Swedish In-Service Testing Program

On Emissions from Heavy-Duty Vehicles 2013

Report for the Swedish Transport Agency

Certification & Regulation Compliance
AVL

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Content

AVL

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List of Abbreviations

CFV	Critical Flow Venturi
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conformity Of Production
CVS	Constant Volume Sampling
ECU	Engine Control Unit
ED95	Ethanol Diesel
EEV	Environmentally Enhanced Vehicle
EGR	Exhaust Gas Recirculation
ESC	European Stationary Cycle
ETC	European Transient Cycle
FC	Fuel consumption
HC	Total hydrocarbons (THC)
HDV/HC	Heavy Duty Vehicle/ Heavy Duty
HFID	Heated Flame Ionization Detector
IUC	In Use Compliance
JRC	Joint Research Centre
MK1	Environmental class 1 diesel
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultraviolet
NO_2	Nitrogen dioxides
NOx	Nitrogen oxides
PASS	Photo-Acoustic principle
PEMS	Portable Emission Measurement System
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SEPA	Swedish Environmental Protection Agency
SRA	Swedish Road Administration
STA	The Swedish Transport Agency
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle

Summary

AVL MTC AB has on the commission of The Swedish Transport Agency (STA) carried out The Swedish In-Service Testing Programme on Emissions from Heavy-Duty (HD) Vehicles. Eight vehicles have been tested on road in accordance with the PEMS (Portable Emission Measurement System) protocol which include urban, suburban, and highway driving. In addition five of these vehicles have also been tested on chassis dynamometer according to the Fige (chassis dynamometer version of European Transient Cycle (ETC)) and the WHVC (Worldwide Harmonized Vehicle Cycle, chassis dynamometer version of WHTC - Worldwide harmonized Transient Cycle). The selection of the vehicles was based on Euro V Euro IV and Vl standard.

The scope of the investigation was, beside in use compliance, to generate emission factors from commercial vehicles during a normal working day and representative driving. In addition aspects of alternative fuels and technologies, driving pattern, fuel quality and loads were taken into consideration.

The vehicles are denoted A – H in this report.

The selection of the test vehicle was done in cooperation with the Swedish Transport Agency.

Vehicle A was a heavy duty truck equipped with a SCR a system. The vehicle was tested on roads during driving conditions and loads representing a normal working day, with and without load. The maximum test weight was 88 000 kg.
During both tests the exhaust temperature was well above the light off temperature of the catalyst i.e. approximately 250 ^{o}C.
Distance specific emissions are higher when driving with load compared to no load, CO 50%, NOx 20%, fuel consumption 45%. The emissions of HC are close to detection limit.

Vehicle B was a medium heavy duty sky lift truck equipped with an EGR system. The vehicle was tested both on roads and on cassis dynamometer with a cargo load of approximately 2 500 kg.
The emissions of CO, NOx, NO and CO2 are significantly higher when driving on road compared to chassis dynamometer. In the case of CO the on road emission are 20 times higher, 6 times higher for NOx and 1.5 times higher for CO2. The emissions of HC were close the detection limit. The NOx include 30 to 50% NO2. The fuel consumption is on average 50% lower during the chassis dynamometer test. Due to the lack of ECU signals no calculations of emissions in g/kWh were possible.

Vehicle C was a medium sized destitution truck with an electric hybrid system equipped with a SCR system fulfilling the requirement of Euro V, EEV. The vehicle was tested with an extra load of 3000 kg during a Euro VI test route and a bus test route. Two test runs were carried out for each route and the average values are presented in this report. During the Euro VI test the exhaust temperature were well above the light off temperature of the catalyst i.e. 250 ^{o}C, thus giving a high reduction of CO, HC and NOx. The start/stop driving in the bus cycle generates temperatures ranging from 190 ^{o}C to 250 ^{o}C which increases the emission with a factor of approximately 2.5. The driving pattern in the bus test route also increases the fuel consumption with 15%. High standard deviation from the measurements of soot for both test cycles makes it impossible to distinguish the two cycles significantly. No ECU signal was obtained.

Vehicle D.The vehicle type chosen was a distribution van, equipped with an EGR and a particulate filter system. The vehicle was tested both on roads and on cassis dynamometer with a cargo load of approximately 2 500 kg. The emissions of CO and CO2 are generally higher when driving on road compared to chassis dynamometer. In the case of CO the on road emission are 40 times higher compared to the chassis test. The emissions of HC were below the detection limit, i.e. 1 mg/km, during the on-board testing. The NO_x emissions are approximately 10% higher on the chassis dynamometer test compared to on road testing. The NOx include 10 to 30% NO2. The fuel consumption is on average 15% lower during the chassis dynamometer test. No ECU signal was obtained.

Vehicle E. The vehicle type chosen was a garbage truck with an electric hybrid system, equipped with a SCR. During the Euro VI test the exhaust temperature were well above the light off temperature of the catalyst i.e. 250 °C, thus giving a high reduction of CO, soot and NOx. The start/stop driving in the bus cycle and the normal working day for a garbage truck generates temperatures ranging from 190 °C to 250 °C which increases the emission compared to the Euro VI route. The driving pattern in the bus and normal working day test routes also increases the fuel consumption, 30%. The emissions of HC were close to the detection limit, thus giving a high standard deviation. Comparing the brake specific emissions with Euro V certification limits all regulated components was higher than the limit value, except CO and on the Euro VI route. However, it must be emphasised that Pems measurement differs from the certification test procedure and can thus not be used as a pass or fail criteria for Euro V vehicles. Pass/fail criteria will be implemented in the Euro VI regulations.
In addition, on board results are soot measurements and the limit value are set for particulate matter (PM). Generally PM consist of 80% soot.

Vehicle F and G. Two vehicles were used in the test program. One was a diesel truck, which were used for the testing with the diesel drop-in fuels. The other vehicle was a dedicated ED95 vehicle. The complete report is presented in Appendix 1.

Vehicle H was a heavy duty truck fulfilling the requirement of Euro VI. . The complete report is presented in Appendix 2.

Introduction

In Europe as well as in USA methods for verifying emission performance have been developed using portable emission measurement system (PEMS), where emissions are measured on board a vehicle during real life operation. The main objective with on board measurement is to find a robust method for verification whether a HD vehicle is meeting set emission requirement.

