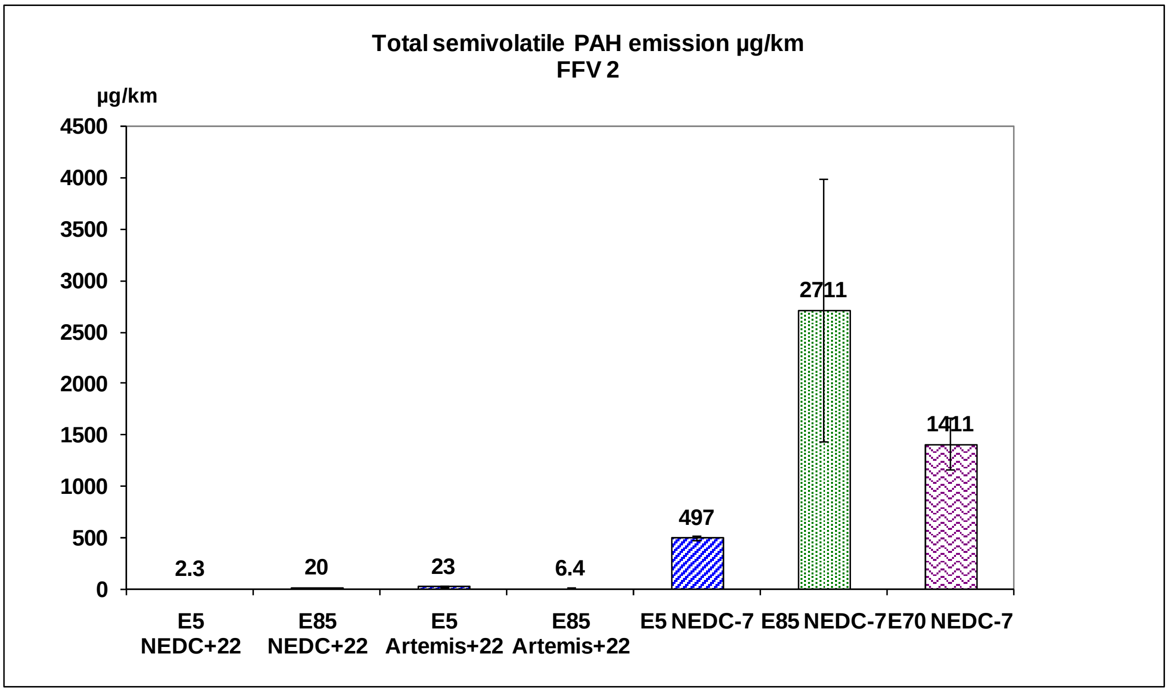

Figure 90. Total semivolatile-associated PAH emissions (µg/km), FFV2.

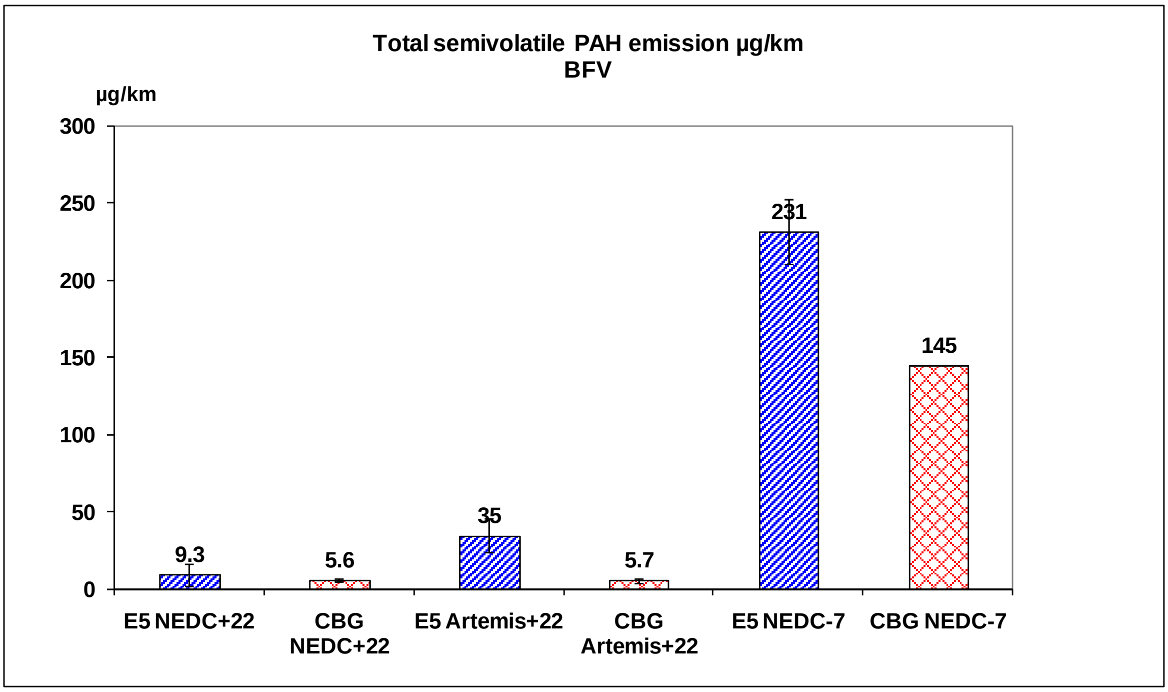

Figure 91. Total semivolatile-associated PAH emissions (µg/km), BFV.

TEF ratio for particulate-associated dibenzopyrenes/B(a)P

In **Figure 92** the TEF ratios are calculated from particulate-associated PAH emissions shown from FFV1 and in **Figure 93** the corresponding values from FFV2 and in **Figure 94** from BFV, respectively.

FFV1: The TEF ratio from particulate-associated PAH emissions ranges from 0,7 (E85, NEDC -7°C) to 2,4 (E5 Artemis +22°C/E5 NEDC -7°C), **Figure 92**. In general, the calculated TEF ratio for the E5 fuel is larger compared to the E70 and the E85 fuels. This is valid for both driving cycles tested at +22°C. At –7°C (NEDC) the calculated TEF ratio is substantially lower. This indicates that increasing the ethanol content in the petrol fuel decreases the relative cancer potency originating from the dibenzopyrenes determined in the exhaust compared to cancer potency from B(a)P at lower ambient temperatures.

FFV2: The TEF ratio from particulate-associated PAH emissions ranges from 0,7 (E85, Artemis +22°C/E70 NEDC -7°C) to 2,2 (E5 NEDC +22°C) , **Figure 93**. In general, the calculated TEF ratio for the E5 fuel is larger compared to the E70 and the E85 fuels. This is valid for both driving cycles tested at +22°C and at –7°C (NEDC) the calculated TEF ratio is lower. This indicates that increasing the ethanol content in the petrol fuel decreases the relative cancer potency originating from the dibenzopyrenes determined in the exhaust compared to cancer potency from B(a)P at lower ambient temperatures.

BFV: The TEF ratio from particulate-associated PAH emissions ranges from 0,8 (CBG, Artemis +22°C) to 2,7 (E5 NEDC +22°C), **Figure 94**. In general, the calculated TEF ratio for the E5 fuel is larger compared to the CBG fuel. This is valid for both driving cycles tested at +22°C and at –7°C (NEDC), the calculated TEF ratio is lower. This indicates that CBG fuel decreases the relative cancer potency originating from the dibenzopyrenes determined in the exhaust compared to cancer potency from B(a)P at lower ambient temperatures.

This highlights the importance to include determination of selected dibenzopyrenes in future exhaust evaluations from engines and vehicles in general to avoid potential underestimations of cancer potencies.

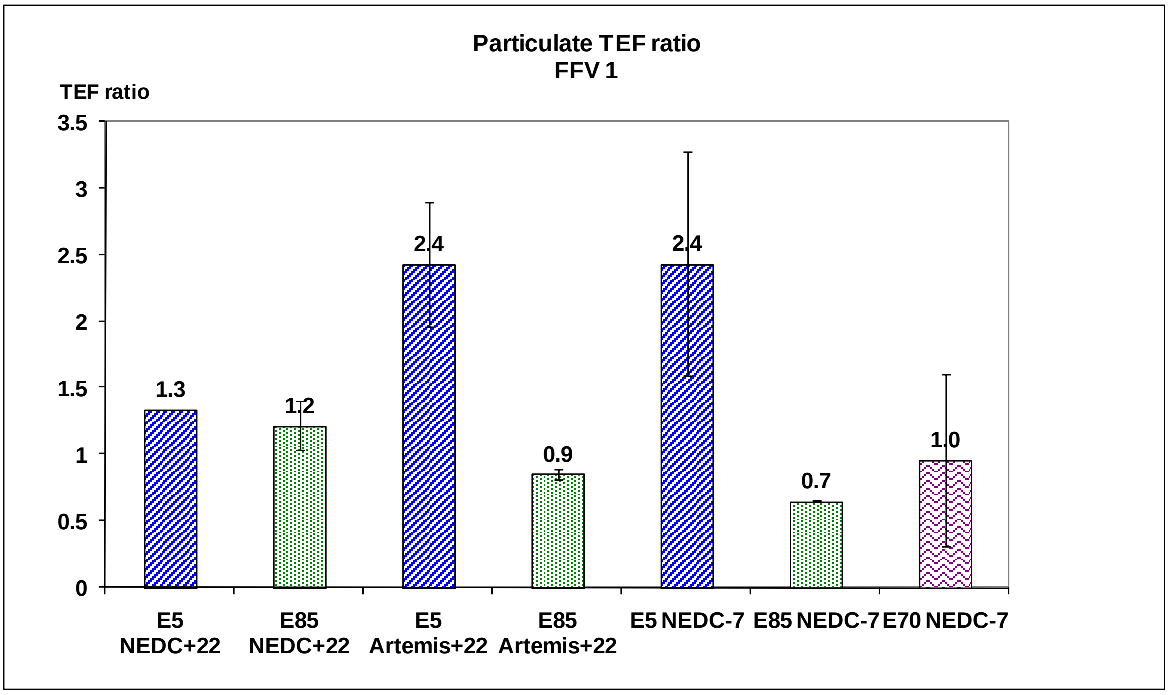

***Figure 92.** TEF ratio for particulate-associated dibenzopyrenes/B(a)P, FFV1 .*

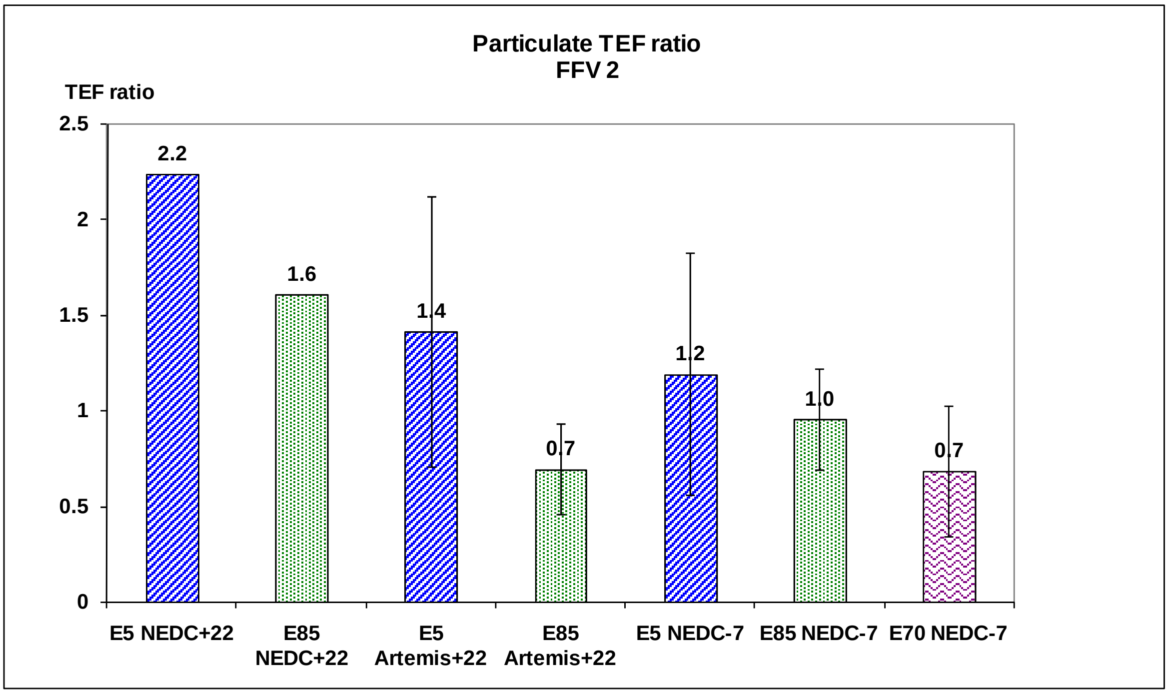

Figure 93. *TEF ratio for particulate-associated dibenzopyrenes/B(a)P, FFV2*

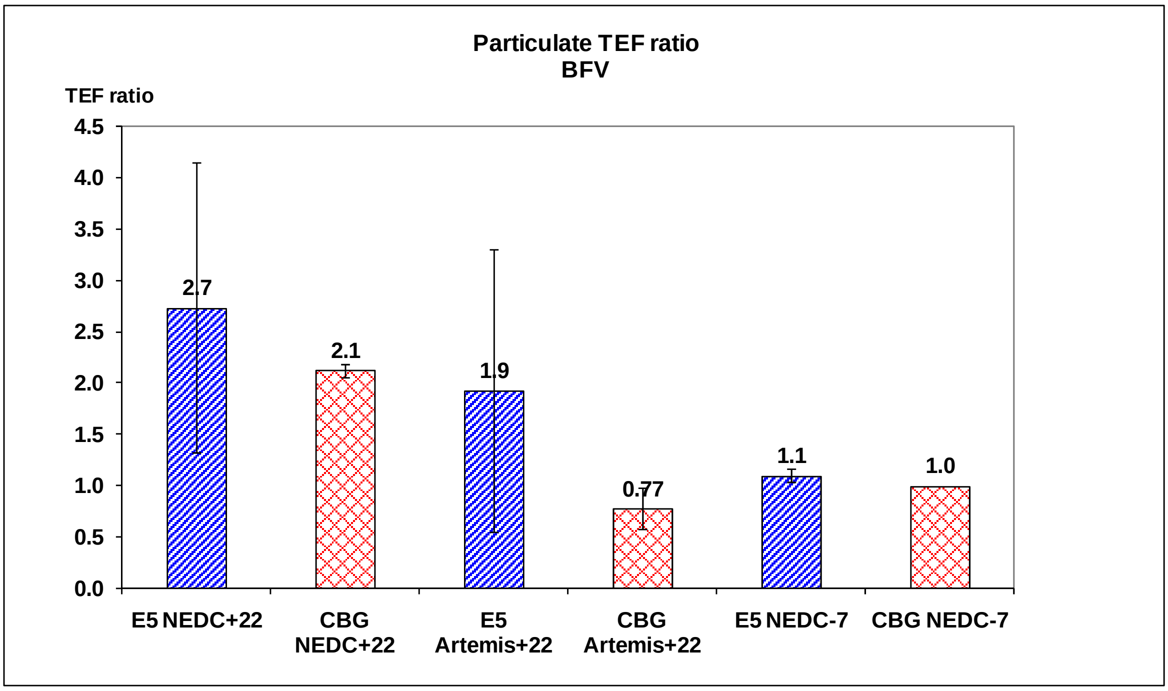

Figure 94. *TEF ratio for particulate-associated dibenzopyrenes/B(a)P, BFV.*

Cancer potency, particulate-associated

In **Figure 95**, is calculated cancer potency from particulate-associated PAH emissions shown from FFV1 and in **Figure 96** corresponding values from FFV2 and in **Figure 97** from BFV, respectively.

FFV1: The calculated cancer potencies for the NEDC driving cycle at +22°C are lower than the corresponding calculated cancer potencies at +22°C for the Artemis driving cycle, **Figure 95**. The E85 fuel gave lower calculated cancer potencies at +22°C compared to the E5 fuel at +22°C. At –7°C, calculated cancer potencies increase compared to tests at +22°and are fuel dependent. The calculated cancer potencies increases with increasing ethanol contents of the petrol blend tested that is E5 (9,2 µg/km*TEF) < E70 (14,9 µg/km*TEF) <E85 (16,3 µg/km*TEF), respectively at –7°C.

FFV2: The calculated cancer potencies at +22°C are lower than the corresponding calculated cancer potencies at –7°C, **Figure 96**. The E85 fuel gave lower calculated cancer potencies at +22°C in the Artemis driving cycle tests. At –7°C, calculated cancer potencies increases compared to tests at +22°and are fuel dependent. The calculated cancer potencies increases with increasing ethanol content of the petrol blend tested that is E5 (14,2 µg/km*TEF) < E70 (21,7 µg/km*TEF) <E85 (23,4 µg/km*TEF), respectively at –7°C.

BFV: The calculated cancer potencies at +22°C are lower than corresponding calculated cancer potencies at –7°C, **Figure 97**. The CBG fuel gave lower calculated cancer potencies at +22°C in the Artemis driving cycle tests. The largest calculated cancer potencies was determined from E5 fuel at –7°C i.e. 17,7 µg/km*TEF. Corresponding value for the CBG fuel was lower (4,5 µg/km*TEF).