In Europe, activities to develop suitable test methods for on-road measurements and associated test protocol have been organized and coordinated by EU Joint Research Centre (JRC). JRC launched a pilot project for measurements of gaseous emissions in 2006 where manufacturer of engines/vehicles, manufacturer of instrument, approval authorities and technical services was invited to participate. The activity was called EU-PEMS project. The Swedish Road administration and then later, The Swedish Transport Agency (STA) participated in the pilot project using data from the In-Service Testing Program as input. The EU-PEMS Pilot project is now finalized and findings, conclusions and comments from stakeholders have been considered and are now included in the European Euro VI emission requirements (Regulation No 595/2009 and EU Regulation No 582/2011).
Further, a common way to calculate and present results from measurements have been introduced by JRC and a standardized test protocol has been established (EMROAD). The protocol is used to verify whether tested vehicles/engines meet the set requirements. The protocol also specifies the measurement points to be used for the calculation.

The result from national activities carried out 2013 is presented in this report.

Test program

Eight vehicles have been tested on road by a portable exhaust measurement system (PEMS). In addition, five of these vehicles have also been tested on chassis dynamometer. The aim of the study was not to pinpoint specific manufacturer thus, the vehicles in this report will be denoted A – H and the engine power is presented as an approximate figure.

Selection of test vehicles

The vehicle selection has been performed in cooperation with the STA. The vehicle type chosen for testing was based on Euro V, and VI technology. The vehicles tested have been served in accordance to the manufacturer specification on a regular basis.

Table 1 EU Emission Standards for HD Diesel Engines

Dates for first registration. entry into service	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PM [g/kWh]	Smoke m^{-1}
Euro V - 2009.10 – 2013.12					
European Stationary Cycle (ESC) and European Load Response (ELR)	1.5	0.46	2	0.02	0.5
European Transient Cycle (ETC)	4	0.55	2	0.03	
Euro VI[1] - 2014.01 –					
Worldwide Harmonized Stationary Cycle (WHSC)	1.5	0.13	0.4	0.01	
Worldwide Harmonized Transient Cycle (WHTC)	4	0.16	0.4	0.01	

[1] Euro VI also include maximum particle number requirements which are 8.0*10^11 #/kWh (WHSC) and 6.0*10^11 #/kWh (WHTC)

Testing on chassis dynamometer

Chassis dynamometer test cell

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

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

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

Measuring methods – gaseous emissions

The sampling- and analysing equipment are based on full flow dilution systems, i.e. the total exhaust is diluted using the Constant Volume Sampling (CVS) concept. The total volume of the mixture of exhaust and dilution air is measured by a Critical Flow Venturi (CFV) system. For the subsequent collection of particulates, a sample of the diluted exhaust is passed to the particulate sampling system. The sample is here diluted once more in the secondary dilution tunnel, a system referred to as full flow double dilution.

According to the regulations for steady state tests, the raw exhaust gases are sampled for further gaseous analysis before the dilution in the tunnel occurs. For transient tests the diluted exhaust gases are both bag sampled and sent for further analysis *and* on-line sampled. Through the CVS system a proportional sampling is guaranteed.

The equipment used for analysing the gaseous regulated emissions consist of double Horiba 9400D systems. Hereby exists the possibility to measure both diluted and raw exhaust emissions on-line simultaneously. The sampling system fulfils the requirements of directive 2005/55/EEC and also the U.S. Federal Register in terms of sampling probes and heated lines etc.

Table 2 Measured components and measurement principles.

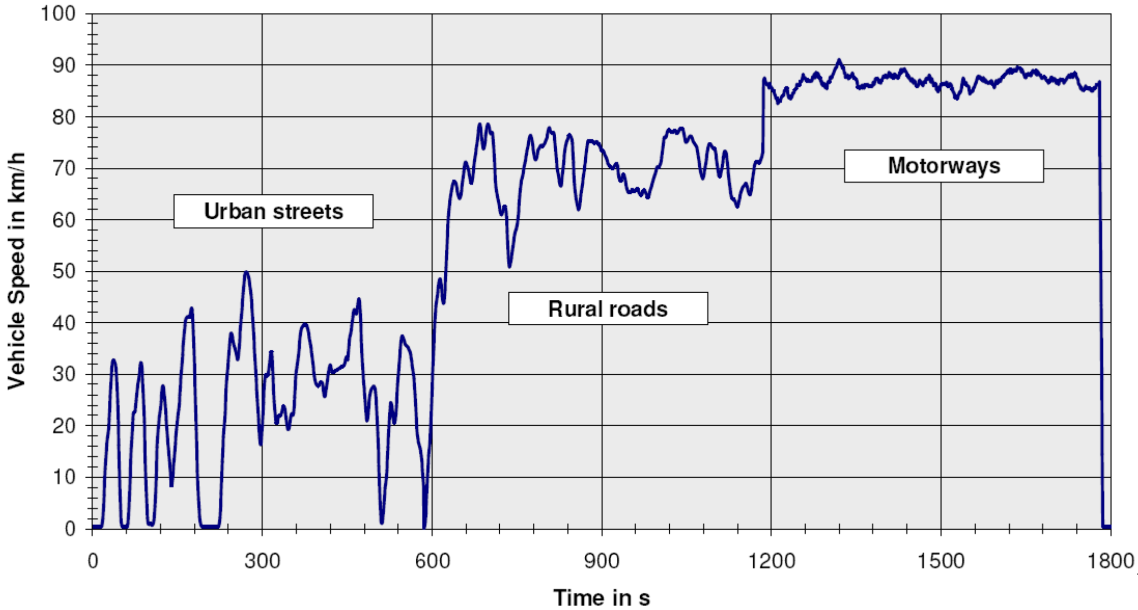
Component	**Measurement principle**
Total hydrocarbons (THC)	HFID (heated flame ionization detector) (190°C)
Carbon monoxide (CO)	NDIR (non-dispersive infrared analyzer)
Carbon dioxide (CO_2)	NDIR
Nitrogen oxides (NO_X)	CL (chemiluminescence)
Fuel consumption (FC)	Carbon balance of HC, CO and CO_2

Measuring methods – particle emissions

The particulate emissions were measured gravimetrically by the use of glass fibre filters. The diluted exhausts were sampled on the filters according to standard procedures. Two filters were used, mounted in series.

Test cycles

The ETC/FIGE driving cycle



ETC cycle (European Transient Cycle) which today is used for certification purposes of diesel engines to be used in heavy duty vehicles. The chassis dynamometer version is normally referred to as the FIGE test cycle.

Different driving conditions are represented by three parts of the ETC/FIGE cycle, including urban, rural and motorway driving.

The duration of the entire cycle is 1800s. The duration of each part is 600s.

- Part one represents city driving with a maximum speed of 50 km/h, frequent starts, stops, and idling.
- Part two is rural driving starting with a steep acceleration segment. The average speed is about 72 km/h
- Part three is motorway driving with average speed of about 88 km/h.

The WHVC/WHTC test cycle

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

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

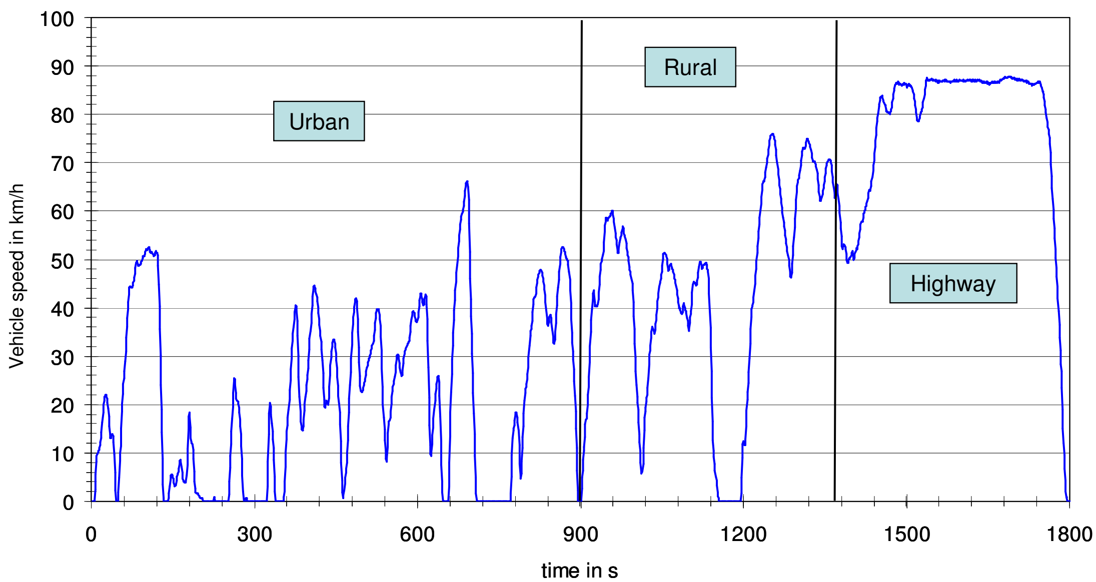


Figure 2 The WHVC test cycle

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

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

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

The duration of the entire cycle is 1800s.

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

On-road measurement

Two different PEMS equipments have been used for the measurements. The Semtech-DS was developed by Sensors and the M.O.V.E (Mobile on-board Vehicle Equipment) was developed by AVL.

Both devices were developed for testing all classes of light as well as heavy duty vehicles under real-world operating conditions. The instruments consists of on-board emissions analyzers which enables tailpipe emissions to be measured and recorded simultaneously while the vehicle is in operation.

The following measurement subsystems are included in the emission analyzers of both instruments:

- Heated Flame Ionization Detector (HFID) for total hydrocarbon (THC) measurement.
- Non-Dispersive Ultraviolet (NDUV) analyzer for nitric oxide (NO) and nitrogen dioxide (NO_2) measurement.
- Non-Dispersive Infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO_2) measurement.
- Electrochemical sensor for oxygen (O_2) measurement.

Both equipments are operated in combination with an electronic vehicle exhaust flow meter, Semtech E_xFM. The equipments uses the flow data together with exhaust component concentrations to calculate instantaneous and total mass emissions. The flow meter is available in different sizes depending on engine size. All tests were carried out with a 4” flow meter, which was suitable for the engine sizes of the tested vehicles.

In addition to the gas analysing instruments an AVL 483 Micro Soot Sensor was used to measure the soot emissions. The AVL 483 Micro Soot Sensor works on a photo-acoustic principle (PASS) and the cell design chosen (called the "resonant measuring cell") allows a detection limit of ≤10 μg/m³, (typically ~ 5 μg/m³).

The instrument is operated in combination with an electronic vehicle exhaust flow meter, Semtech E_xFM. The Semtech-DS instrument uses the flow data together with exhaust component concentrations to calculate instantaneous and total mass emissions. The flow meter is available in different sizes depending on engine size. A 4” flow meter was used, which is suitable for the engine size of the tested vehicles.

The PM PEMS combines the AVL the photo-acoustic soot measurement principle with a gravimetric PM measurement. The complete system consists of two 19” enclosures for the Micro Soot Sensor Measuring Unit (MSS), the Gravimetric Filter Module (GFM) and an external heated dilution cell and transfer line.

The program for emission calculation (EMROAD) from the PEMS instruments was supplied by JRC (Joint Research Centre).

The on-road testing and calculation has for all vehicles been performed in accordance with the PEMS protocol. According to the PEMS protocol the measurements should be carried out during a normal working day representative for the vehicle type and if possible include hill climbs, segments with cruising at constant speed and segments that is highly transient in their character as well as different altitudes.

Frequently used PEMS test routes

PEMS pilot test route.

The AVL "PEMS pilot test route" starts at the AVL headquarters at Armaturvägen in Haninge, continues through Handens centrum, Årsta Havsbad, Ösmo and ends back at Armaturvägen. The route has been inspected and accepted by JRC.