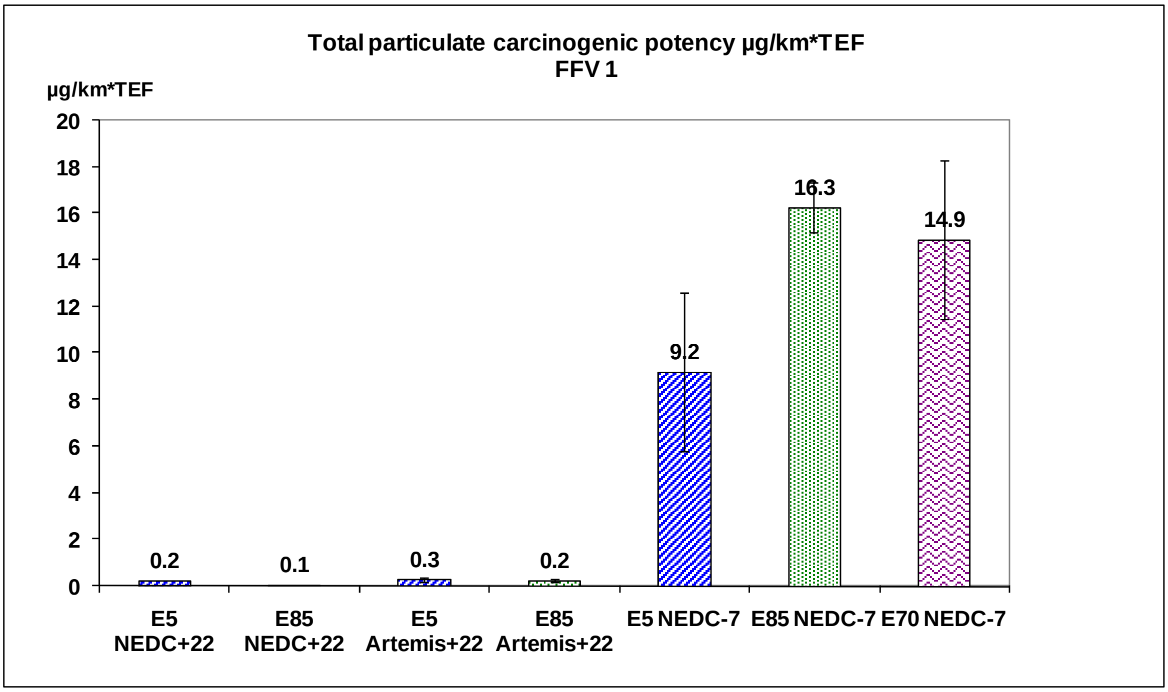

*Figure 95. Particulate-associated cancer potency (µg/km*TEF), FFV1.*

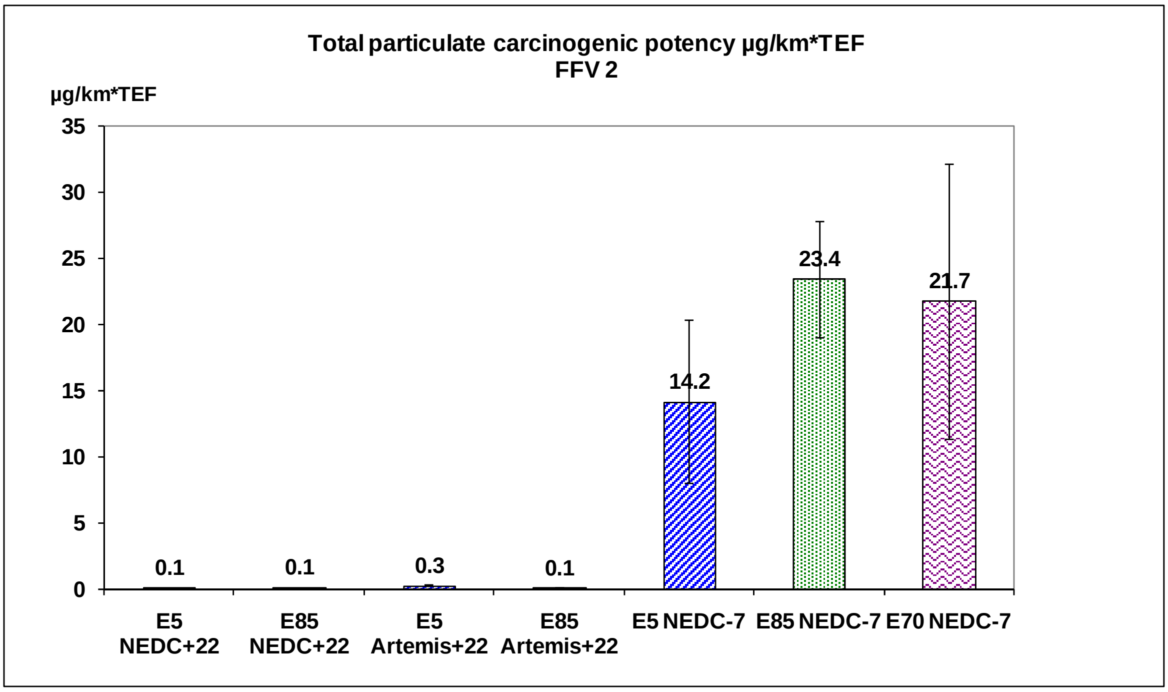

Figure 96. *Particulate-associated cancer potency (µg/km*TEF), FFV2.*

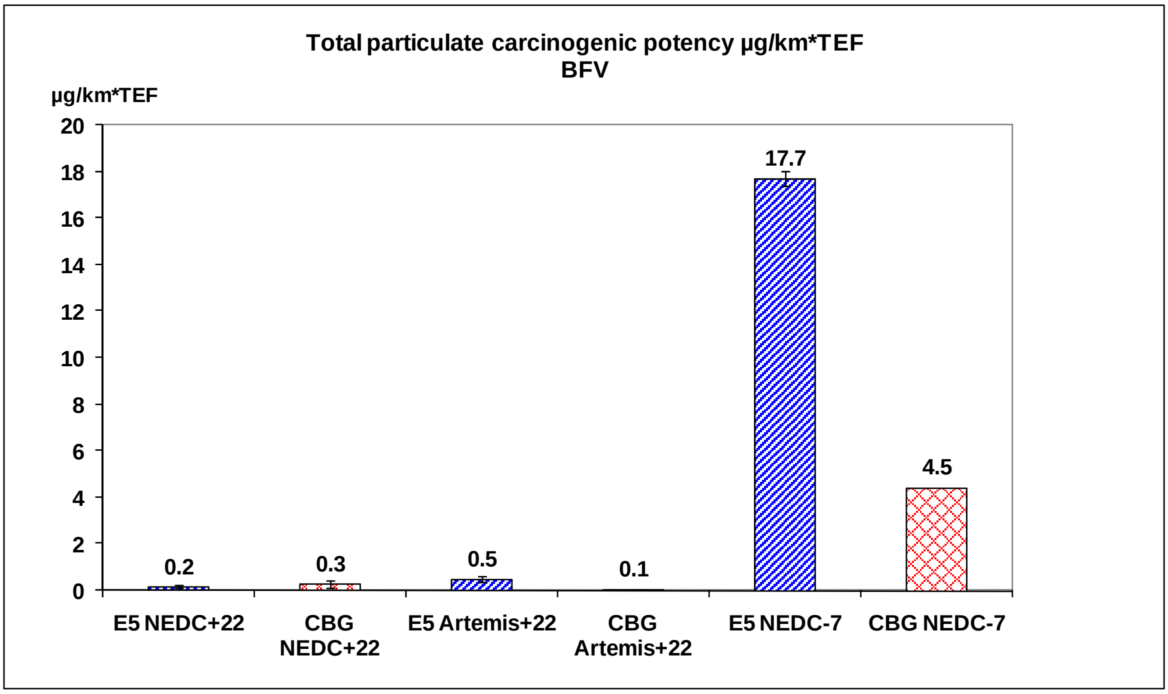

Figure 97. *Particulate-associated cancer potency (µg/km*TEF), BFV.*

Cancer potency, semivolatile-associated PAH

In **Figure 98**, the cancer potency from the semivolatile-associated PAH emissions is calculated and shown for FFV1, in **Figure 99** the corresponding values for FFV2 and in **Figure 100** from BFV, respectively.

FFV1: The calculated cancer potencies for the NEDC driving cycle at +22°C are lower than the corresponding calculated cancer potencies at +22°C for the Artemis driving cycle, **Figure 98**. The E85 fuel gave lower calculated cancer potencies at +22°C compared to the E5 fuel at +22°C. At –7°C calculated cancer potencies increases compared to tests at +22°and are fuel dependent. The calculated cancer potencies increases with increasing ethanol contents of the petrol blend tested that is E5 (3,1 µg/km*TEF) <E70 (8,5 µg/km*TEF) <E85 (12,2 µg/km*TEF), respectively at –7°C. However, the Artemis test at +22°C and the E5 fuel gave a larger calculated cancer potency compared to corresponding value for NEDC driving cycle at –7°C (E5 fuel).

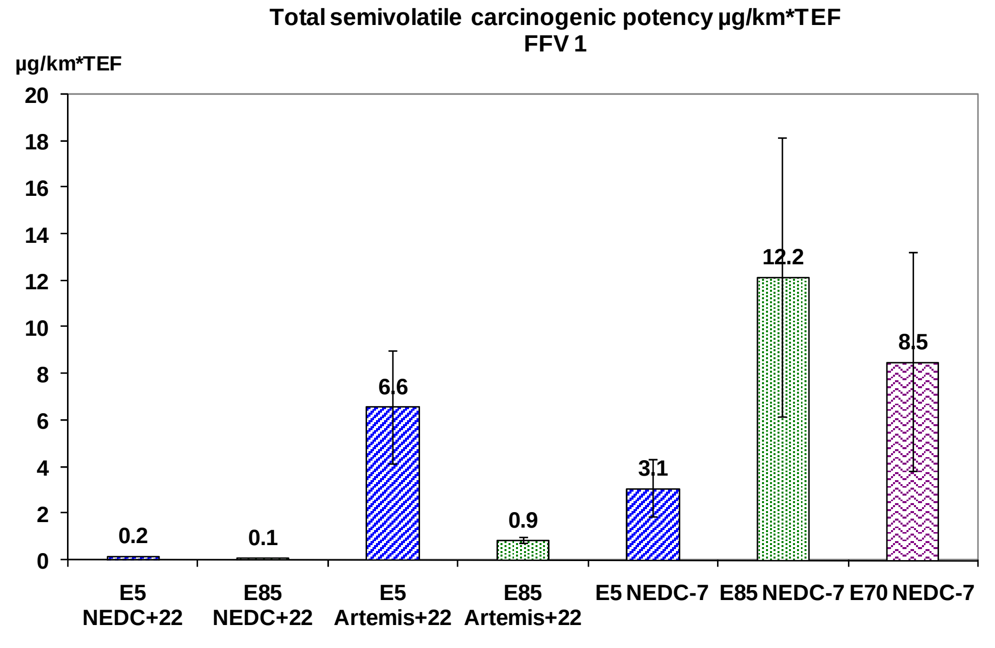

*Figure 98. Semivolatile-associated cancer potency (µg/km*TEF), FFV1.*

FFV2: The calculated cancer potencies at +22°C are lower than the corresponding calculated cancer potencies at -7°C, **Figure 99**. A relative increase of calculated cancer potency was observed for the Artemis driving cycle (E5 fuel) at +22°C. At –7°C calculated cancer potencies increases compared to tests at +22°and are fuel dependent. The calculated cancer potencies increases with increasing ethanol contents of the petrol blend tested that is E5 (6,2 µg/km*TEF) <E70 (20,9 µg/km*TEF) <E85 (37,1 µg/km*TEF), respectively at –7°C.

<u>BFV</u>: The calculated cancer potencies for the E5 fuel increases with decreasing temperatures, **Figure 100**. This is also valid for the CBG fuel. Furthermore, the CBG calculated cancer potencies are generally lower compared to the E5 fuel. In the Artemis driving cycle at +22°C, calculated cancer potency for the E5 fuel is rather large comparable with the CBG fuel at –7°C.

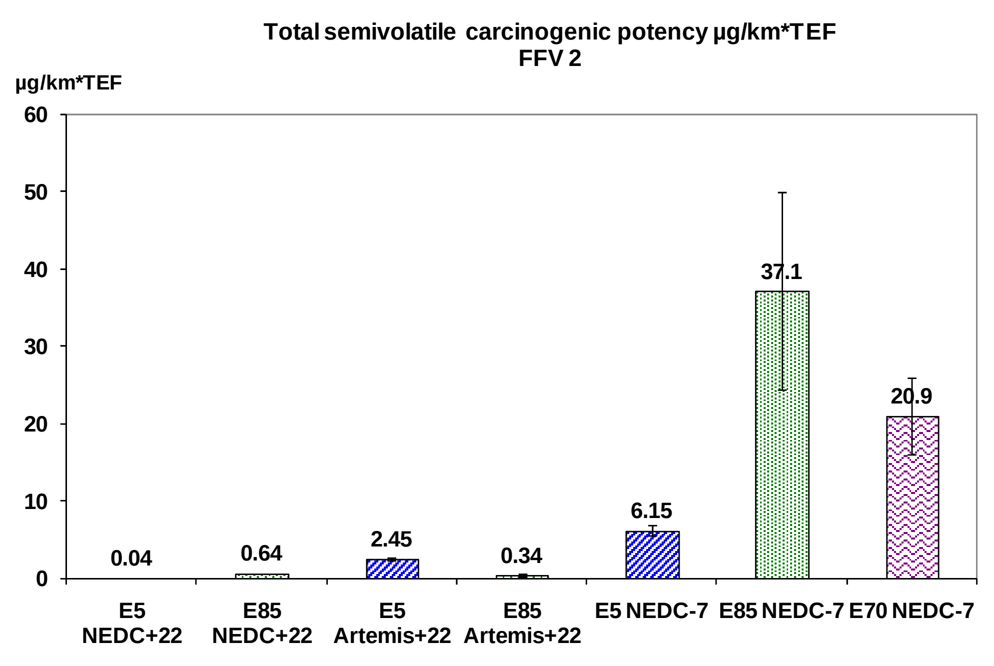

Figure 99. *Semivolatile-associated cancer potency (µg/km*TEF), FFV2.*

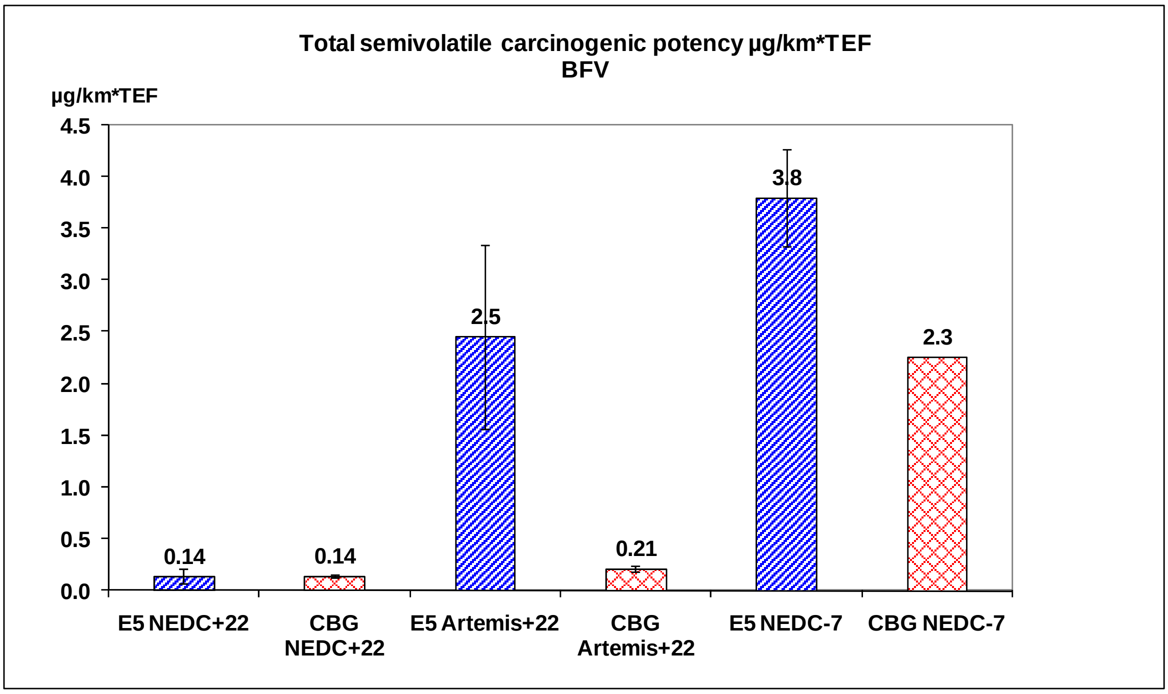

Figure 100. *Semivolatile-associated cancer potency (µg/km*TEF), BFV.*

Total cancer potency

In **Figure 101**, cancer potency from particulate-associated PAH and calculated cancer potency from semivolatile-associated PAH emissions is calculated and shown from FFV1 and in **Figure 102** corresponding values from FFV2 and in **Figure 103** from BFV, respectively. In principal, the figures in this section show the importance to include sampling and determination of semivolatile-associated PAH in chemical characterisations of vehicle exhaust. As shown, the calculated cancer potency from the semivolatile-associated PAH emissions dominate over the calculated cancer potency from particulate-associated PAH, especially from tests run at +22°C. At tests performed at -7°C, the calculated cancer potency from particulate-associated PAH become more dominating. For the BFV at -7°C, **Figure 103**, calculated cancer potency from particulate-associated PAH are more dominating, which is valid for both fuels tested i.e. E5 and CBG.

In the Artemis cycles on E5 fuel, the calculated cancer potency is dominated by semivolatile-associated PAH. On E85 fuel for FFV cars and on CBG on the BFV car, the level is generally significantly lower than for E5 fuel.