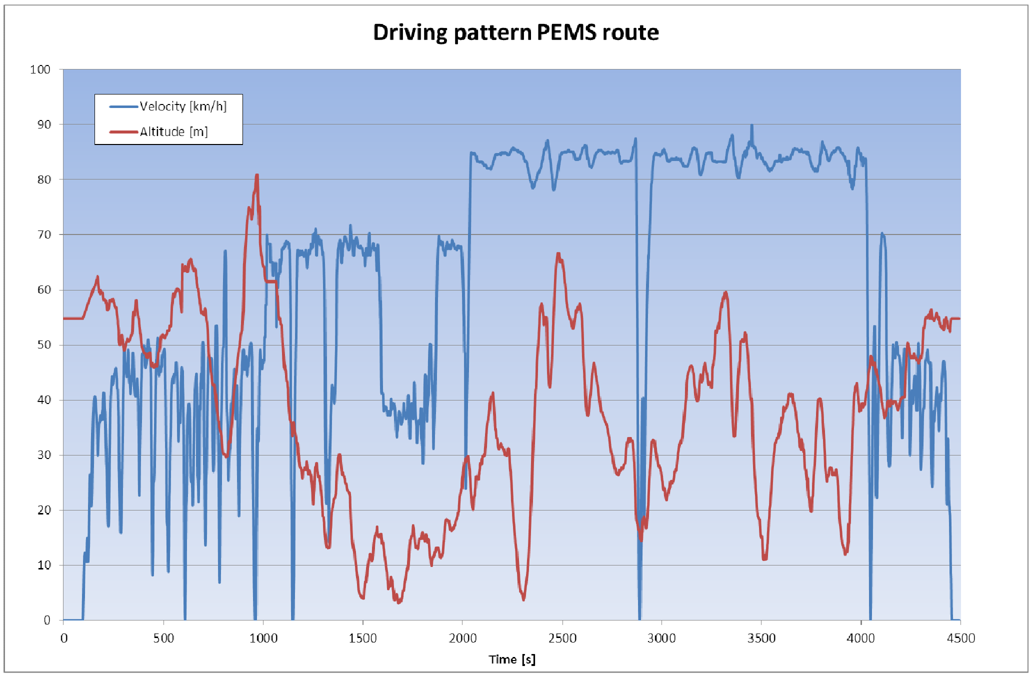


Figure 3. PEMS pilot route (EuroV) driving pattern.

Table 3

Trip duration (s)	4500
Trip distance (km)	77
Average speed (km/h)	55
Urban %	43
Rural %	17
Highway %	40
Cruising %	57
Idle %	7

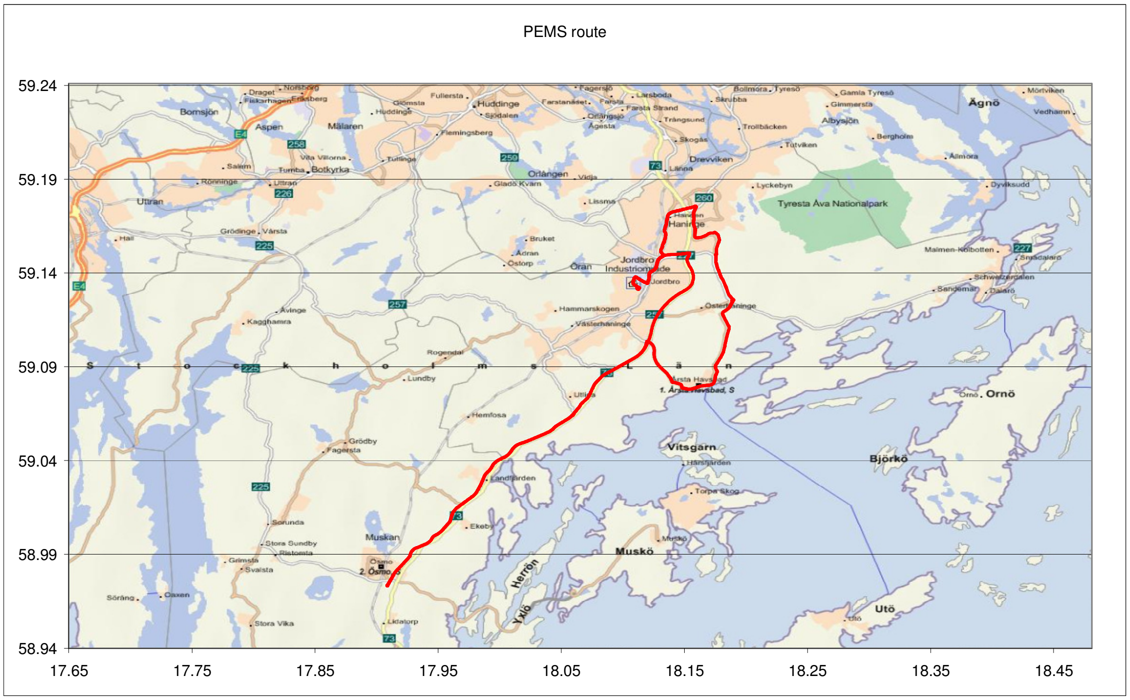


Figure 4 The PEMS test route.

Bus test route.

The AVL "bus route" is a true bus route in southern Stockholm. It starts in Lillgården, Tungelsta and ends at Coop Forum, Haninge. The route contains 22 bus stops.

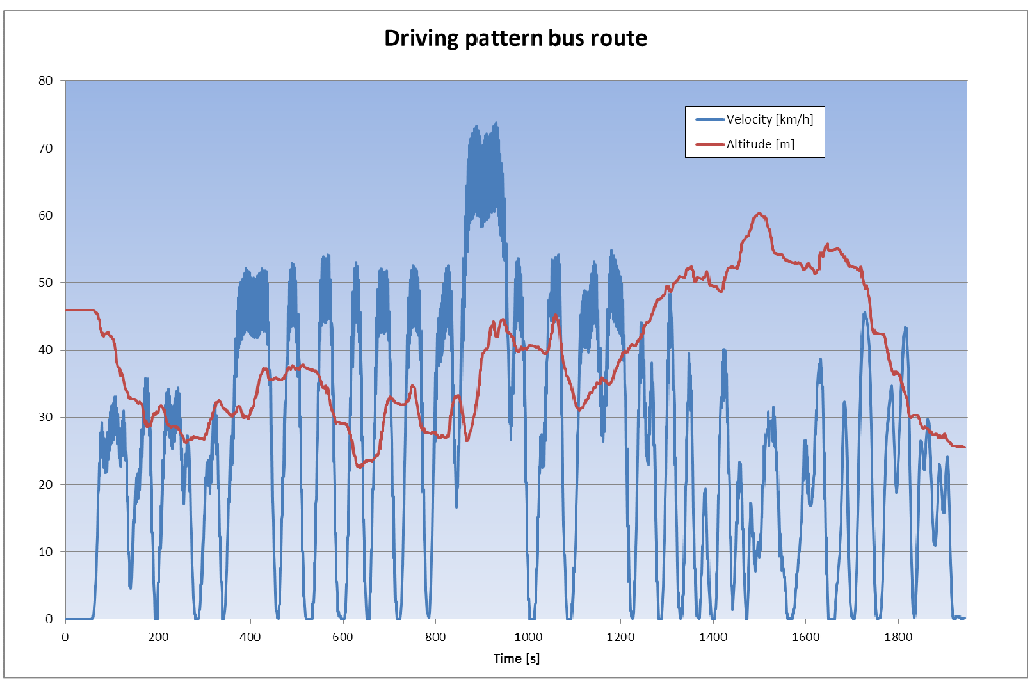


Figure 5. Bus route driving pattern.

Table 4. Route data.

Trip duration (s)	1900
Trip distance (km)	13.5
Average speed (km/h)	26
Urban %	90
Rural %	10
Highway %	0
Cruising %	11
Idle %	10

Eutro VI test route.

Euro VI route is designed to meet the requirements specified by the regulation for all N_3 vehicles. The route has the following main data:

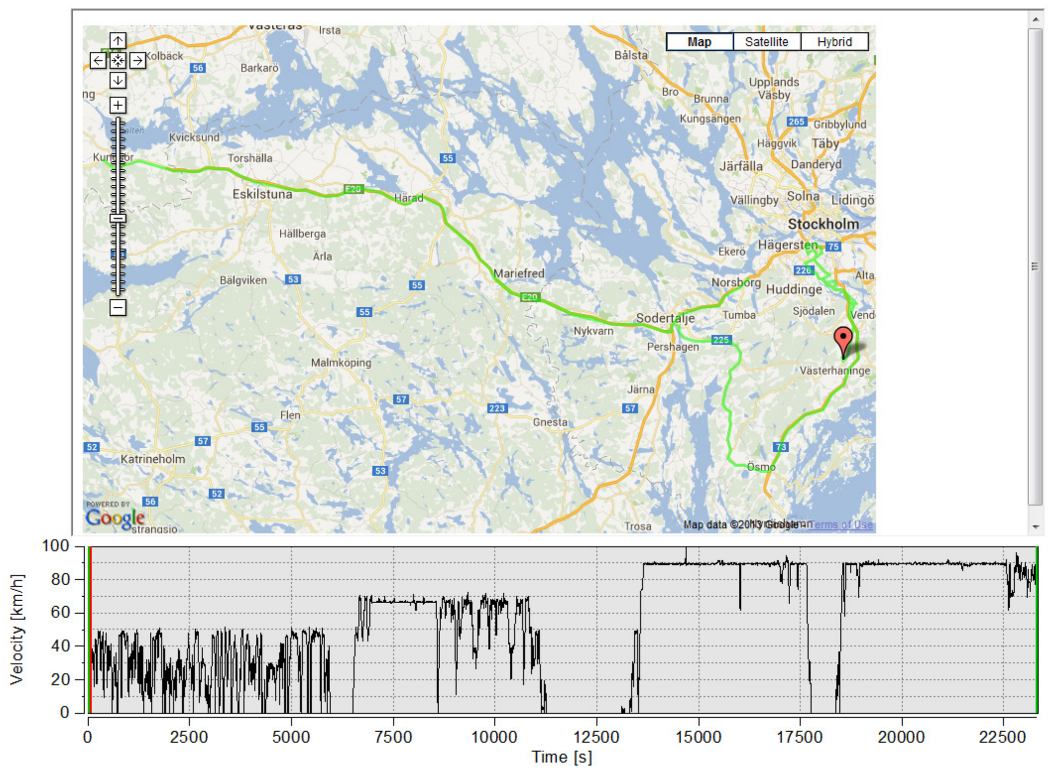


Figure 6. Euro VI route driving pattern.

Table 5. Test route data.

Trip duration (s)	23300
Trip distance (km)	343
Average speed (km/h)	53
Urban %	24
Rural %	23
Highway %	53
Idle %	14

Test Fuel

Commercially available fuels fulfilling the specification of Environmental class 1 diesel (Mk1) has been used. Swedish MK1 fuel is a low sulphur diesel i.e. less than 10 ppm, and has a boiling point interval of 180-290°C. The fuel consists of 50-70% parafines, 30-45% naphtenes and 3-5% aromatics.

ED95 is an ethanol based fuel adapted for diesel engines. It consists of 95% (at least 92.4%) ethanol and 5% additives such as ignition improvers and denaturation- and corrosion inhibitors. It has a cetane number of approximately 10 and an energy density of ~20,5 MJ/l.

Vehicle A.

The vehicle type chosen was a heavy duty truck for ore transportation from a mine. The vehicle was equipped with a SCR a system. The vehicle was tested on roads during driving conditions and loads (21 000 – 88 000 kg) representing a normal working day in the northern part of Sweden.

The tests were carried out with commercially available Environmental class 1 diesel (Mk1). The vehicle was served in accordance to the manufacturer specification.

Table 6. Test route and vehicle data..

	With load	Without load
Trip duration (s)	2500	4000
Trip distance (km)	43.7	72.6
Average speed (km/h)	63	65
Average humidity (%)	52	43
Average temperature C	17	21
Year model	2013	
Mileage, km	62300	
Power, kW	550	
Euro standard	V	

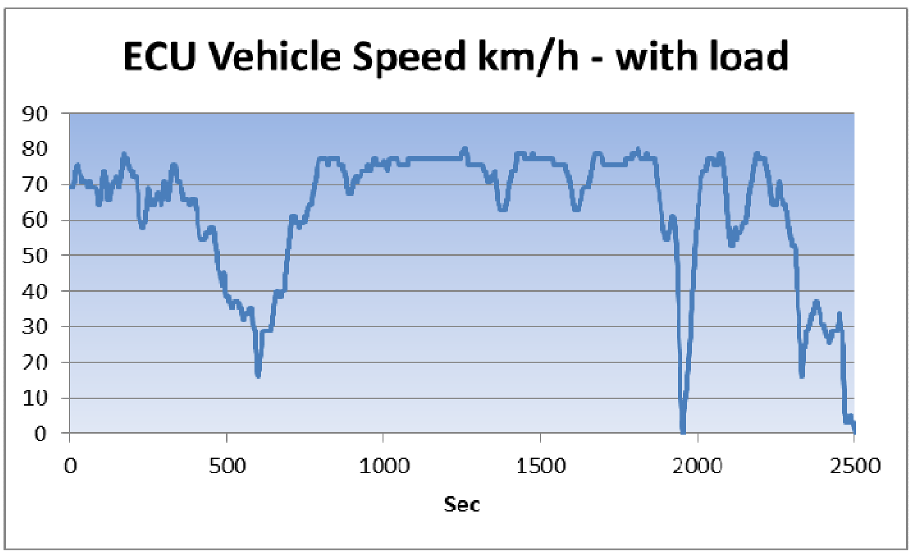


Figure 7.The test route with load.