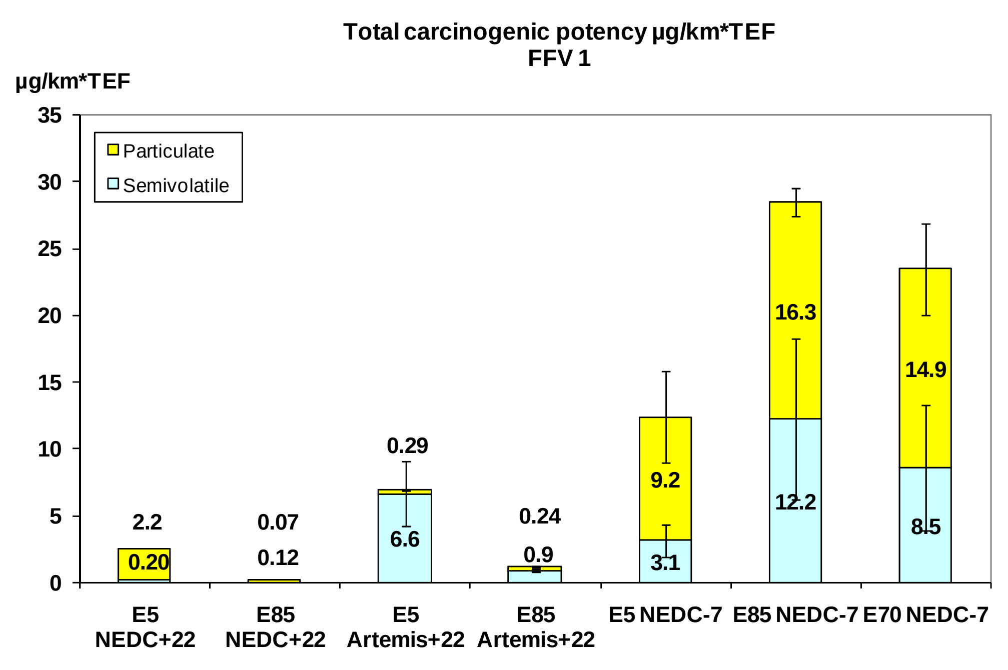

Figure 101. *Total cancer potency (µg/km*TEF), FFV1.*

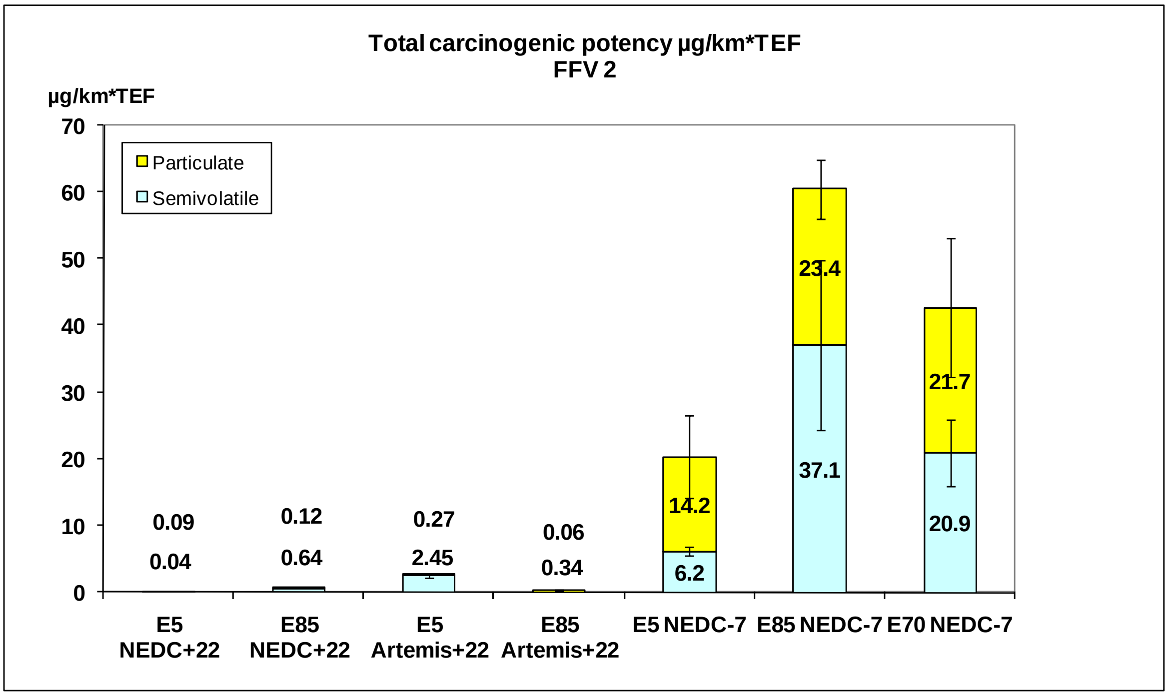

Figure 102. *Total cancer potency (µg/km*TEF), FFV2.*

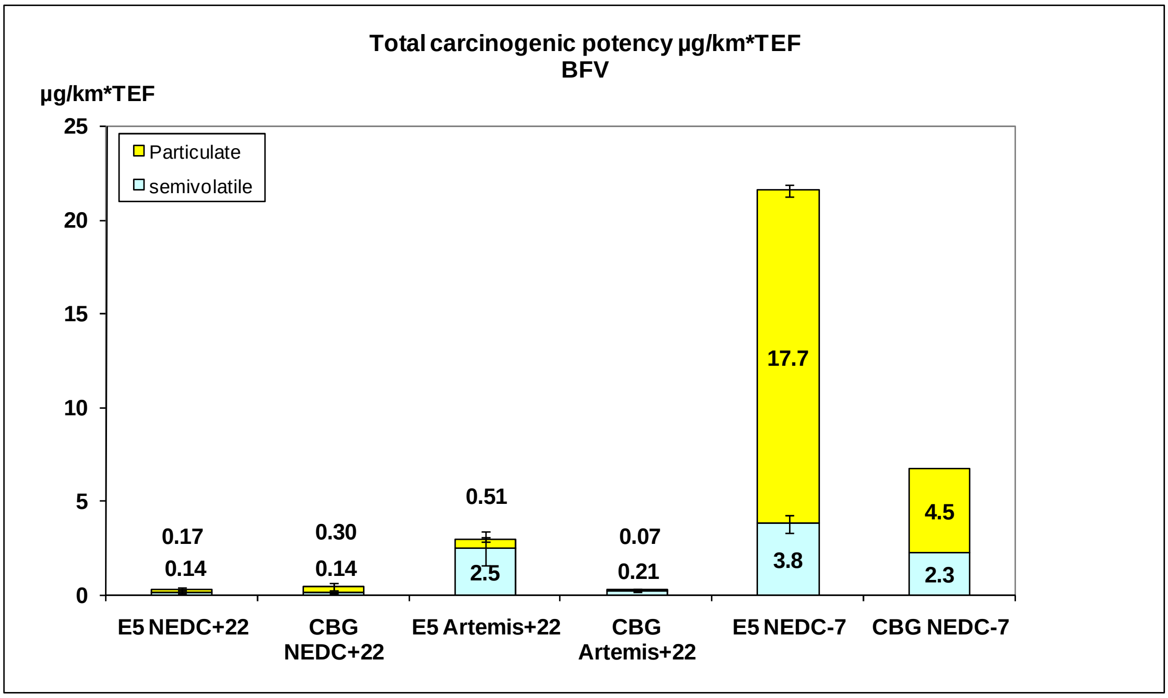

Figure 103. *Total cancer potency (µg/km*TEF), BFV.*

3.3 Evaporative emissions

Evaporative HC emissions were examined for the FFVs using E85 and E5 fuels for FFVs and for the BFV using CBG. The sum of the hot soak and the diurnal soak for FFVs is presented in **Figure 104**. A leakage of gas was detected during BFV diurnal test, and the vehicle was sent twice to the authorised workshop for reparation without success. Thus, no diurnal results are available for the vehicle. Very high HC evaporative emissions were observed during diurnal test of the FFV2 car with E5 fuel. The tests were repeated several times and the high HC evaporative emissions were confirmed.

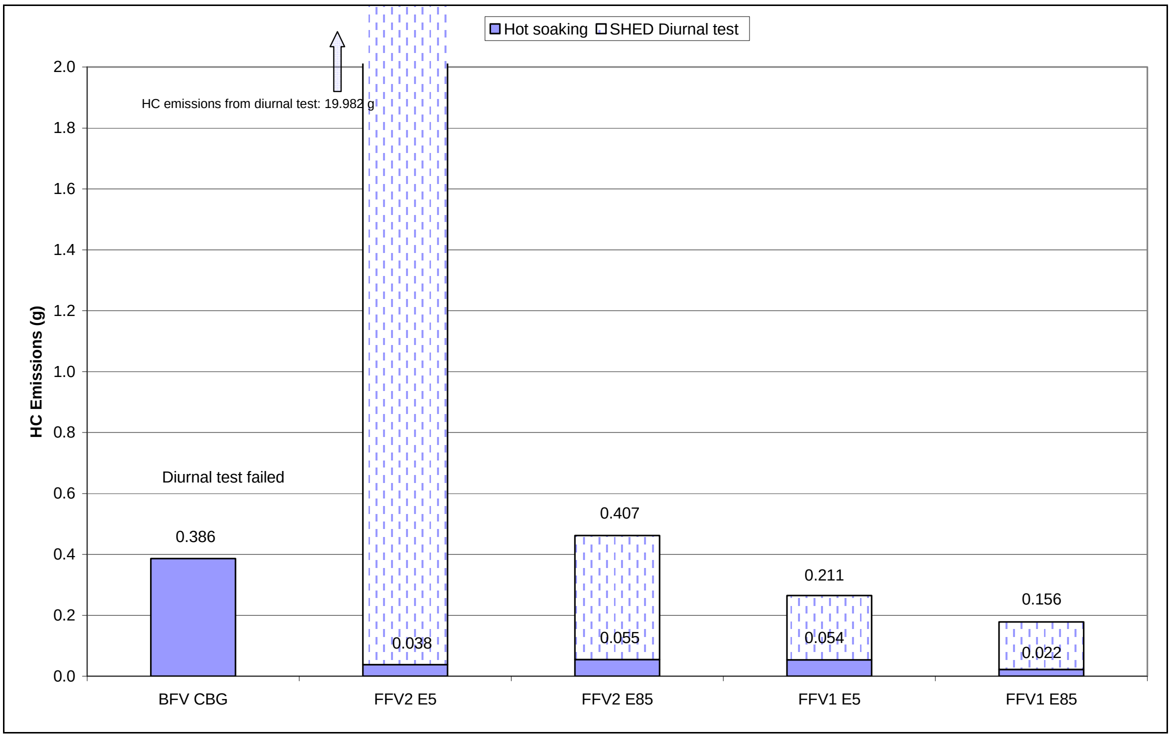

Figure 104. VT-SHED HC emission results.

3.4 Fuel consumption and energy consumption

Fuel and energy consumptions (FC & EC) from the test vehicles are presented in **Figure 105** to **Figure 110**. Energy consumption is a commonly used term but strict scientifically, it is not correct. “Energy use” would be a better term in that respect. However, energy consumption is so commonly used that it is used also in the present report.

Due to the differences in energy contents of the fuels, the flex fuel vehicles have always the following volumetric fuel consumptions sequence when the same test cycle is applied, i.e. E85 > E70 > E5. Taking into account the energy contents, both the FFV2 and the FFV1 have lower ECs with E85 than the E5 at the +22°C test cycles. At cold climate tests, the differences in ECs among the E70, E85 and E5 are negligible.

It is difficult to compare FC between CBG and E5 since the two fuels have completely different physical properties. However, these results are shown here anyway, since the fuel consumption is of public interest due to the importance of this parameter on fuel cost per distance driven. **Figure 108** shows that the CBG always has lower EC than the E5 when one comparing the same test cycle.

A clear conclusion valid for all three vehicles tested is that AU has the highest EC and FC and AR the lowest. Tests at lower ambient temperatures always lead to higher FC and EC compared to tests at +22°C.

It can be noted that fuel consumptions were higher from the present measurement than the certification data. Normally manufactures use coast down data from individual vehicles to optimise fuel consumption, whereas water brake settings (permitted by the directive) were used for dynamometer settings in the present study. Furthermore, E5 was used instead of petrol in this case. The fuel consumption data (from certification) for individual vehicles are included in **Table 13**.

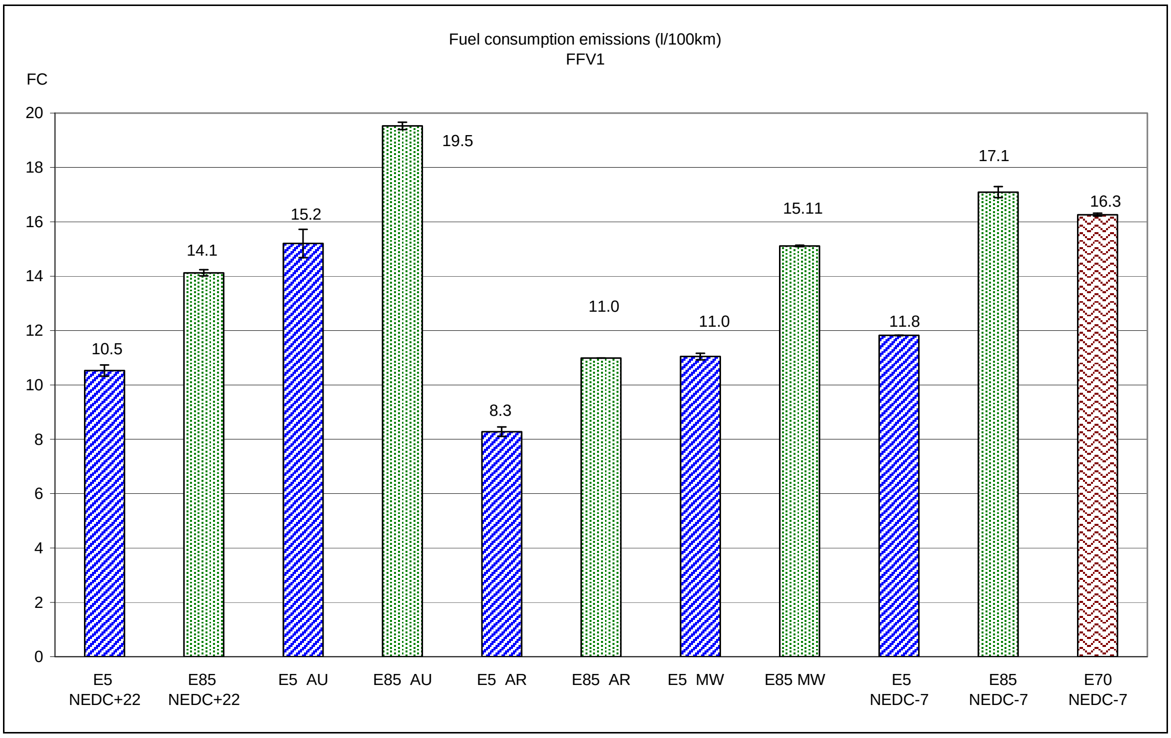

Figure 105. Fuel consumption for FFV1.

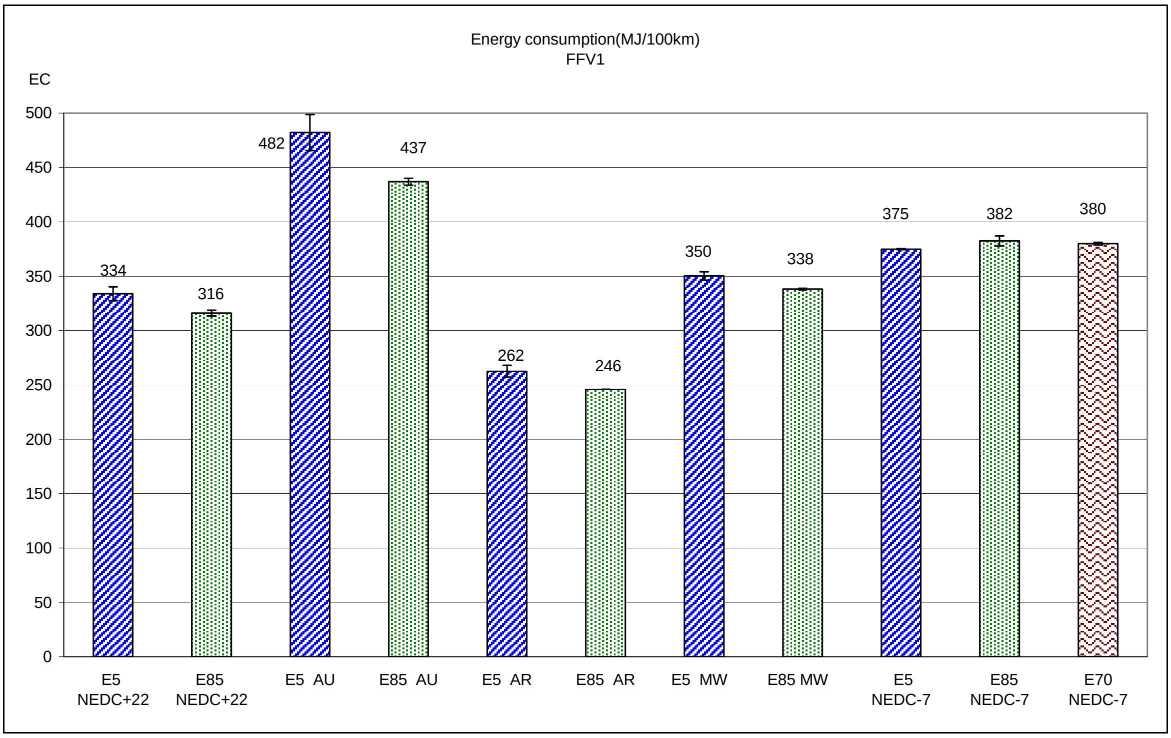

Figure 106. *Energy consumption for FFV1.*

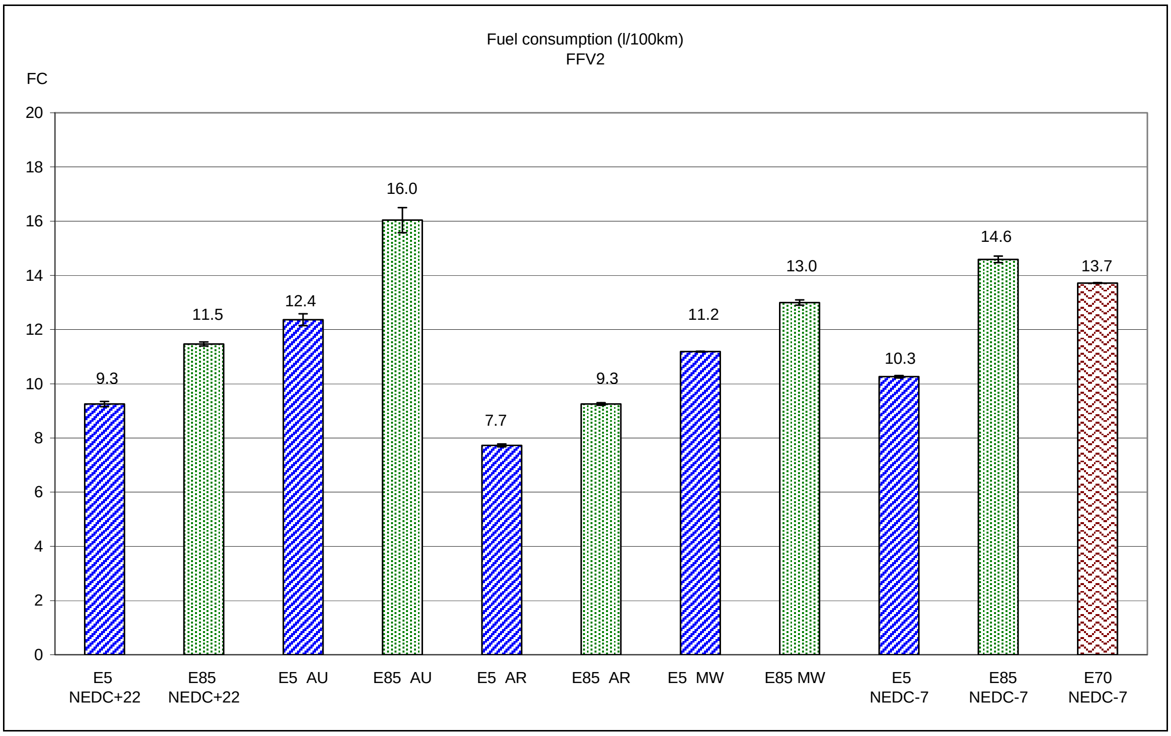

Figure 107. *Fuel consumption for FFV2.*

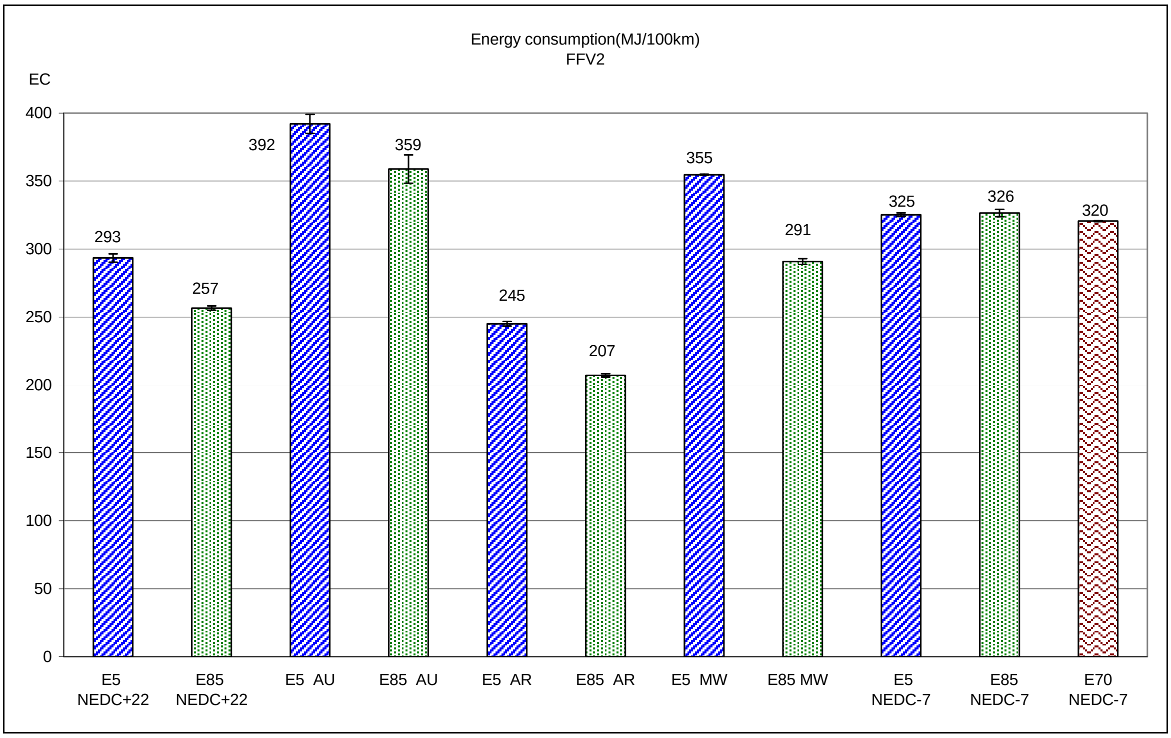

Figure 108. *EC emission from FFV2.*

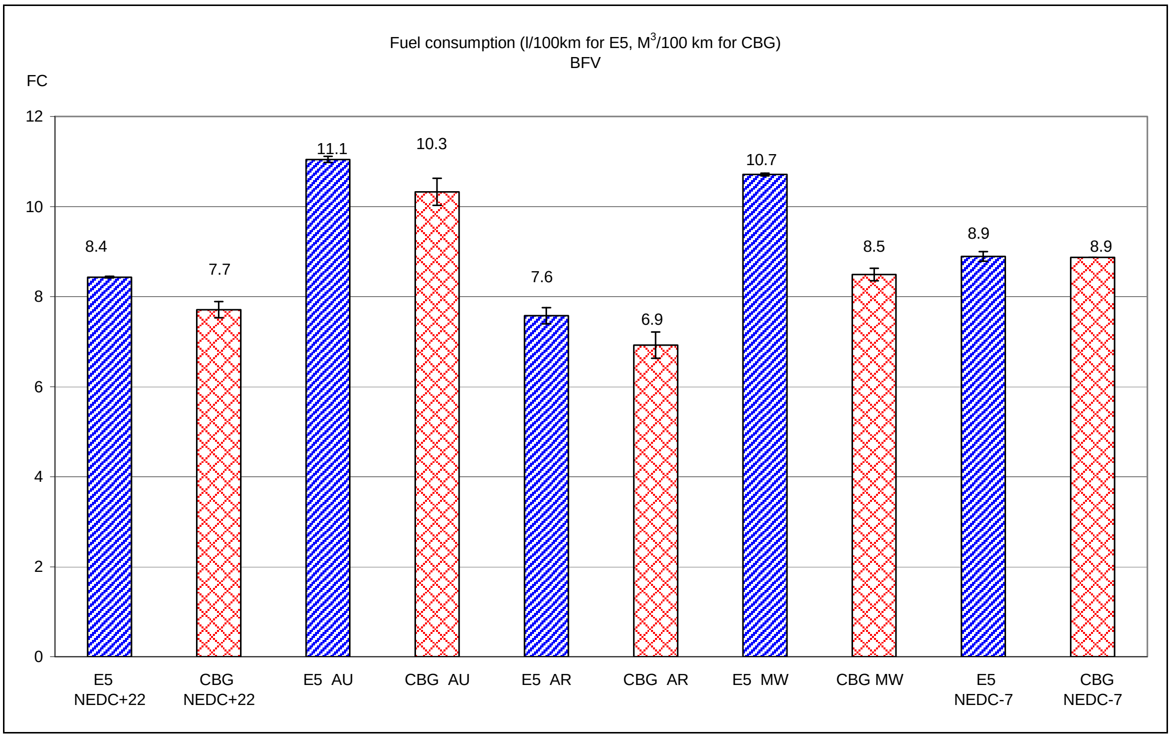

Figure 109. *Fuel consumption for BFV.*

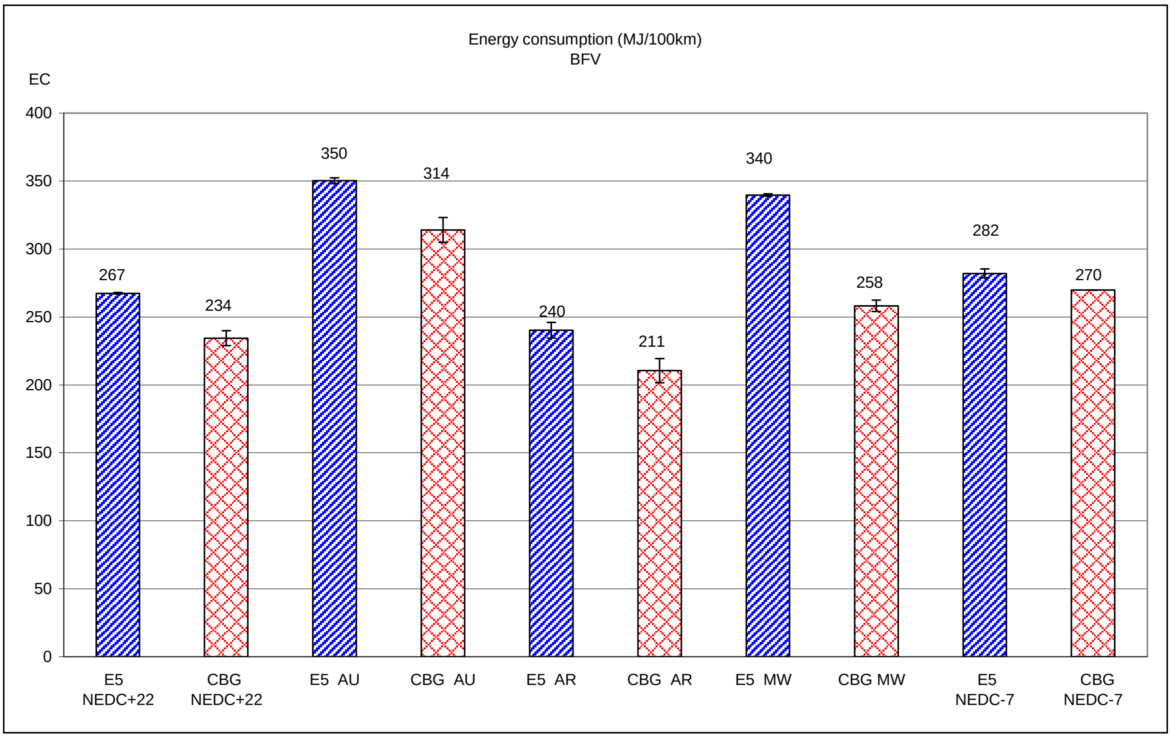

Figure 110. *Energy consumption for BFV.*

3.5 PMP dilution

Normally, pressure and temperature fluctuations have an impact on the instantaneous dilution ratio for partial dilution devices. In the CVS tunnel, pressure fluctuations are generally low but there is some variation in temperature. Dilution ratio is continuously calculated on a second-by-second basis in the FPS dilution system. It is of interest to look at the fluctuation of the dilution ratio during a whole test cycle to determine to what extent the dilution system can manage to keep the dilution ratio constant. If not, it could be necessary to take instantaneous dilution ratio into account instead of using averaged data.

During the whole test series, only a few settings of dilution ratios were used. The lowest was about 1:16 and the highest was 1:80. In general, high dilution ratios were used when the concentrations were high, such as, e.g. during cold start at -7°C and in the Artemis motorway cycle. Under all other test conditions, the lower dilution ratio was used. To show some results of how dilution ratio varies with time, two more or less randomly selected tests are shown below. Both tests were on the BFV car. E5 fuel was used in both cases and the test temperature was and -7°C and -22°C, respectively.

In **Figure 111**, the dilution ratio versus time is shown for a NEDC test with a nominal dilution ratio of about 1:16. The test temperature was +22°C in this case. As can be seen in **Figure 111**, there is some fluctuation in dilution ratio. The standard deviation is less than 0,6 %, which must be considered as an excellent result.

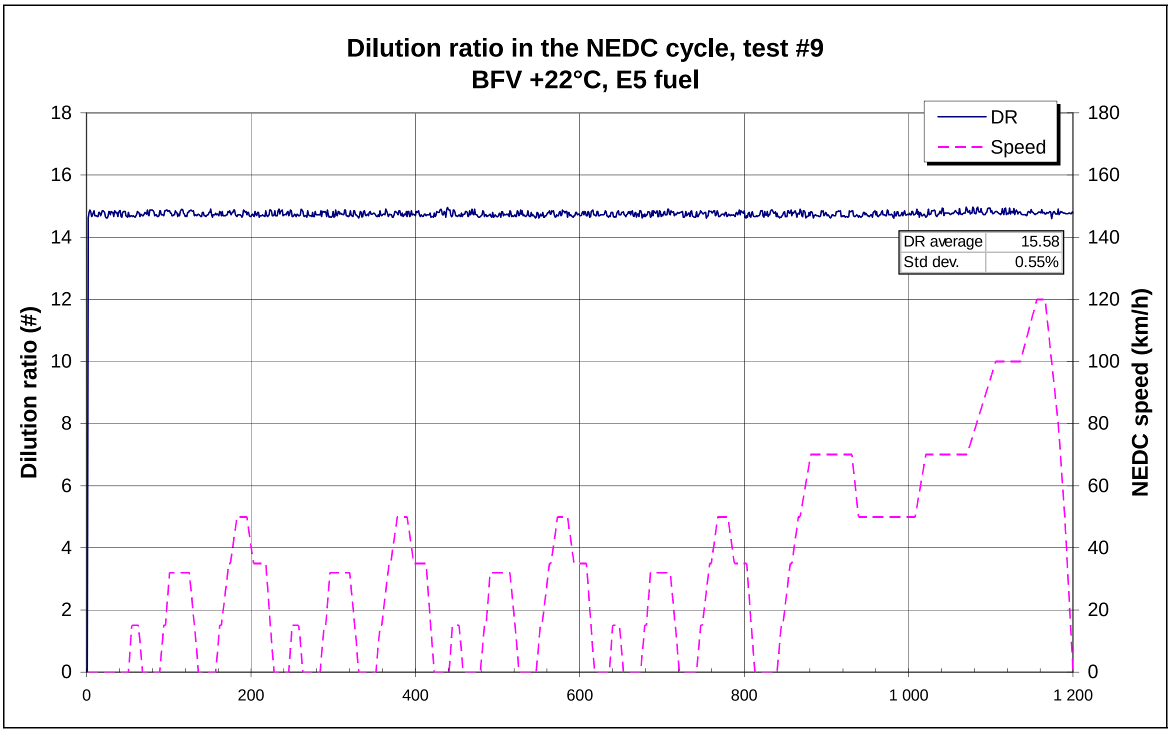

Figure 111. *Dilution ratio trace at a low dilution ratio (NEDC).*

In **Figure 112**, the dilution ratio versus time is shown for a NEDC test with a nominal dilution ratio of about 1:80. The test temperature was -7°C in this case.

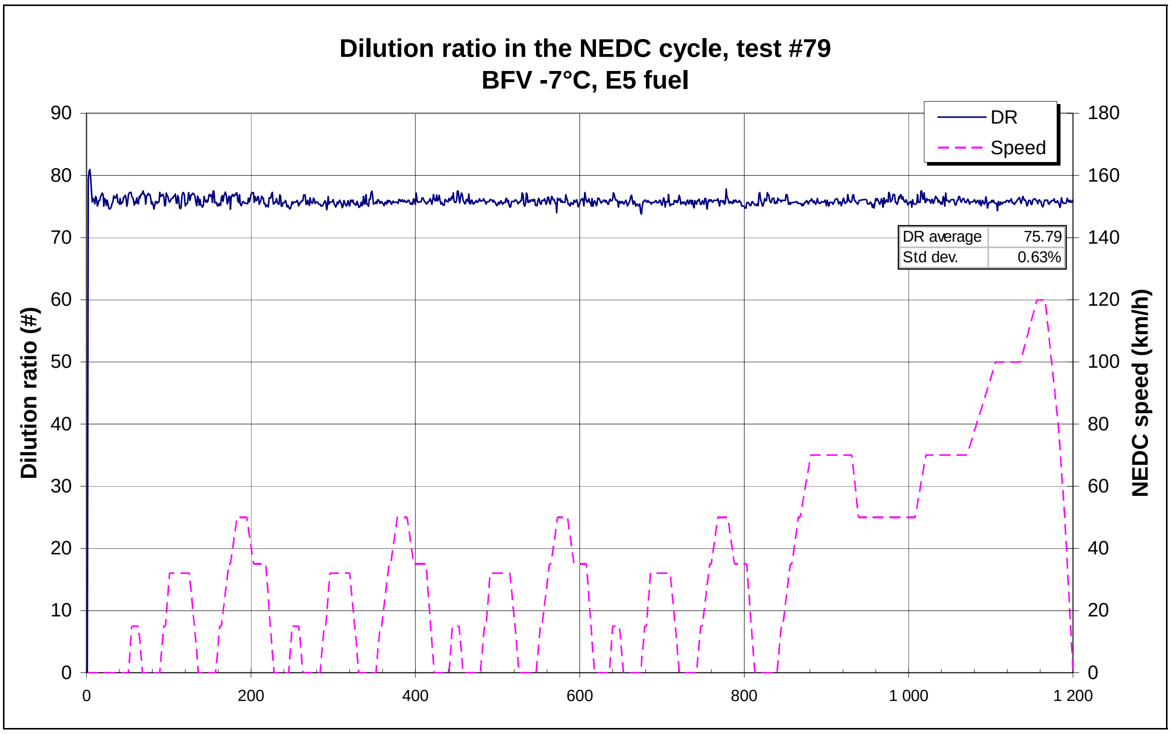

Figure 112. *Dilution ratio trace at a high dilution ratio (NEDC).*

There is a somewhat higher scatter of the dilution ratio at higher dilution ratios, as the data in **Figure 112** shows. By principle, there should be higher scatter at higher dilution ratios with the FPS. The FPS mixes three flows; the sample flow and the flow from the first and second dilution stages. At higher dilution ratios, the sample flow is low and the dilution flows are high. It is conceivable that there will be a higher variation of dilution ratios under these conditions than at the lower dilution ratios, where the flows are more similar. However, the scatter at the higher dilution ratio is still very low in this case. During testing, it was seen visually on the screen that the scatter increased when even higher dilution ratios were used but no measurements were carried out at these conditions so the scatter could not be quantifies.

All in all, the results indicate that the operation of the dilution system proved to be stable and satisfactory.

3.6 Results from on-board emission testing

3.6.1 Test setup

All tests were carried out by using on-board measurement of methane with a FID instrument and by driving on public roads. The test equipments were mounted on a trailer and all tests were carried out in similar ways (**Figure 113**). Gaseous-fuelled cars were always started initially on petrol fuel, since this was the strategy chosen in the electronic control unit of the vehicles. After some minutes the fuel was shifted to the CBG fuel. After that, a test route was driven, first with gas fuel and then with petrol fuel. By using the same test route it was possible to compare differences in emission levels for the two fuel types.

Figure 113. *Test setup on the car and the trailer.*

3.6.2 On-board test results

Only two of nine tested gas cars showed acceptable emission levels of un-burned hydrocarbons (methane) by using CBG as fuel. Whereas, by using petrol as fuel, all nine gas cars showed low emission levels of hydrocarbons. An explanation for this behaviour may be that the catalytic activity for oxidation of methane decline over time (this has also been showed in previous studies). The results (present and previous studies) indicate that the life time for a catalytic converter for CNG/CBG cars (activity expressed as oxidation of methane) could be in the order of maximum 10 000 km.

Emission of un-burned hydrocarbons from a typical CBG car, shown as HC traces versus time, is presented in **Figure 114**. It is fully clear that the emission of hydrocarbons is significantly higher when gas is used as fuel compared with petrol fuel.

There were no differences in hydrocarbon emissions if ethanol (E85) or petrol (E5) was used as fuel for the fuel-flexible FFV1 car.

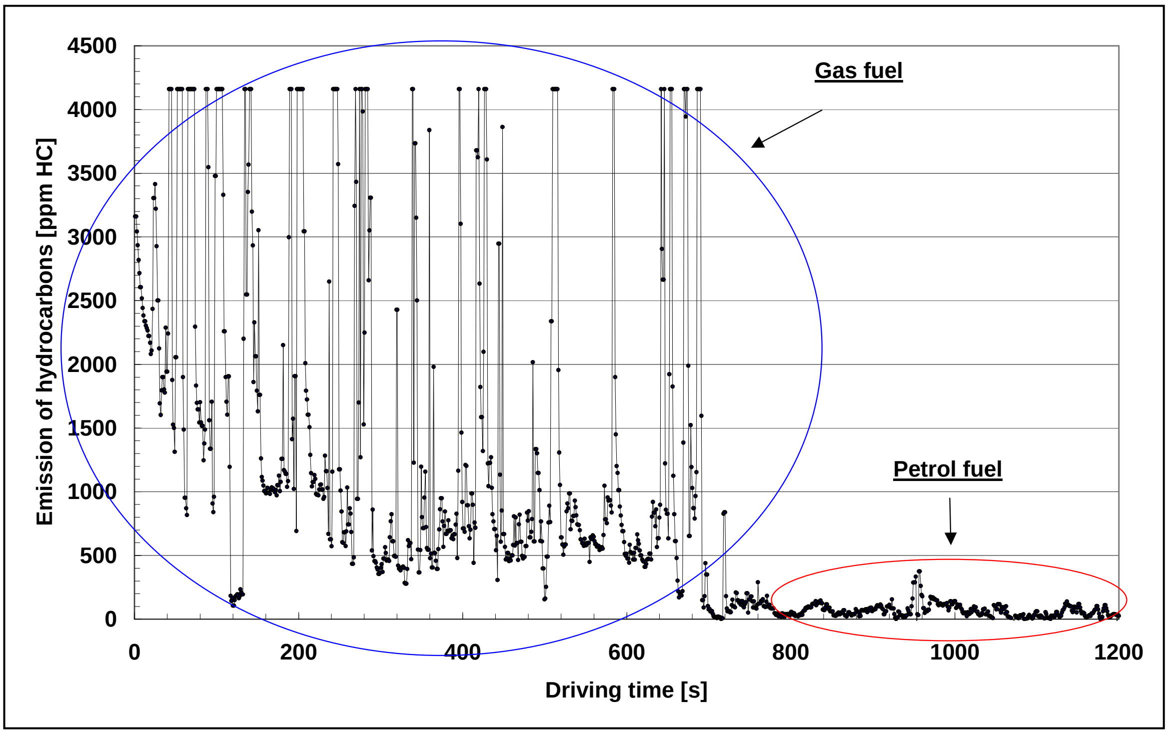

Figure 114. *HC emissions (in ppm).*

During 2004 and 2005 similar on-board measurements as in the present project were carried out on 10 city buses (unpublished summary of results) and 3 waste trucks (Eriksson, 2004). Some general conclusions from the test results on these 13 tested vehicles can be drawn. The exhaust gas aftertreatment system worked properly on four vehicles (<4 000 km odometer reading) and one vehicle (odometer reading of 85 000km). The exhaust aftertreatment system had very low catalytic activity on five vehicles (model year 1997 to 2000). There was some activity of the exhaust aftertreatment, but it did not work properly on one vehicle. The exhaust aftertreatment system had full activity on two vehicles. However, one of these vehicles had high HC emissions anyway, which was probably linked to high engine-out emissions.

The results reported in the present study and the older studies on the vehicles described above indicate that the emission level of unburned methane might be very high for a significant part of the vehicle fleet (both light and heavy-duty vehicles) in Sweden. Fast ageing of the catalytic converter may be the explanation. Emission tests carried out by the Swedish Motor Vehicle Inspection Company during the yearly vehicle inspection will not indicate this high level, since this measurement method is not dedicated to detect methane emissions.

4 SUMMARY AND CONCLUSIONS

4.1 Specific conclusions

Generally valid for all cars tested are that each car is compared individually with its exhaust emissions generated in the NEDC driving cycle at +22°C using E5 as fuel which is set to 1 by definition (baseline) in **Table 22**, **Table 23** and **Table 24** below.