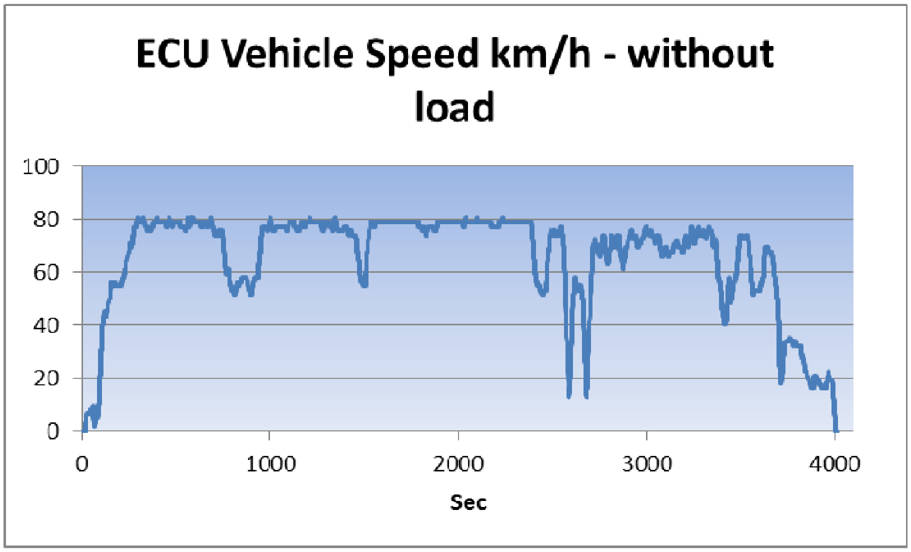


Figure 8. The test route without load.

The results are presented as distance specific emissions in Figure 9 and as brake specific emissions in Figure 10. From the figures some general conclusions can be made. During both tests the exhaust temperature was well above the light off temperature of the catalyst i.e. approximately 250 ºC.
Distance specific emissions are higher when driving with load compared to no load, CO 50%, NOx 20%, fuel consumption 45%. The soot and HC emissions are in the same order of magnitude. The emissions of HC are however close to detection limit.
Comparing the brake specific emissions with Euro V certification limits both NOx and soot values were higher when driving with and without load. However, it must be emphasised that Pems measurement differs from the certification test procedure and can thus not be used as a pass or fail criteria for Euro V vehicles. Pass/fail criteria will be implemented in the Euro VI regulations.

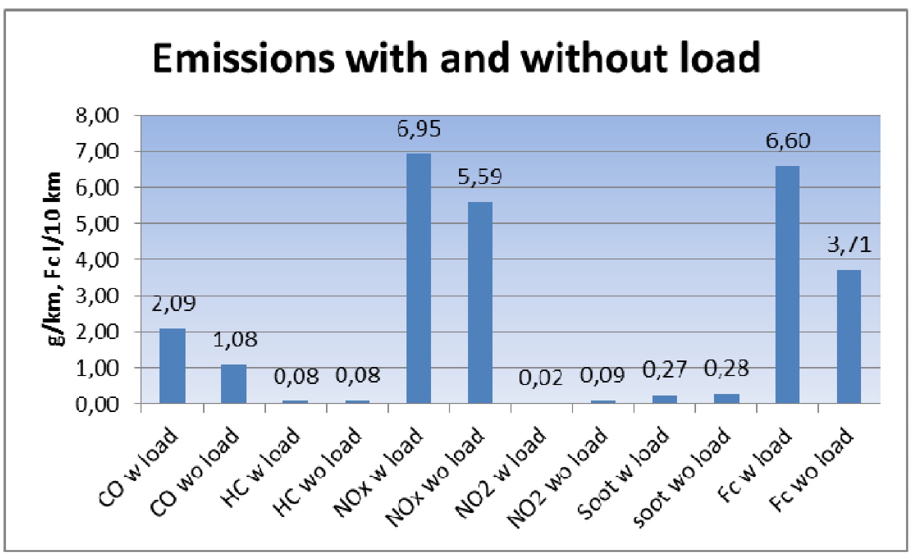


Figure 9. Distance specific CO mass emission.

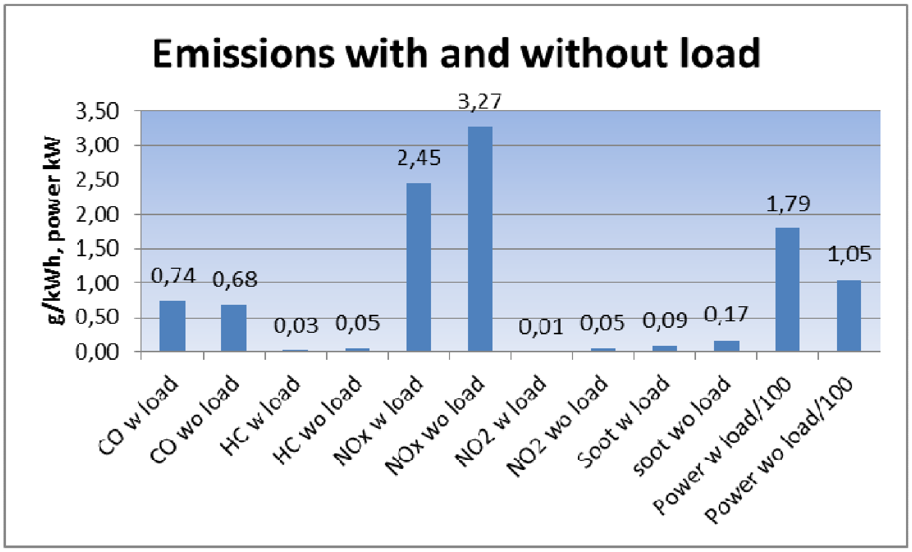


Figure 10. Brake specific CO mass emission.

The overall impression of the vehicle emission performance is good and no mil light indicated exhaust after treatment failure.

Vehicle B.

The vehicle type chosen was a sky lift truck equipped with an EGR system. The vehicle was tested both on roads and on cassis dynamometer with a cargo load of approximately 2 500 kg. The tests were carried out with commercially available Environmental class 1 diesel (MK1). The vehicle was served in accordance to the manufacturer specification.

Table 7. Test vehicle data.

Model year	2009
Mileage (km)	50000
Power (kW)	100
Net vehicle weight (kg)	3500
Test weight (kg)	3600
Emission standard	Euro IV
Aftertreatment system	EGR

Test program

The vehicle has been tested both on chassis dynamometer and on road. The tests were carried out with commercially available Environmental class 1 diesel (Mk1). The Chassis dynamometer tests were:

- 2 FIGE (chassis dynamometer version of ETC – European Transient Cycle) warm start
- 2 WHVC (World harmonized vehicle chassis dynamometer test - warm start)
- 1 WHVC (World harmonized vehicle chassis dynamometer test - cold start)
- 2 NEDC (New European Driving Cycle chassis dynamometer test for light duty vehicles)

The on-board measurement cycles were:

- 2 Euro VI PEMS test routes
- 2 PEMS pilot study test routes

The NEDC test cycle

The New European Driving Cycle is a driving cycle designed to assess the emission levels of car engines and fuel economy in passenger cars. The NEDC is supposed to represent the typical usage of a car in Europe. It consists of four repeated ECE-15 Urban Driving Cycles (*UDC*) and an Extra-Urban driving cycle (*EUDC*).