4.1.1 Conclusions regarding the FFV1 car

Summary and conclusions for the FFV1 car in the NEDC driving cycle and the Artemis driving cycles i.e. AU, AR and MW are presented in **Table 22**, below, respectively. Baseline for all comparisons, if not stated otherwise, is the NEDC, E5 fuel at +22°C for the FFV1 car. Thus, a factor lower than one (<1) means lower emissions compared to baseline and a factor higher than one (>1) that the emissions are higher than baseline.

From the summary of results in **Table 22** from the FFV1 car, a number of conclusions can be drawn when tested in the NEDC driving cycle.

When comparing the results using E5 and E85 fuels at +22°C, the following conclusions can be drawn:

- At +22°C many emission components are lower for E85 than for E5. This is due to the dilution effect of blending more ethanol in E5 to obtain E85. However, the increased aldehyde emissions shown in the table for the E85 fuel is due to the increased ethanol content in the fuel.
- As expected, unburned ethanol emissions are higher for the E85 fuel than for the E5 fuel.
- The energy use is about 5 % lower for the E85 fuel compared to the E5 fuel. The volumetric fuel consumption is 34 % higher in the E85 case.

When the temperature is reduced from +22°C to -7°C with the E5 fuel, the following conclusions can be drawn:

- By decreasing temperature from +22°C to -7°C, CO and HC emissions increase by a factor of 3 and 5, respectively. There is a more than 30-fold increase in NO_X emissions by decreasing temperature, however, from a very low absolute level. Particulate emissions increase by a factor of approximately 40.
- Particulate-associated PAH increases by a factor of 16. Corresponding calculated cancer potency for particulate-associated PAH is a factor of close to 50 times higher.
- Semivolatile-associated PAH increases by a factor of 17. Corresponding calculated cancer potency for semivolatile-associated PAH is a factor of more than 15 higher.

Table 22. *Overview of emission results for FFV1.*

	NEDC				**Artemis E5**			**Artemis E85**		
Parameter	**E5**	**E85**		**E70**	**AU**	**AR**	**MW**	**AU**	**AR**	**MW**
Temperature	-7°C	+22°C	-7°C	-7°C	+22°C	+22°C	+22°C	+22°C	+22°C	+22°C
CO	3,0	1,76	7,67	8,19	0,06	0,37	2,57	0,11	0,09	0,69
HC	5,0	1,33	29,5	20,00	0,14	0,10	0,24	0,17	0,06	0,13
NO_X	35[a]	0,5	4,0	2,5	1,22	0,29	0,15	0,35	1,21	1,99
PM	40	2	47	51	4,95	5,70	38,1	11,4	3,61	16,5
Methane	2	2	13	7	0,7	0,4	0,6	1,5	0,4	0,4
NO_2	2	2	13	7	1[a]					
Formaldehyde	m.v[b]	3	13	m.v[b]	0,24	0,27	0,09	0,22	0,07	0,07
Acetaldehyde	m.v[b]	14,7	>100	m.v[b]	0,17	0,07	0,14	0,24	0,08	0,19
Ethanol	m.v.[b]	13	240	m.v.[b]	n.d.[c]	n.d.[c]	0,17	n.d.[c]	n.d.[c]	0,07
Ethene	m.v.[b]	2,5	9,5	m.v.[b]	n.d.[c]	n.d.[c]	0,29	n.d.[c]	n.d.[c]	0,18
Propene	m.v.[b]	0,33	4,67	m.v.[b]	n.d.[c]	n.d.[c]	0,60	n.d.[c]	n.d.[c]	0,41
1,3-Butadiene	m.v.[a]	0,4	4,2	m.v.[a]	n.d.[c]	n.d.[c]	0,54	n.d.[c]	n.d.[c]	0,43
Benzene	m.v.[b]	0,5	8	m.v.[a]	n.d.[c]	n.d.[c]	1,28	n.d.[c]	n.d.[c]	0,38
Toluene	m.v.[b]	0,5	9,33	m.v.[b]	n.d.[c]	n.d.[c]	0,39	n.d.[c]	n.d.[c]	0,03
PAH-part	16,2	0,32	51	38,3	0,68			0,63		
PAH-semi	17	0,4	58	42	4,2			1,1		
TEF ratio	1.8	0.92	0.5	0.77	1.8			0.65		
CP-PAH-part	47,5	0,5	81,5	74,5	1,5			1,0		
CP-PAH-semi	15,5	0,5	61	43	33			4,5		
PN_{PMP}	m.v.[b]	0,5	15	m.v.[b]						
PN_{ELPI}	m.v.[d]	1,0	35	m.v.[d]						
PM_{DMM}	m.v.[d]	0,57	2,2	4,7	1,7	4,8	1	1,9	1,3	2,9
Fuel cons.	1,12	1,34	1,63	1,55	1,44	0,79	1,05	1,85	1,04	1,44
Energy use	1,12	0,95	1,14	1,14	1,44	0,79	1,05	1,31	0,74	1,01

Notes:

[a] See discussion about the high NO_X in **Figure 22** in section 3.2.1 about Regulated emissions.

[b] NO_2 is calculated by subtracting NO from NO_X but due the so-called “cancellation effect”, measurement scatter can sometimes give negative values, why no values in this table has been reported.

[c] Not detected (n.d.), i.e. below the detection limit.

[d] Missing value: m.v.

- From the table it can be concluded that the TEF ratio increases when the ethanol contents are reduced in fuel independent of starting temperature and driving cycle.

This can be interpreted as that the relative contents of lighter PAHs increase relatively more compared to heavy molecular weight PAHs. However, in absolute numbers, PAH emissions increases at -7°C, **Figure 86** and **Figure 89**.

- The fuel consumption and energy use are 12 % larger when the temperature is decreased to -7°C compared to +22°C.

Comparing the fuels E5, E85 and E70 at -7°C, these conclusions can be drawn:

- At -7°C, all regulated emission components but NO_X increase by increasing the ethanol content in the fuel.
- At -7°C, practically all unregulated emission components are generally higher for E85 and E70 compared to E5.
- Methane emissions increase with increasing ethanol content but the absolute level is low in all cases.
- As expected, aldehyde and unburned ethanol emissions are highest for the fuel with the highest ethanol content, i.e. E85.
- Particulate-associated PAH emissions increase with increasing ethanol content in the fuels tested.
- Semivolatile-associated PAH emissions increase with increasing ethanol content in the fuels tested.
- Calculated cancer potency from particulate-associated PAH emissions increases with increasing ethanol content in the tested fuels. Compared to E5 fuel at -7°C, the cancer potency for E85 increases by about 70 % and the corresponding increase for E70 is roughly 60 %.
- Calculated cancer potency from semivolatile-associated PAH emissions increases with increasing ethanol content in the tested fuels. Compared to E5 fuel at -7°C, the cancer potency for E85 increases by about a factor of 3,9 and the corresponding increase for E70 is about 2,7. However, the increase is more than 40 times for E70 and 60 times for E85 compared to E5 at +22°C.
- Particle number is a factor of 15 (PN_{PMP}) or 35 (PN_{ELPI}) higher for E85 at -7°C compared to E5 at +22°C. Other comparisons cannot be made due to missing data.
- The PM measured with the DMM instrument shows a relatively similar trend as the gravimetric PM measurements.
- As expected, the volumetric fuel consumption is higher with higher ethanol content in the fuels. The relative increase in energy use is higher for E85 and E70 (+14 %) than for E5 (+12 %) when the temperature is reduced in all cases.

From the summary of results in **Table 22** for the FFV1 car (baseline is E5 in NEDC at +22°C), a number of conclusions can be drawn when tested in the Artemis driving cycle i.e. when using E5 and E85 fuels at +22°C:

- Comparing the results in Artemis AU for E5 with E85, the emissions of CO, HC, PM methane and acetaldehyde increases, while, NO_X, and formaldehyde emissions decreases.
- Comparing the results in Artemis AR for E5 with E85, the emissions of CO, HC, PM and formaldehyde decreases, while the NO_X and acetaldehyde emission increases. Emissions of HC and methane are relative unaffected.
- Comparing the results in Artemis MW for E5 with E85, almost all emissions decrease, while NO_X and acetaldehyde emissions increase.
- Valid in all sub parts of the Artemis driving cycle is that volumetric fuel consumption increases and energy use decreases when using the E85 fuel, which is however expected.
- PAH emissions and calculated cancer potencies reported in the Artemis driving cycle are determined (calculated) as a integrated value originating from the Artemis driving cycle sub parts, i.e. AU, AR and MW. A comparison reveals that the PAH emissions decreases and consequently the cancer potencies are reduced when using the E85 fuel.
- From the table it can be concluded that the TEF ratio increases when the ethanol contents are reduced independent of driving cycle. This can be interpreted as that the relative contents of lighter PAHs increase relatively more compared to heavy molecular weight PAHs.

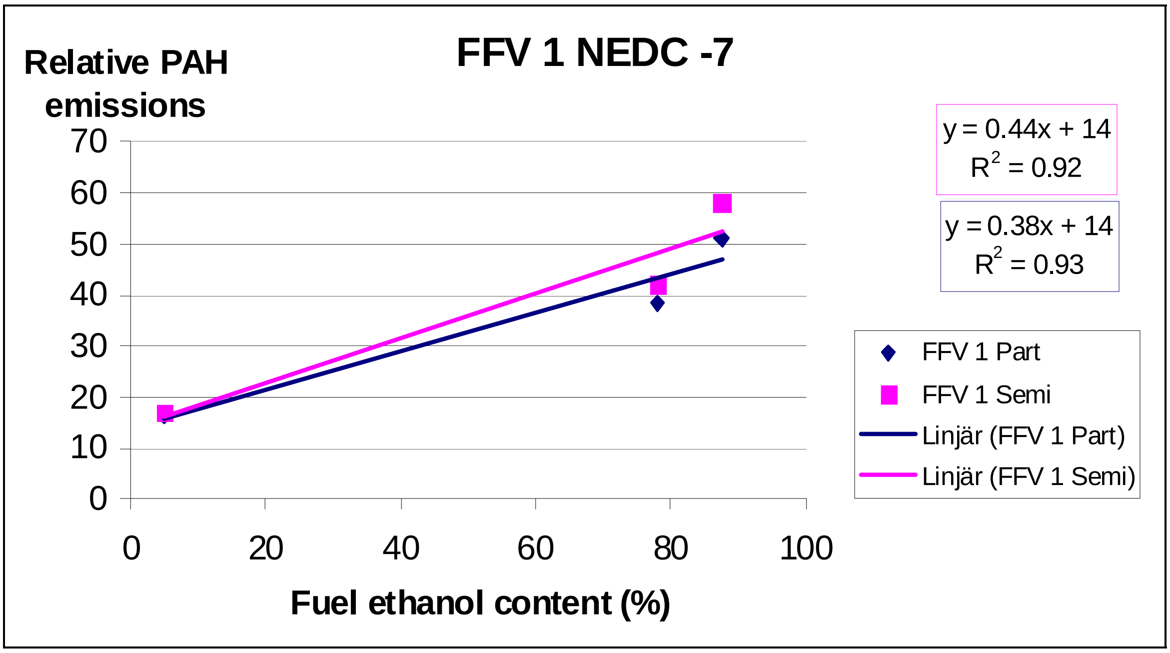

*Figure 115. Relative PAH emissions (**Table 18**) versus fuel ethanol contents.*

In **Figure 115**, the relative PAH emissions (**Table 22**) versus fuel ethanol contents are shown. From **Fel! Hittar inte referenskälla.** it can be concluded that PAH emissions increases with increased fuel ethanol contents when testing FFV1 in the NEDC driving cycle at -7°C. The slope of the particulate and the semivolatile associated PAH are quite similar which shows that particulate and the semivolatile associated PAH covariates. Furthermore, as PAH emissions increases also the cancer potency increases with increased fuel ethanol contents when running FFV1 in the NEDC driving cycle at -7°C.

4.1.2 Conclusions regarding the FFV2 car

Summary and conclusions for the FFV2 car in the NEDC driving cycle and the Artemis driving cycles, i.e. AU, AR and MW, are presented in **Table 23** below, respectively. Baseline for all comparisons, if not stated otherwise, is the NEDC, E5 fuel at +22°C for the FFV2 car. Thus, a factor lower than one (<1) means lower emissions compared to baseline and a factor higher than one (>1) that the emissions are higher than baseline.

From the summary of results in **Table 23** for the FFV2 car, a number of conclusions can be drawn when tested in the NEDC driving cycle.

When comparing the results using E5 and E85 fuels at +22°C, the following conclusions can be drawn:

- At +22°C many emission components are lower for E85 compared to E5. This is due to the dilution effect of blending ethanol in petrol. However, the increased aldehyde emissions shown in the **Table 23** for the E85 fuel is due to the increased ethanol content in the fuel.
- As expected, unburned ethanol emissions are higher for E85 than for E5.
- The volumetric fuel consumption is 24 % higher in the E85 case. The energy use is about 12 % lower for E85 compared to E5.

When the temperature is reduced from +22°C to -7°C with E5 fuel, the following conclusions can be drawn:

- By decreasing temperature from +22°C to -7°C, CO and HC emissions increase by a factor of 5 and 6, respectively, and NO_X emissions are reduced by some 25 %. Particulate emissions increase by a factor of approximately 8.
- Formaldehyde, acetaldehyde methane and ethanol emissions increased by decreasing temperature, as expected.
- There was a general increase in alkene emissions by a factor of approximately 2-3 times. Corresponding increase for benzene and toluene emissions was around 8 times.
- Particulate-associated PAH increases by a factor of 40. Corresponding calculated cancer potency for particulate-associated PAH is a factor of about 140 times higher.
- Semivolatile-associated PAH increases by approximately a factor of 250. Corresponding calculated cancer potency for semivolatile-associated PAH is a factor of 150 times higher.
- Particle number (PN) emissions increase 3 and 6 times depending on the measurement principle, i.e. CPC and ELPI, respectively. This relative increase is smaller than the increase by a factor of almost 8 for PM emissions, indicating that the particle size increases by decreasing temperature.

Table 23. *Overview of emission results for FFV2.*

	NEDC				**Artemis E5**			**Artemis E85**		
Parameter	**E5**	**E85**		**E70**	**AU**	**AR**	**MW**	**AU**	**AR**	**MW**
Temperature	-7°C	+22°C	-7°C	-7°C	+22°C	+22°C	+22°C	+22°C	+22°C	+22°C
CO	5,18	0,26	6,82	4,90	0,89	0,71	11,3	0,30	0,40	1,02
HC	6,14	0,71	17,86	16,29	0,10	0,05	0,29	0,07	0,05	0,11
NO_X	0,75	0,75	1,25	2,0	3,31	0,78	0,59	2,58	0,63	0,53
PM	7,75	0,5	11,5	8,0	1,93	0,77	11,3	0	0	0
Methane	2,0	1,0	9,0	9,0	0	0	1,8	0,8	0,6	1,2
NO_2	n.d.[a]	n.d.[a]	n.d.[a]	n.d.[a]	1[b]	0,2	0	1,4	0,2	0,2
Formaldehyde	1,33	2,67	5,33	6,0	0,15	0,04	0	0,23	0	0
Acetaldehyde	5,15	7,92	71,8	87,6	0,24	0,07	0,11	0,19	0,07	0,16
Ethanol	24	68	1 223	1 207	n.d.[a]	n.d.[a]	n.d.[a]	n.d.[a]	n.d.[a]	n.d.[a]
Ethene	2,25	0,75	14,0	14,0	n.d.[a]	n.d.[a]	0,81	n.d.[a]	n.d.[a]	n.d.[a]
Propene	3,25	0,25	4,0	3,0	n.d.[a]	n.d.[a]	0,47	n.d.[a]	n.d.[a]	n.d.[a]
1,3-Butadiene	2,0	0,12	3,0	2,5	n.d.[a]	n.d.[a]	0,43	n.d.[a]	n.d.[a]	n.d.[a]
Benzene	7,5	0,08	14,0	5,0	n.d.[a]	n.d.[a]	1,55	n.d.[a]	n.d.[a]	n.d.[a]
Toluene	8,0	0,14	7,42	5,42	0	0	0,39	0	0	0
PAH-part	41,1	1,2	106	100	1,7			0,3		
PAH-semi	249	10	1 350	706	11,5			3,0		
TEF ratio	0.54	0.72	0.45	0.31	0.64			0.27		
CP-PAH-part	142	1	234	217	3,0			1,0		
CP-PAH-semi	155	15	928	523	61			8,5		
PN_{PMP}	3,33	0,17	6,67	5,0						
PN_{ELPI}	5,71	0,14	7,14	5,71						
PM_{DMM}	18,5	5,2	94,5	45,9	m.v.[c]	52,5	m.v.[c]	4,13	7,1	0,67
Fuel cons.	1,11	1,24	1,57	1,47	1,34	0,83	1,21	1,73	1,0	1,40
Energy use	1,11	0,88	1,11	1,09	1,34	0,83	1,21	1,22	0,71	0,99

Notes:

[a] Not detected (n.d.), i.e. below the detection limit.

[b] As no value from E5 NEDC at +22°C is reported, the Artemis Urban test with E5 has been used as the reference value for comparison.

[c] Missing value: m.v.

- The fuel consumption and energy use are 11 % larger when the temperature is decreased to -7°C.

Comparing the fuels E5, E85 and E70 at -7°C, these conclusions can be drawn:

- At -7°C, all regulated emission components but NO_X increase by increasing the ethanol content in the fuel. Also PM emissions increase with increasing ethanol content in the fuel.
- At -7°C, all unregulated emission components are generally higher (except benzene and toluene for E70) for E85 and E70 compared to E5.
- Methane emissions increase with increasing ethanol content but the absolute level is low in all cases.
- As expected, aldehyde and emissions are higher for the E70/E85 fuels. Unburned ethanol fuel emissions are more than 40 times higher for E70 and E85 fuels.
- Particulate-associated PAH emissions increase with increasing ethanol content in the fuel.
- Semivolatile-associated PAH emissions increase substantially with increasing ethanol content in the fuel.
- Calculated cancer potency from particulate-associated PAH emissions increases with increasing ethanol content in the fuel. Compared to E5 fuel at -7°C, the cancer potency for E85 increases by about 60 % and the corresponding increase for E70 is about 50 %. However, the increase is more than 200 times for E70 and E85 compared to E5 at +22°C.
- Calculated cancer potency from semivolatile-associated PAH emissions increases with increasing ethanol content in the fuel. Compared to E5 fuel at -7°C, the cancer potency for E85 increases by about 6 times and the corresponding increase for E70 is about 3 times. However, the increase is more than 500 times for E70 and 900 times for E85 compared to E5 at +22°C.
- As shown in the table, all the TEF ratios are below one in all tests runs with the FFV2 car. From the table it can be concluded that the TEF ratio increases when the ethanol contents are reduced in fuel independent of starting temperature (E70 excluded) and driving cycle. This can be interpreted as that the relative contents of lighter PAHs increase relatively more compared to heavy molecular weight PAHs. However, in absolute numbers, PAH emissions increases at -7°C, **Figure 87** and **Figure 90**.
- Particle number from both CPC and ELPI increases by increased ethanol content. The relative maximum increase is about a factor of 2. However, it should be noted as a somewhat uncertain conclusion considering that the normal scatter in these types of measurements is relatively high.
- The PM measured with the DMM instrument shows a relatively similar trend as the gravimetric PM measurements.

- As expected, the volumetric fuel consumption is higher with higher ethanol content. However, the energy use is relatively unaffected by ethanol content in the tested fuels.

From the summary of results in **Table 23** for the FFV2 car (baseline is E5 in NEDC at +22°C), a number of conclusions can be drawn when tested in the Artemis driving cycle i.e. when using E5 and E85 fuels at +22°C:

- Comparing the results in Artemis AU for E5 with E85, the emissions of CO, HC, NO_X, PM and acetaldehyde decreases, while methane, NO_2, and formaldehyde emissions increases.
- Comparing the results in Artemis AR for E5 with AR E85 emissions of CO, NO_X, PM and formaldehyde decreases, while methane emission increases and HC, NO_2, acetaldehyde and are relatively unaffected.
- Comparing the results in Artemis MW for E5 with E85 almost all emissions decreases, while NO_2 and acetaldehyde emissions increase. Formaldehyde is relatively unaffected.
- Valid in all sub parts of the Aremis driving cycle is that fuel consumption increases and energy use decreases when using the E85 fuel, which is however expected.
- PAH emissions (particulate and semivolatile associated) and corresponding calculated cancer potencies reported in the Artemis driving cycle are determined (calculated) as a integrated value originating from the Artemis driving cycle sub parts i.e. AU, AR and MW. A comparison reveals that the PAH emissions decreases and consequently the cancer potencies are reduced when using the E85 fuel.
- As shown in the table, all the TEF ratios are below one in all tests runs with the FFV2 car. From the table it can be concluded that the TEF ratio increases when the ethanol contents are reduced in fuel independent of driving cycle. This can be interpreted as that the relative contents of lighter PAHs increase relatively more compared to heavy molecular weight PAHs.

In **Figure 116**, relative PAH emissions (**Table 23**) versus fuel ethanol contents are shown. From it can be concluded that PAH (particulate and semivolatile associated PAH) emissions increases with increased fuel ethanol contents when running FFV2 in the NEDC driving cycle at -7°C. The increase is more prominent for the semivolatile associated PAH emissions. Furthermore, as PAH emissions increases, the cancer potency also increases with increased fuel ethanol contents when running FFV2 in the NEDC driving cycle at -7°C.

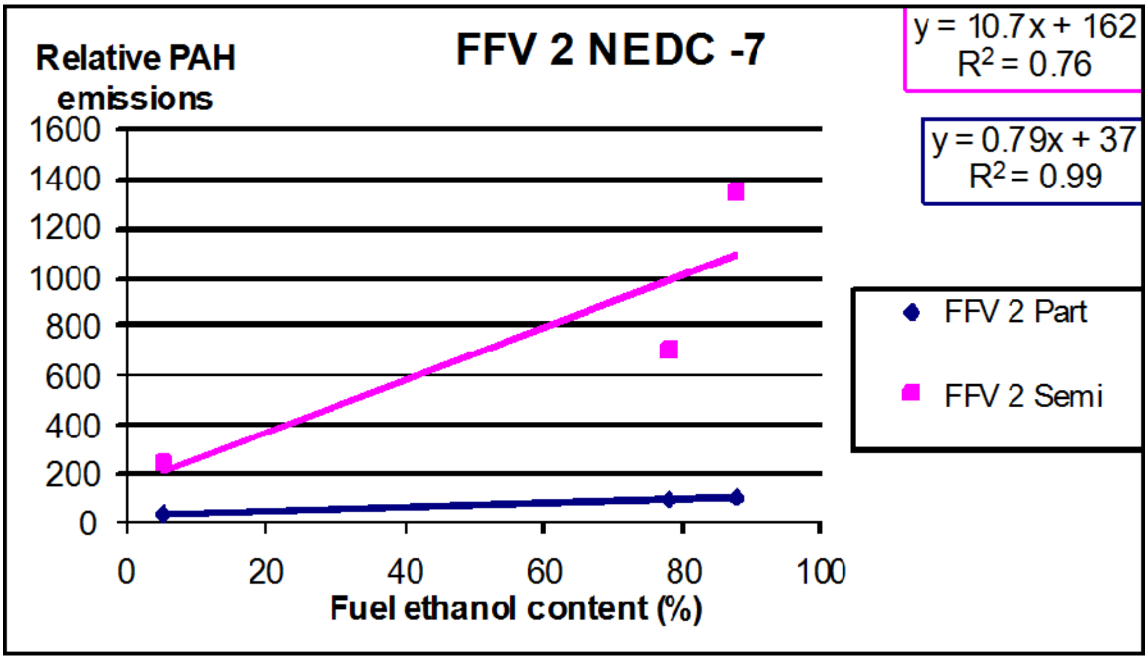

Figure 116. *Relative PAH emissions* ***(Table 23)*** *versus fuel ethanol contents.*

4.1.3 Conclusions regarding the BFV car

Summary and conclusions for the BFV car tested in the NEDC and the Artemis driving cycles i.e. AU, AR and MW are shown in **Table 24** below, respectively. Baseline for all comparisons, if not stated otherwise, is the NEDC, E5 fuel at +22°C for the BFV car. Thus, a factor lower than one (<1) means lower emissions compared to baseline and a factor higher than one (>1) that the emissions are higher than baseline.

It must be pointed out that the CO emissions running on E5 fuel at +22°C are more than a factor of 2 above the emission limit for this emission component. This fact implies that this car is not operating in optimum condition and thus, conclusions regarding CO emissions from the BFV car under other test conditions are questionable. This could also have an impact on the interpretation of results for other emission components. Consequently, the results and conclusions below are somewhat indicative.

From the summary of results in **Table 24** for the BFV car, a number of conclusions can be drawn when tested in accordance to the NEDC driving cycle.

When comparing the results using E5 and CBG fuels at +22°C, the following conclusions can be drawn:

- At +22°C most of the emission components, i.e. both regulated and unregulated emission components, are lower for CBG than for E5. Exceptions are total HC emissions, ethanol and methane.
- The cancer potency for the particulate-associated PAH for CBG is 50 % higher than for E5. The cancer potency for the semivolatile -associated PAH for CBG is similar.

Table 24. *Overview of emission results for BFV.*

	NEDC			**Artemis E5**			**Artemis CBG**		
Parameter	**E5**	**CBG**		**AU**	**AR**	**MW**	**AU**	**AR**	**MW**
Temperature	-7°C	+22°C	-7°C	+22°C	+22°C	+22°C	+22°C	+22°C	+22°C
CO	0,87	0,27	1,10	0,58	1,0	11,3	0,08	0,38	0,73
HC	6,0	1,17	6,0	0,12	0,10	0,77	0,13	010	0,94
NMHC	6,7	0,4	6,2	0,26	0,11	0,41	0,03	0,01	0,09
NO_X	1,2	0,40	0,40	4,91	0,56	0,07	3,10	1,54	14,1
PM	3,3	0,08	0,92	0,92	0,43	2,59	0,10	0,15	2,69
Methane	>2	>5	>10	0	0	4,3	1,2	0,9	9,2
NO_2	m.v[a]	m.v[a]	m.v[a]	1[a]	0	0	0,8	0,6	93
Formaldehyde	1,0	0,40	1,4	0,60	0,13	0	0,29	0,15	0,03
Acetaldehyde	2,0	0,5	1,4	0,79	0,23	0,31	0,38	0,12	0,11
Ethanol	6,5	1,5	10	n.d.	n.d.	0	n.d.	n.d.	0,01
Ethene	5,5	<0,25	6,0	n.d.	n.d.	1,6	n.d.	n.d.	0,01
Propene	4,5	0,5	5,5	n.d.	n.d.	0,73	n.d.	n.d.	0,01
1,3-Butadiene	4,5	<0,25	6,0	n.d.	n.d.	1,16	n.d.	n.d.	0,10
Benzene	5,0	<0,25	4,0	n.d.	n.d.	4,43	n.d.	n.d.	0,01
Toluene	8,8	0,2	9,2	n.d.	n.d.	0,64	n.d.	n.d.	0,01
PAH-part	54,0	0,83	14,3	2,6			0,5		
PAH-semi	25,7	0,67	16,1	3,9			0,7		
TEF ratio	0.41	0.78	0.37	0.70			0.29		
CP-PAH-part	35,4	1,5	22,5	2,5			0,5		
CP-PAH-semi	27	1	16	25			2,0		
PN_{PMP}	10	0,33	2,3						
PN_{ELPI}	10	0,75	5,0						
PM_{DMM}	>200	9,3	140	m.v.[c]	m.v.[d]	29	27	7,4	6,1
Fuel cons.	1,06	n.r.[c]	n.r.[c]	1,31	0,90	1,27	n.r.[d]	n.r.[d]	n.r.[d]
Energy use	1,06	0,88	1,01	1,31	0,90	1,27	1,17	0,79	0,97

Notes:

[a] As level for methane in E5 NEDC at +22°C was at or below the detection limit, the Artemis Urban test with E5 has been used as the reference value for comparison.

[b] Not detected (n.d.), i.e. below the detection limit.

[c] Missing value: m.v.

[d] Not relevant: n.r.

- The particle number emissions are 25 % (PN_{ELPI}) to 66 % (PN_{CPC}) lower for CBG compared to E5. However, as previously stated, this is a somewhat uncertain conclusion considering that the normal scatter in these types of measurements is relatively high.
- Comparison of volumetric fuel consumption for CBG and E5 is irrelevant. However, the energy use is about 12 % lower for CBG compared to E5, which is a substantial reduction.

When the temperature is reduced from +22°C to -7°C with E5 fuel, the following conclusions can be drawn:

- Somewhat surprising, CO emissions are lower at -7°C compared to the level at +22°C. The cause for this observation is the relatively high level of CO emissions at +22°C as discussed above. By decreasing temperature from +22°C to -7°C, HC emissions increase by a factor of 6 times and NO_X emissions are increased by some 20 %. Particulate emissions increase by a factor of approximately 3 times.
- Formaldehyde emissions are unaffected by decreased temperature while acetaldehyde emissions increase somewhat. Ethanol emissions increased 6 times.
- There was a general increase in alkene emissions by a factor of approximately 4 to 5 times. Corresponding increase for benzene and toluene emissions was around 5 and 9 times, respectively.
- Particulate-associated PAH increases by a factor of 50. Corresponding calculated cancer potency for particulate-associated PAH is a factor of about 35 times higher.
- Semivolatile-associated PAH increases by a factor of 25. Corresponding calculated cancer potency for semivolatile-associated PAH is a factor of 27 higher.
- As shown in the table, all the TEF ratios are below one in all tests runs with the BFV car. From the table it can be concluded that the TEF ratio increases with the E5 fuel compared to CBG fuel and independent of driving cycle. This can be interpreted as that the relative contents of lighter PAHs increase relatively more compared to heavy molecular weight PAHs. However, in absolute numbers, PAH emissions increases at -7°C, **Figure 88** and **Figure 91**.
- Particle number (PN) emissions increased 10 times independent on the measurement principle, i.e. CPC and ELPI, respectively. This relative increase is larger than the increase by a factor of about 3 for PM emissions, indicating that the particle size decreases by decreased temperature.
- The fuel consumption and energy use are 6 % larger when the temperature is decreased to -7°C.

Comparing the fuels E5, and CBG at -7°C, these conclusions can be drawn:

- CO emissions for CBG at -7°C are somewhat higher than for E5, which is not expected. HC and NMHC emissions are similar, while NO_X and lower and PM emissions are somewhat lower.
- Methane emissions increase but the absolute level is low in all cases.

- At -7°C, aldehydes, alkenes, benzene and toluene emissions are similar.
- Ethanol emissions are somewhat higher for CBG compared to E5.
- Particulate and semivolatile-associated PAH emissions are generally lower, i.e. a factor of 3 and 1,5, respectively, from CBG compared to E5.
- Calculated cancer potency for particulate-associated PAH decreases for CBG compared to E5 fuel at -7°C. However, the increase is more than 20 times for CBG and approximately 35 times for E5 compared to E5 at +22°C.
- Calculated cancer potency for semivolatile-associated PAH decreases for CBG compared to E5 fuel at -7°C. However, the increase is more than 16 times for CBG and approximately 25 times for E5 compared to E5 at +22°C.
- Particle number from CPC and ELPI are 5 and 2 times lower, respectively, compared to E5. However, it should be noted as a somewhat uncertain conclusion in the ELPI case considering the scatter in this type of measurement.
- The PM measured with the DMM instrument shows a relatively similar trend as the gravimetric PM measurements.
- Comparison of volumetric fuel consumption for CBG and E5 is irrelevant. However, the energy use is about 5 % lower for CBG compared to E5 fuel.

From the summary of results in **Table 24** from the BFV car, a number of conclusions can be drawn when tested in the NEDC driving cycle i.e. when using the E5 and the CBG fuel at +22°C:

- Comparing the results in Artemis AU for E5 with CBG emissions of CO, NMHC, NO_X, PM, NO_2, formaldehyde and acetaldehyde decreases while methane increases. HC emissions is relative unaffected.
- Comparing the results in Artemis AR for E5 with CBG, emissions of CO, NMHC, PM and acetaldehyde decreases, while NO_X NO_2, methane and formaldehyde emissions increases. The HC emissions is relative unaffected.
- Comparing the results in Artemis MW E5 with CBG, emissions of CO and NMHC decreases while HC, NO_X, PM, methane, and NO_2, emissions increases. Formaldehyde, acetaldehyde, ethene, alkenes and light aromatic decreases in principle.
- Valid in all sub parts of the Aremis driving cycle is that the fuel consumption and the energy use decreases when using the CBG fuel, which is, however, expected.
- PAH emissions and calculated cancer potencies reported in the Artemis driving cycle are determined (calculated) as a integrated value originating from the Artemis driving cycle sub parts i.e. AU, AR and MW. A comparison reveals that the PAH emissions decreases and consequently the cancer potencies are reduced when using the CBG fuel.
- As shown in the table, all the TEF ratios are below one in all tests runs with the BFV car. From the table it can be concluded that the TEF ratio increases with E5 fuel compared to CBG fuel and independent of driving cycle. This can be inter-

preted as that the relative contents of lighter PAHs increase relatively more compared to heavy molecular weight PAHs.

4.2 Concluding remarks

The present investigation originates from a limited number of tested vehicles. Thus, the conclusions drawn here are not necessarily valid for fuel-flexible vehicles or biogas-fuelled vehicles in general.

4.2.1 E85-fuelled cars

Cold start emissions at low ambient temperatures are generally a problem area regarding exhaust emissions from petrol-fuelled cars. This present report clearly shows that this problem is also valid for ethanol-fuelled fuel-flexible vehicles. It should be noted, though, that currently there are no legislative limits for cold start emissions from E85 fuelled cars at low ambient temperatures and thus, it is not likely that the car manufacturers have optimised the vehicles for this kind of operation.

Increased ethanol content in petrol increases cold start emissions for most regulated and unregulated emission components determined. Particulate emissions from the fuel-flexible light-duty vehicles investigated using E85 or E5 as fuel are similar at +22°C. However, at the lower ambient temperature investigated, i.e. at -7°C, particulate emission increases 10 to 50 times in comparison to the level at +22°C. Corresponding increase for particulate-associated PAH emissions are in the range of 15 to 100 times and for semivolatile-associated PAH emissions in the range of 17 to more than 1 000 times. Calculated cancer potency for particulate-associated PAH at -7°C are in the range of 45 (E5) to more than 200 times (E85) higher than for E5 at +22°C. Calculated cancer potency for semivolatile-associated PAH at -7°C are in the range of 15 (E5) to more than 900 times (E85) higher than for E5 at +22°C.

4.2.2 Gaseous-fuelled cars

The literature survey has shown that cold start emissions from gaseous-fuelled cars generally should be very low at low ambient temperatures due to that the fuel is already in gaseous state when injected and does not have to be evaporated during air/fuel preparation, as for liquid fuels. However, this potential for low emissions has not been fulfilled on the particular car tested in this project, since the present car always starts on petrol independent on ambient temperature.

The particular BFV car tested is always started on petrol, which implies that the full potential for very low cold start emissions is not utilised. In the test programme, the car was manually switched over as quickly as possible from petrol operation to CBG operation. Due to this measure, most emissions at -7°C were generally lower for CBG than for petrol. This conclusion is on the condition, though, that the driver does switch fuel as fast as these tests. This does not necessarily have to be the case for an ordinary driver. Thus, the cold start emissions with CBG might be higher in practical operation for this car in comparison to the level as shown in the present study. However, the potential for significant emission reduction is apparent if the car could be started on CGB only at all ambient temperatures.

The on-board emission testing on the ten cars (1 FFV and 9 CBG cars) investigated in this sub-project showed high levels of unburned methane for most of the nine CBG cars tested. Only the cars with very low odometer readings had low methane emission levels. This indicates that there is a problem with catalyst durability regarding its activity with respect to methane oxidation.

4.2.3 PAH and cancer potency

A general conclusion is that particulate and semivolatile PAH emissions increase at lover ambient temperatures. The cancer potency originating from both particulate and semivolatile PAH emissions increase at lover ambient temperatures. Furthermore, particulate and semivolatile PAH emissions increase and the corresponding calculated cancer potency originating from both particulate and semivolatile PAH emissions increase. The observed increasing trends for PAH emissions and calculated cancer potencies co-variate with increased ethanol contents in the petrol/ethanol fuel blend. However, this does not necessarily have to be related to the fuel itself but could as well be linked to the engine technology used. In the literature survey, several potential technical solutions to this specific problem have been suggested.

The TEF ratios calculated in this present report shows the importance to include determination of selected dibenzopyrenes in future exhaust evaluations from engines and vehicles in general to avoid potential underestimations of cancer potencies.

4.2.4 Engine and aftertreatment development

A general conclusion is that either the FFV cars or the CBG car are optimised for low emissions when running on E70/E85 or biogas, respectively. This is particularly important for the FFV cars regarding cold start emissions at low ambient temperatures. The use of E70 during wintertime instead of E85 provides some improvement of the exhaust emissions. The literature survey and the results generated in the present study have indicated several areas where improvements could be made. One example is an improvement of the air/fuel preparation by, e.g., using second generation direct injection that has a great potential to reduce cold start emissions at low ambient temperatures.

4.2.5 General conclusions for further research

There is a need for updated emission factors of both regulated and unregulated exhaust emissions from new conventional vehicles run on standard petrol and diesel fuels at +22°C and at low ambient starting temperatures. This will allow intercomparisons with new engine/vehicle concepts and new alternative fuels regarding exhaust emissions. The literature survey showed that there is a lack of updated relevant emission data for modern cars.

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Onboard measurements on 10 biofuel vehicles

A test report for Ecotraffic ERD^3 AB

ExIS
INSTRUMENTS & MEASUREMENTS

Lars Eriksson

July 2007

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Summary

On board measurements on nine biogas-fuelled and one ethanol (E85) fuelled light duty vehicles have been carried out in this test programme. Both vehicles types were either so called flexi-fuel (ethanol/petrol) or bi-fuel (gas/petrol) cars.

Only two of the nine tested biogas cars showed acceptable emission levels of unburned hydrocarbons (methane) by using biogas as fuel. Whereas, by using petrol as fuel, all nine gas cars showed low emission levels of hydrocarbons. An explanation for this behaviour may be that the catalytic activity for oxidation of methane decline over time (this has also been shown in previous studies). The results (present and previous studies) indicate that the lifetime for a catalytic converter for gaseous-fuelled cars (activity to oxidation of methane) is at maximum some 10.000 km. The emission tests at the Swedish Motor Vehicle Inspection Company (Bilprovningen[1]) will not indicate if a car has high methane emission. The measurement method is dedicated only for cars driven on petrol fuel.