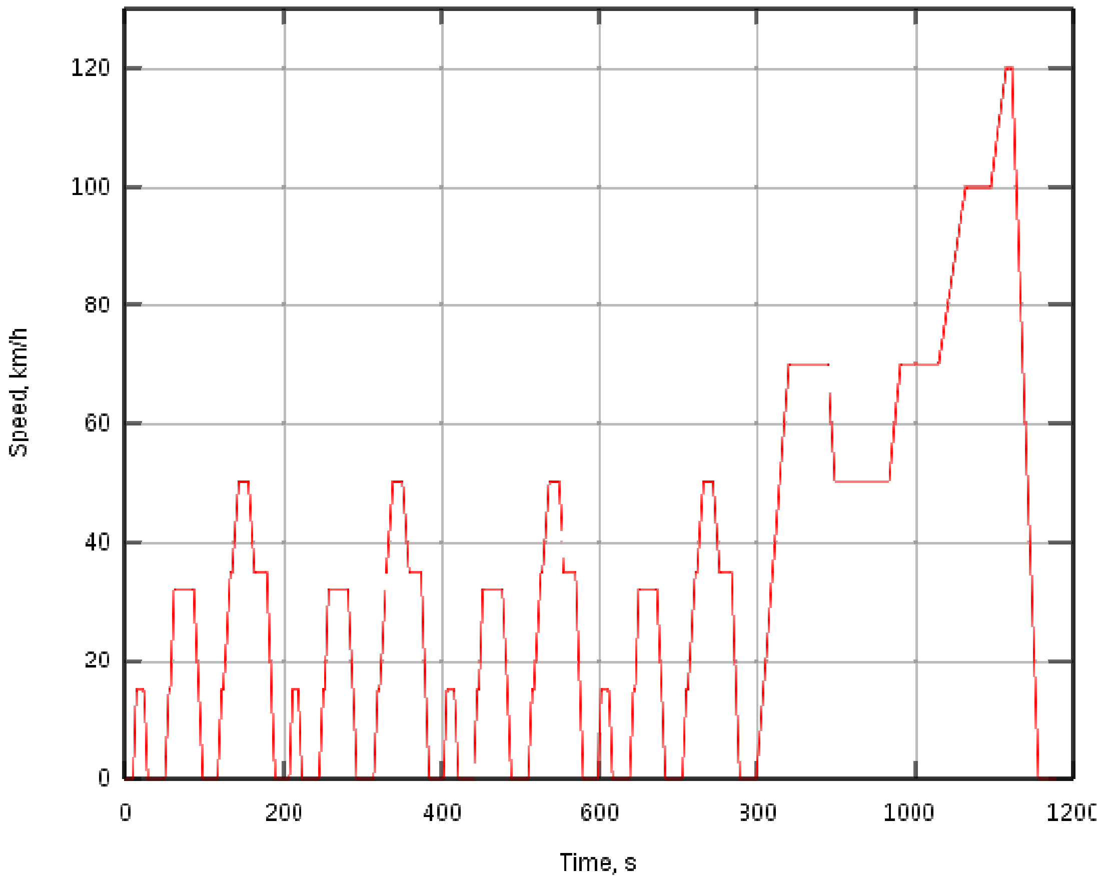


Figure 11. The NEDC test cycle.

Test results

The results are presented in Figure 12 – 17. From the figures some general conclusions can be made. The emissions of CO, NOx, NO and CO2 are significantly higher when driving on road compared to chassis dynamometer. In the case of CO the on road emission are 20 times higher, 6 times higher for NOx and 1.5 times higher for CO2. The emissions of HC were close the detection limit. The NOx include 30 to 50% NO2. The fuel consumption is on average 50% lower during the chassis dynamometer test.

The results of PM measurements are presented in Figure 10. The average values from on board measurements and the average values from the chassis dynamometer test and are in the same order of magnitude. However, it must be emphasised that on board results are soot measurements and the results from chassis dynamometer test are particulate matter (PM). Generally PM consist of 80% soot.

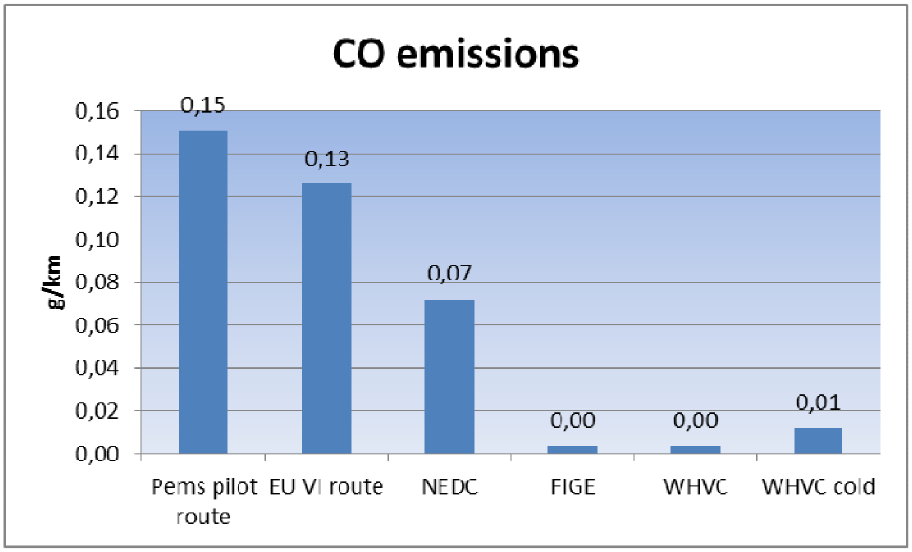


Figure 12. Emissions of CO. Certification value (NEDC) 0.233 g/km.