There was no difference in hydrocarbon emissions if ethanol (E85) or petrol (E5) was used as fuel for the flexi-fuel car.

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[1] Bilprovningen is by appointment of the Swedish government solely responsible for inspecting all vehicles registered in Sweden.

1 BACKGROUND

During year 2004 and 2005, the company ExIS has, in co-operation with Ecotraffic carried out onboard measurements on heavy duty vehicles; i.e. 10 city buses and 3 waste trucks. Based on the results from these, in total, 13 vehicles tested, it was clear that:

- The exhaust gas aftertreatment system worked properly, on four (4) new vehicles (4 000 km) and one (1) one year old vehicle (85.000 km)
- The exhaust gas aftertreatment system did not work properly (very low catalytic activity) on five (5) vehicles (1997 – 2000)
- The exhaust gas aftertreatment system worked, but not fully properly, on one (1) vehicle (2003, 85 000 km)
- The exhaust gas aftertreatment system worked to satisfaction on two (2) vehicles. The emissions of hydrocarbons were high on one of these vehicles but it is not clear if the problem was related to the high engine-out emission level or to the operation of the catalytic converter.

The fact that the emission level for methane were acceptable, only for 4 of in total 13 vehicles, indicates that the exhaust gas aftertreatment systems does not work properly one these vehicles. Based on that background information, the present work, i.e. onboard measurement on 10 light duty gas cars, was initiated.

2 EXPERIMENTAL

All tests were carried out by using onboard measurement of methane and by driving on public roads. The test equipment was mounted on a trailer and all tests were carried out in a similar way. The gaseous-fuelled cars were always started on petrol fuel. After some minutes, the operation was shifted over to biogas fuel. The test route was then completed, first with biogas as fuel and then with petrol fuel. By using the same test route it was possible to compare differences in emission levels for the two fuel types.

2.1 Test equipment

For the hydrocarbon measurements a FID analyser was used. The analyser was calibrated with 990 ppm methane before and after the tests. The exhausts were sampled in the end (>20 cm, upstream) of the exhaust pipe and pumped through a heated (180°C) sampling probe to the analyser. All test equipment were mounted in a trailer and was powered by an external petrol-driven generator (no power from the test vehicles were used). Pictures of instrument mounting on the trailer and a close-up of the instrumentation are shown in **Figure 1** and **Figure 2**, respectively.

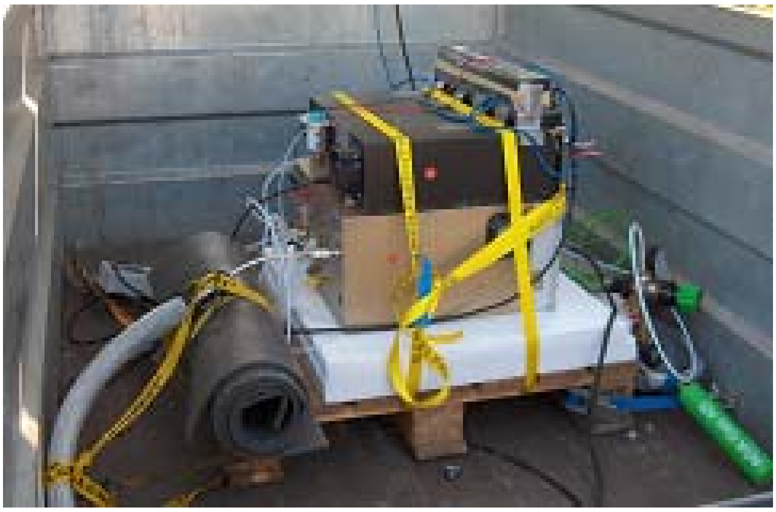


Figure 1. *Instrument mounting on the trailer*

2.2 Test vehicles

In total, 9 biogas-fuelled cars (bi-fuel) and one ethanol (E85 flexi-fuel) car were tested. The biogas-fuelled cars were tested by using both biogas and petrol fuel and the ethanol car were tested using E85 and petrol (E5) as fuels. All the biogas used in the cars was delivered by Stockholm Vatten (the sewage treatment company for the municipality of Stockholm) and the E85 and petrol fuel used in the E85 car was commercial fuels (Statoil). Some selected data for the tested cars is shown in **Table 1**.

***Figure 2**. FID, Pumps, heated sampling hose and data logging system.*

Table 1. *Test vehicles*

Vehicle #1 Gas / petrol			
Model	VW Golf Var 2.0 Biofuel		
Reg.no..	UGO 913	**Year**	2003
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Passenger car	**Environmental class**	2005 (Euro IV)
Vehicle weight	1490 kg	**Total weight**	1880 kg
Maximum speed	195 km/h	**Speed limit**	Yes
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	CNG (bio)
Odometer	66 000 km	**Gear box**	Manuell

Vehicle #2 Gas / petrol			
Model	VW Golf Var 2.0 Biofuel		
Reg.no..	UGY 718	**Year**	2003
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Passenger car	**Environmental class**	2005 (Euro IV)
Vehicle weight	1490 kg	**Total weight**	1880 kg
Maximum speed	195 km/h	**Speed limit**	Yes
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	CNG (bio)
Odometer	44 800 km	**Gear box**	Manuell

Vehicle #3 Gas / petrol			
Model	VW Transporter 2.0		
Reg.no..	XOC 881	**Year**	2006
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Truck	**Environmental class**	2005 (Euro IV)
Vehicle weight	2600 kg	**Total weight**	2850 kg
Maximum speed		**Speed limit**	No
		Passenger no.	1
Fuel	Benin	**Alternative fuel**	CNG (bio)
Odometer	4750 km	**Gear box**	Manuell

Vehicle #4 Gas / petrol			
Model	VW Pick-up		
Reg.no..	SMT 260	**Year**	2001
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Truck	**Environmental class**	3
Vehicle weight	1880 kg	**Total weight**	2600 kg
Maximum speed		**Speed limit**	Nej
		Passenger no.	2
Fuel	Benin	**Alternative fuel**	CNG (bio)
Odometer	53 700 km	**Gear box**	Automat
Exemption to 2007-12-31 –use only to – 25°C			

Vehicle #5 Gas / petrol			
Model	VW Pick-up		
Reg.no..	SNC651	**Year**	2001
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Truck	**Environmental class**	3
Vehicle weight	2410 kg	**Total weight**	2890 kg
Maximum speed		**Speed limit**	No
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	CNG (bio)
Odometer	33 800 km	**Gear box**	Manuell
Exemption to 2007-12-31 –use only to – 25°C			

Vehicle #6 Gas / petrol			
Model	VW Pick-up		
Reg.no..	SNC 653	**Year**	2001
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Lastcar	**Environmental class**	3
Vehicle weight	2460 kg	**Total weight**	2890 kg
Maximum speed		**Speed limit**	No
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	CNG (bio)
Odometer	39 314 km	**Gear box**	Manuell
Exemption to 2007-12-31 –use only to – 25°C			

Vehicle #7 Gas / petrol			
Model	VW Pick-up		
Reg.no..	SLU 069	**Year**	2001
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Truck	**Environmental class**	3
Vehicle weight	2430 kg	**Total weight**	2890 kg
Maximum speed		**Speed limit**	No
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	CNG (bio)
Odometer	73 600 km	**Gear box**	Manuell
Exemption to 2007-12-31 –use only to – 25°C			

Vehicle #8 Gas / petrol			
Model	VW Pick-up		
Reg.no..	SNE 657	**Year**	2001
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Lastcar	**Environmental class**	3
Vehicle weight	2480 kg	**Total weight**	2890 kg
Maximum speed		**Speed limit**	No
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	CNG (bio)
Odometer	72 300 km	**Gear box**	Manuell
Exemption to 2007-12-31 –use only to – 25°C			

Vehicle #9 Gas / petrol			
Model	VW Golf Var 2.0 Biofuel		
Reg.no..	WAY 479	**Year**	2005
Cylinder volume	1984 cm^3	**Engine Power**	85 kW
Vehicle type	Passenger car	**Environmental class**	2005 (Euro IV)
Vehicle weight	1490 kg	**Total weight**	1880 kg
Maximum speed	195 km/h	**Speed limit**	Yes
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	CNG (bio)
Odometer	20 000 km	**Gear box**	Manuell

Vehicle #10 Petrol / ethanol			
Mo	Saab 9-5 Sportcombi		
Reg.no..	XYH 058	**Year**	2006
Cylinder volume	1985 cm^3	**Engine Power**	110 kW
Vehicle type	Passenger car	**Environmental class**	2005 (Euro IV)
Vehicle weight	1680 kg	**Total weight**	2150 kg
Maximum speed	205 km/h	**Speed limit**	Yes
		Passenger no.	4
Fuel	Petrol	**Alternative fuel**	E85
Odometer	2 100 km	**Gear box**	Automatic

3 RESULT & DISCUSSION

In the appendix, all results are presented. In **Table 2** below, results from the tests are summarised.

Table 2. *Summary of test results*

Emission of hydrocarbons (HC) during driving on public roads.				
Vehicle	**MY**	**Odometer**	**Petrol fuel**	**Gas or ethanol fuel**
1. VW Golf 2.0 Biofuel	2003	66 000 km	Low Emission	Medium to High Emission
2. VW Golf 2.0 Biofuel	2003	44 800 km	Low Emission	Medium Emission
3. VW Transporter	2006	4 750 km	Low Emission	Low Emission
4. VW Pick up	2001	53 700 km	Low Emission	High Emission
5. VW Pick up	2001	33 800 km	Low Emission	High Emission
6. VW Pick up	2001	39 300 km	Low Emission	High Emission
7. VW Pick up	2001	73 600 km	Low Emission	High Emission
8. VW Pick up	2001	73 300 km	Low Emission	High Emission
9. VW Golf 2.0 Biofuel	2005	20 000 km	Low Emission	Low Emission
10. Saab 9-5 Biopower	2006	22 000 km	Low Emission*	Low Emission*

Notes:

Low Emission = Full function of the catalytic aftertreatment

Medium Emission = Reduced function of the catalytic aftertreatment

High Emission = Poor function of the catalytic aftertreatment

* High emission of hydrocarbons during fast accelerations.

Five of the, in total, nine tested biogas-fuelled vehicles showed very high emissions of un-burned hydrocarbon (methane) and two of the nine vehicles showed low emissions. However, these two low emitters were relatively new with odometer readings of 4.000 and 20.000 km, respectively. All nine gas cars showed low emissions of hydrocarbons on petrol fuel – which indicate that the exhaust gas aftertreatment systems works properly for petrol fuel.

An explanation for the behaviour observed in this study may be that the catalytic activity for oxidation of methane decline over time. This has also been shown in previous studies. The results (present and previous studies) indicate that the lifetime for a catalytic converter for biogas-fuelled cars (activity to oxidation of methane) is, at maximum, some 10.000 km. These kind of measurements (on-board) is not as exact as tests carried out in a dedicated test cell but accurate enough to find high emitters and similar vehicles.

There were no notable differences in hydrocarbon emissions when ethanol (E85) and petrol (E5) was used as fuels on the ethanol-fuelled car. It seams that the catalytic converter may start to work earlier by using E85 compared with petrol fuel but this is not fully confirmed in this study.

The emission tests at the Swedish Motor Vehicle Inspection Company (Bilprovningen) will not indicate if a car has high methane emission. The measurement method is dedicated for cars driven on petrol fuel only.

4 ACKNOWLEDGEMENTS

Stockholm Vatten is acknowledged for supporting this project by providing test cars and the biogas fuel used in these tests.

5 APPENDIX – DATA FILES

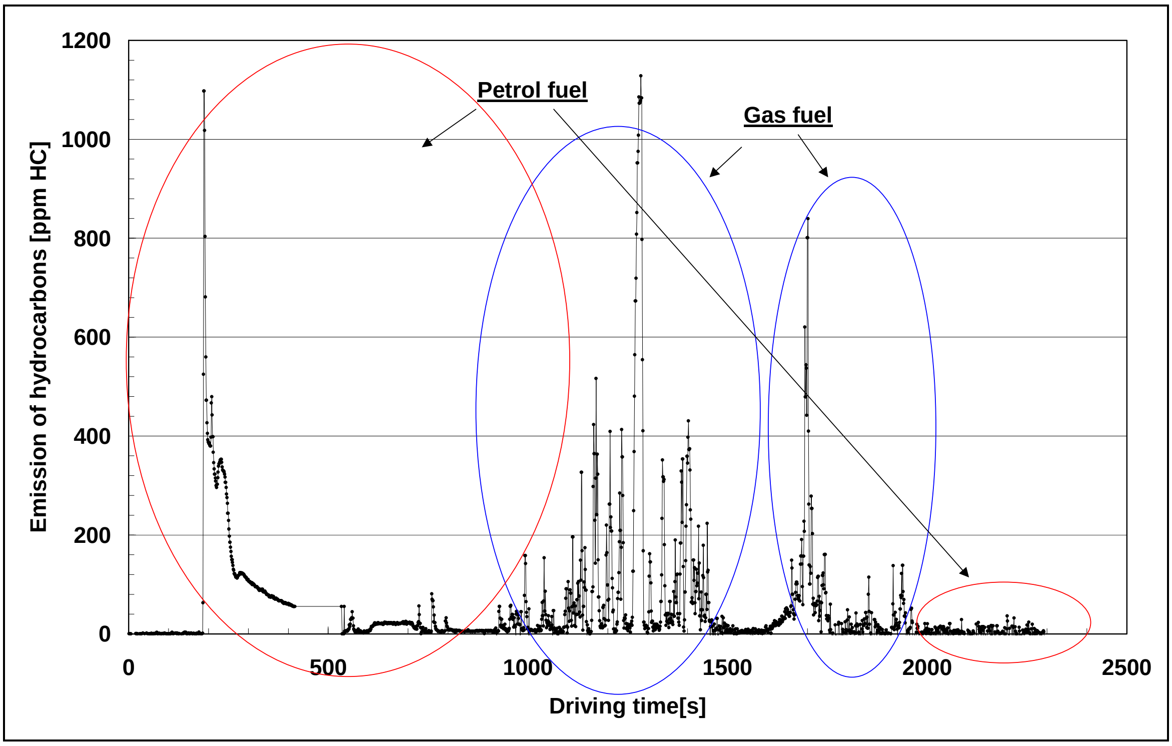


Figure 3. *Car 1: UGO 913: VW Golf Var 2.0 Biofuel*

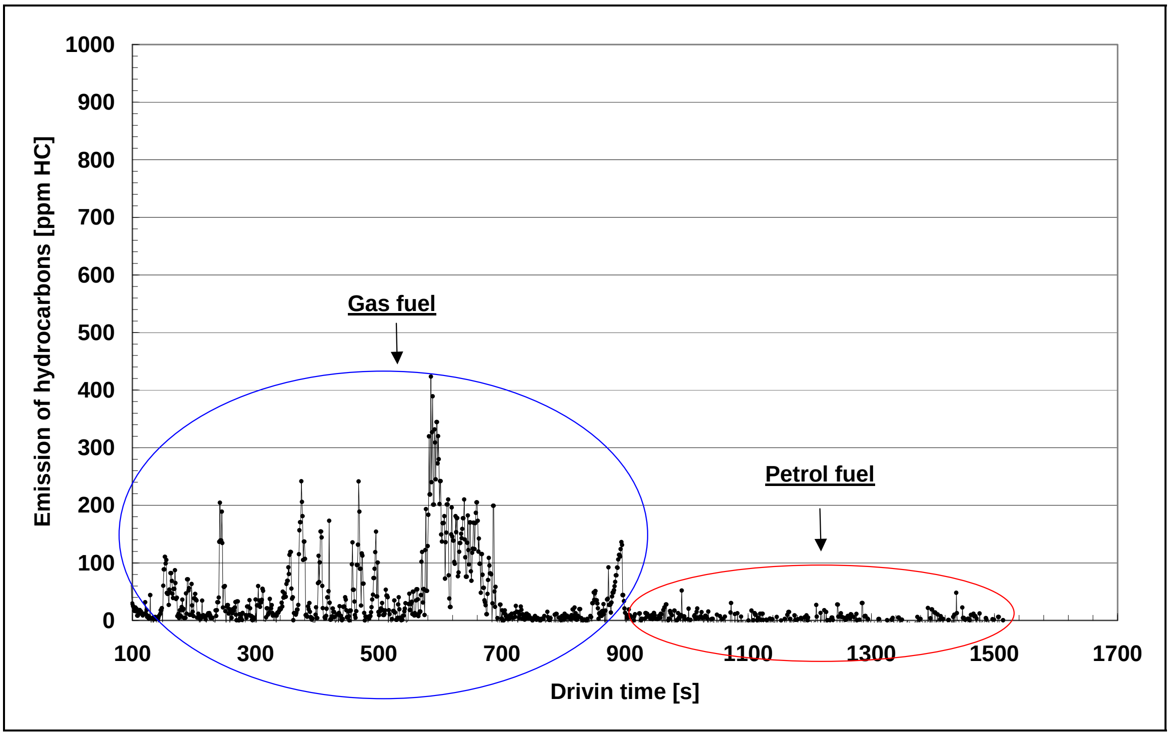


Figure 4. *Car 2. UGY 718: VW Golf Var 2.0 Biofuel*

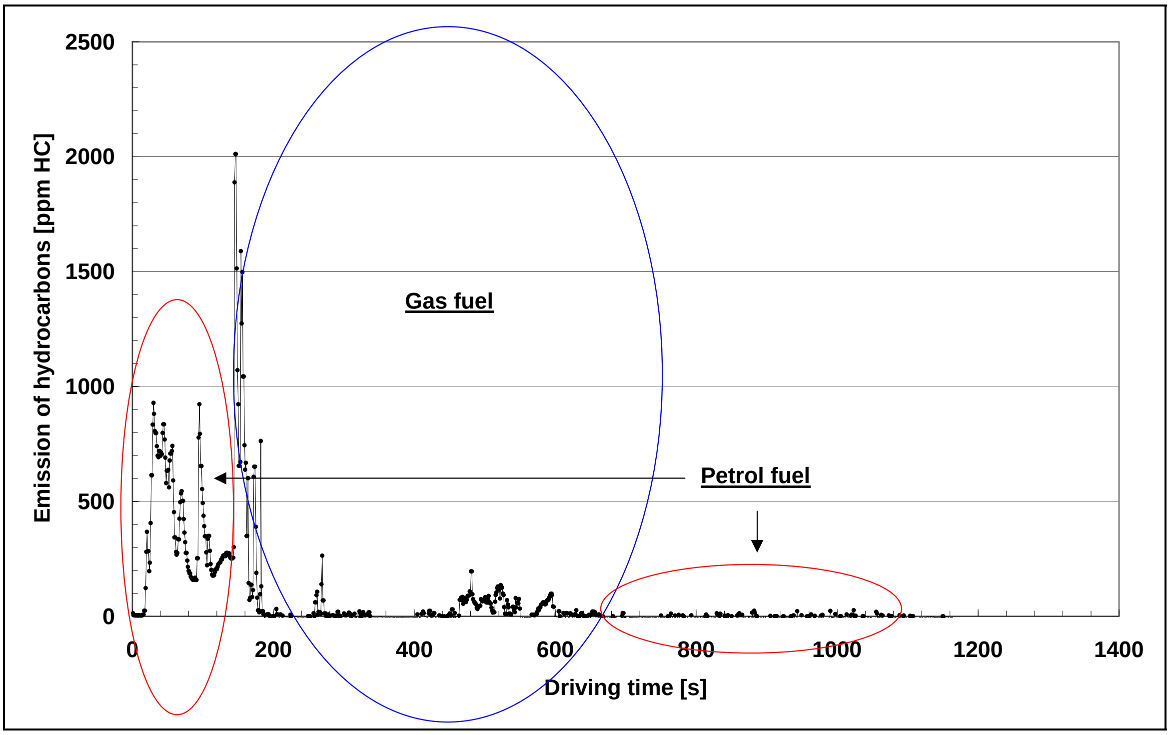


Figure 5. *Car 3. XOC 881: VW Transporter 2.0*

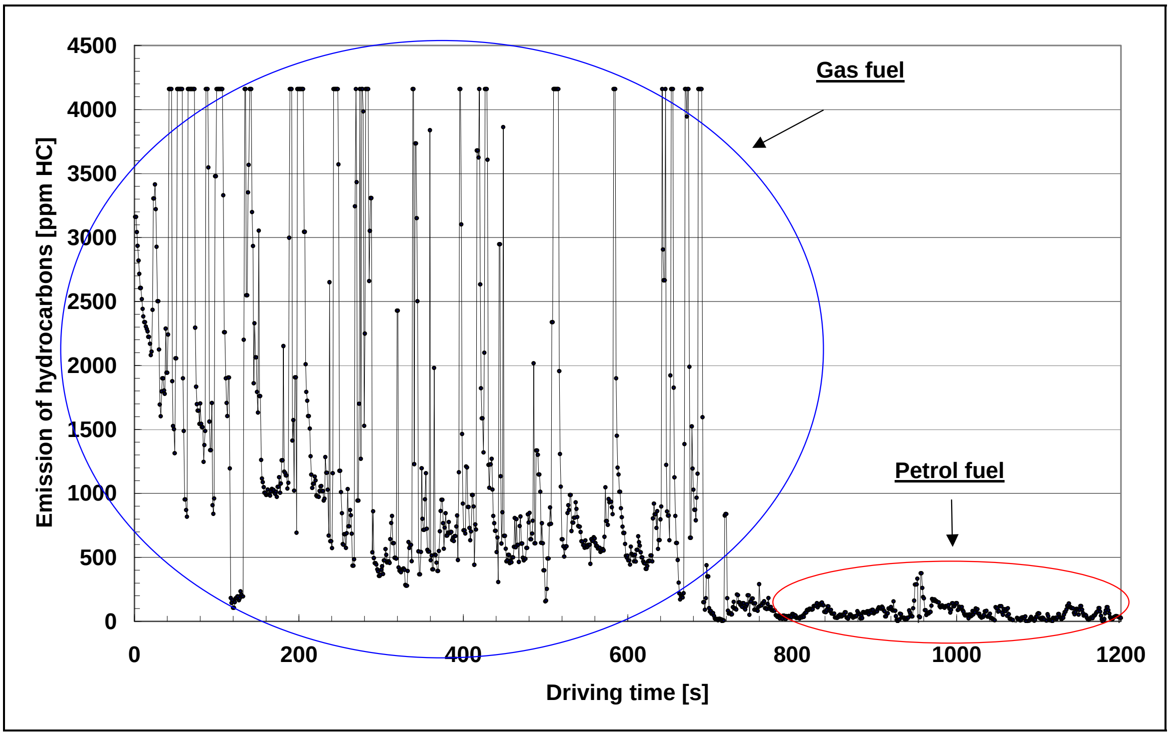


Figure 6. *Car 4. SMT 260: VW Transporter 2.0*

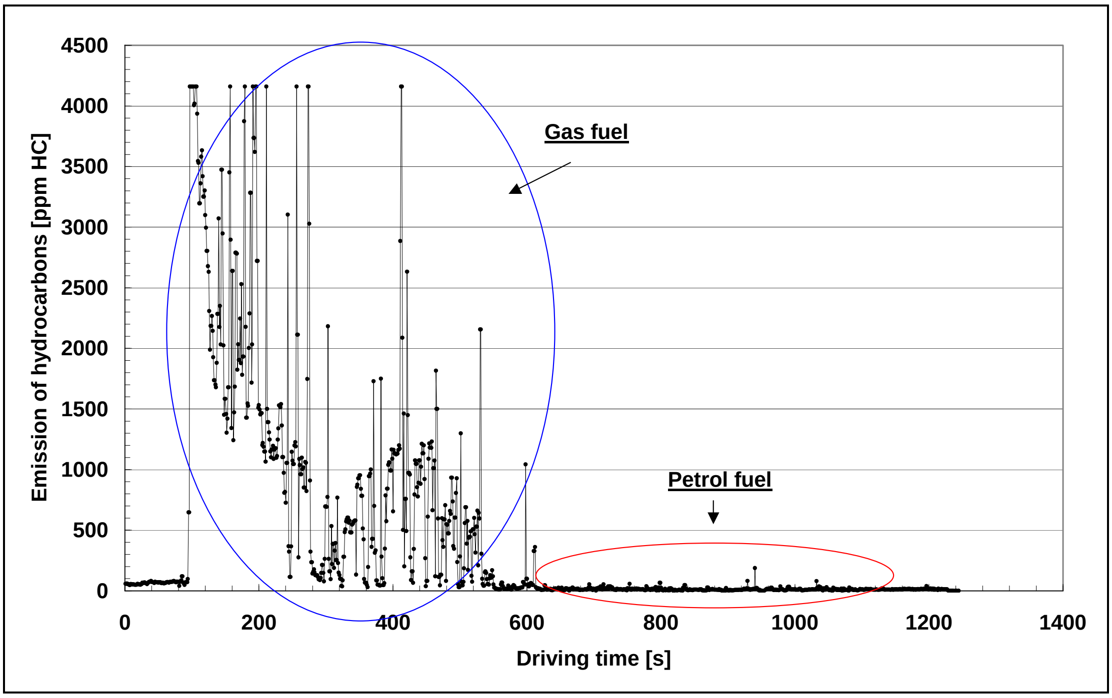


Figure 7. *Car 5. SNC 651: VW Pick-up*

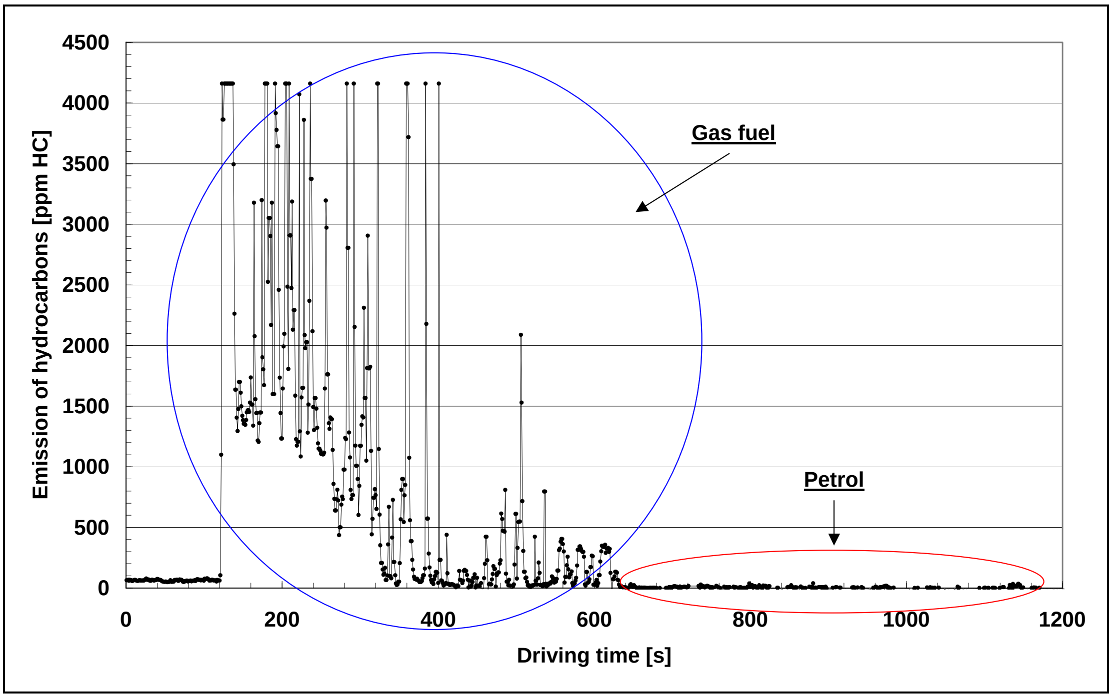


Figure 8. *Car 6. SNC 653: VW Pick-up*

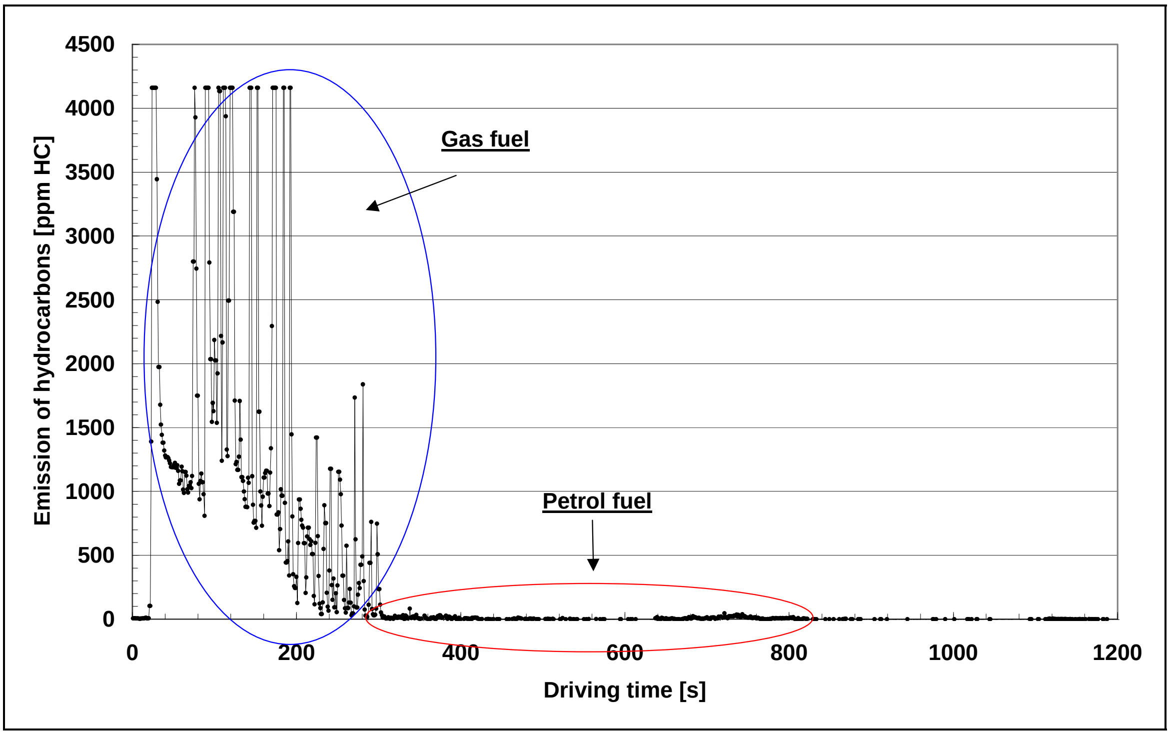


Figure 9. *Car 7. SLU 069: VW Pick-up*

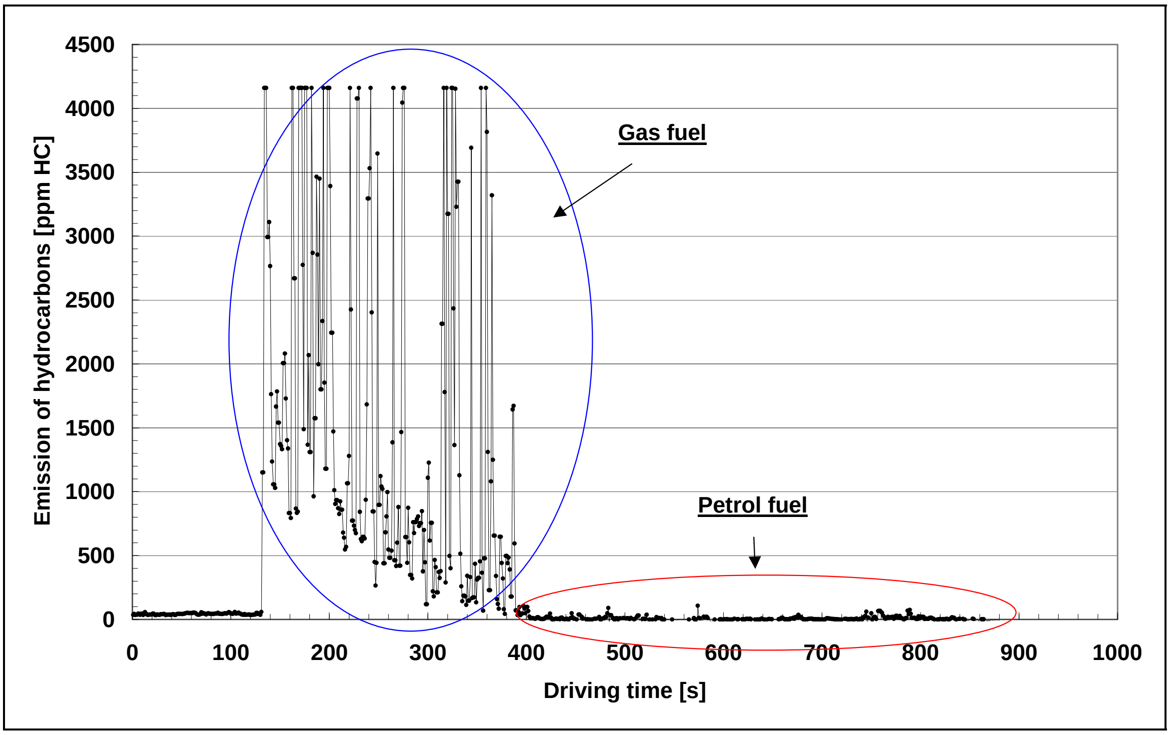


Figure 10. *Car 8. SNE 657: VW Pick-up*

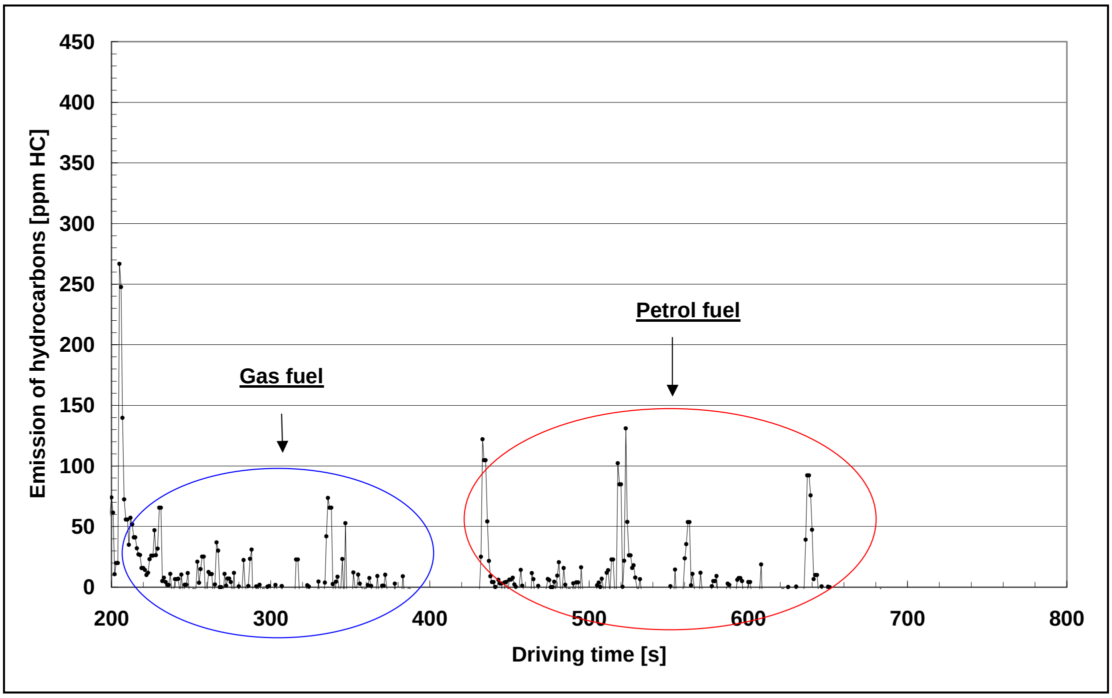
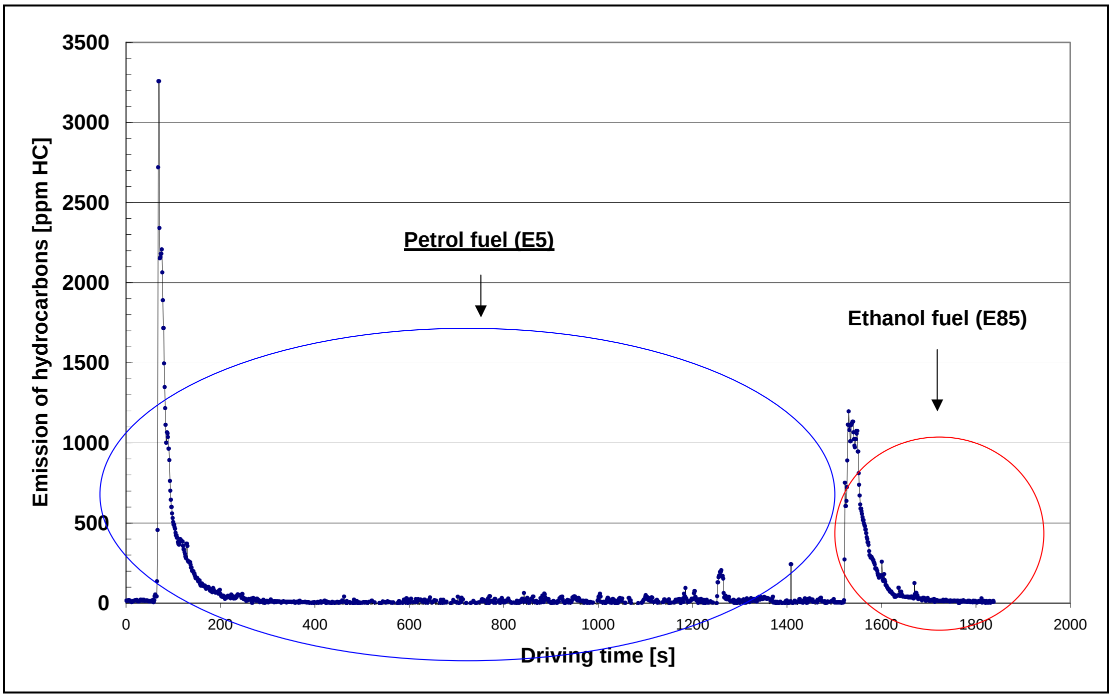


Figure 11. *Car9. WAY 479: VW Golf Var 2.0 Biofuel*



Car

Figure 12*. Car 10. XYH 058: Saab 9-5 BioPower.*

Note that results shown in the figure originate from two separate tests. In practice, the time between the two tests was four days. Both tests was carried out at a temperature of + 15°C (+/- 2°C).