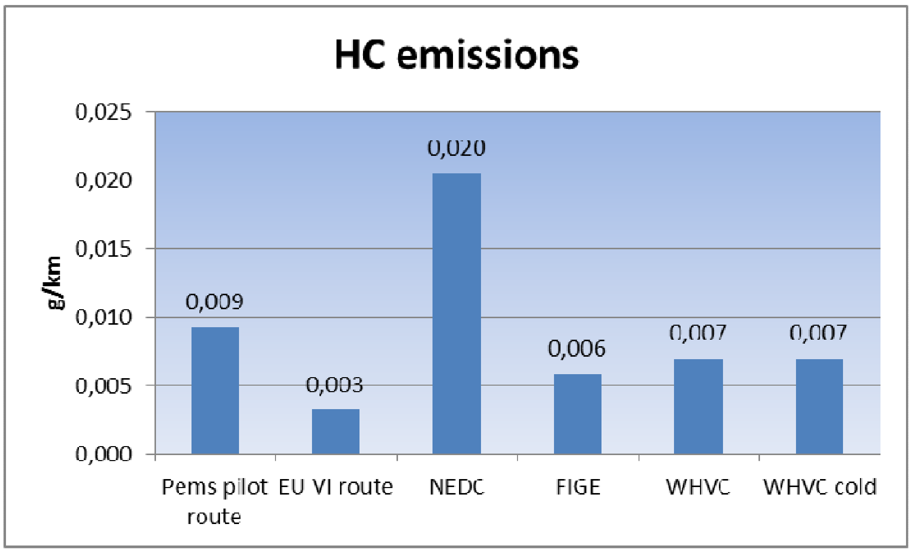


Figure 13. Emissions of HC. Certification value (NEDC) THC + NOx 0.399 g/km.

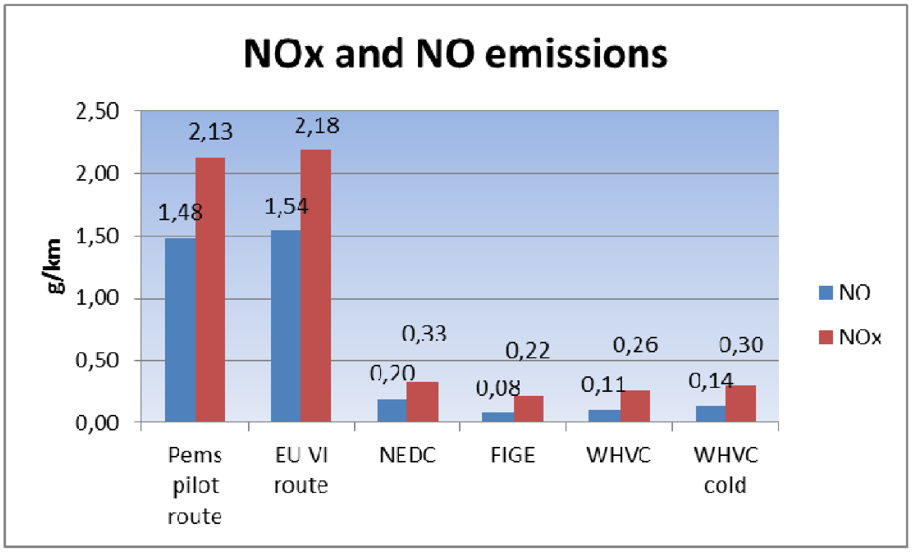


Figure 14. Emissions of NOx. Certification value (NEDC) THC + NOx 0.399 g/km.

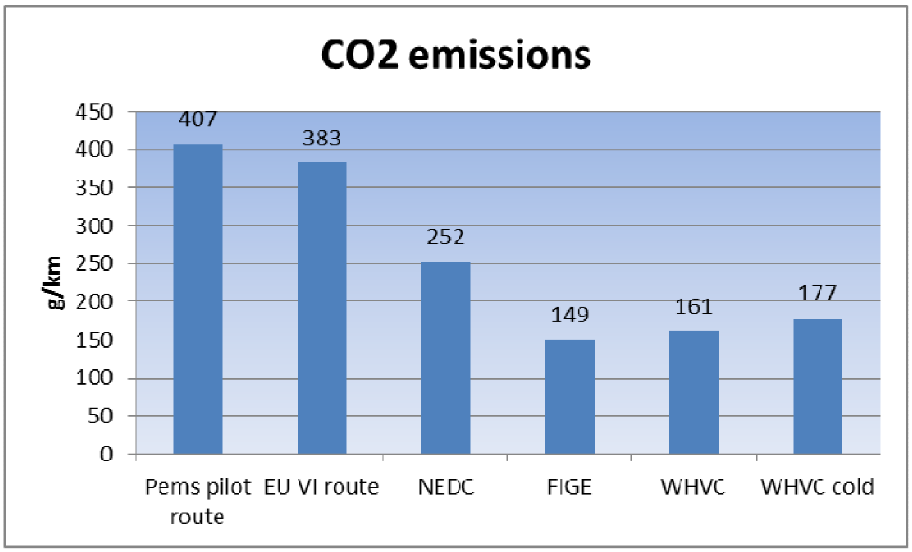


Figure 15. Emissions of CO_2. Certification value (NEDC) 266 g/km

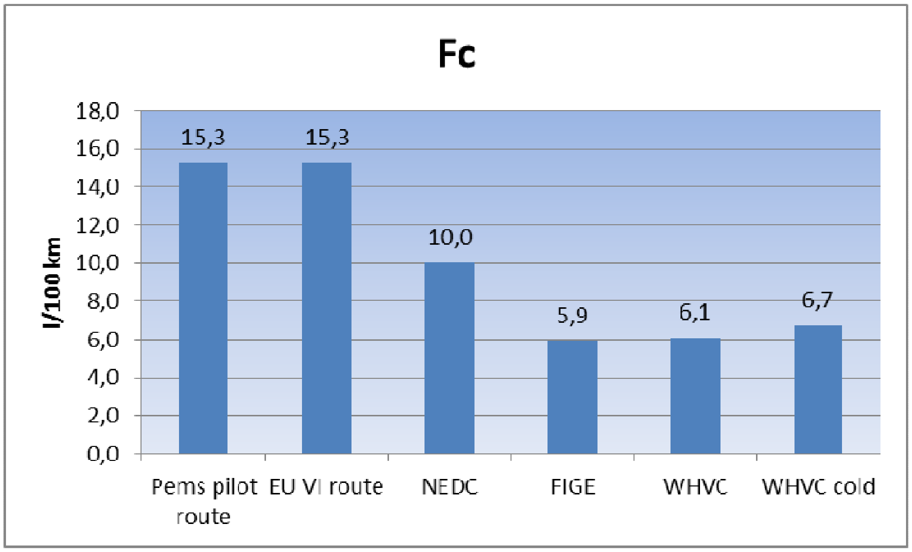


Figure 16 Fuel consumption. Certification value (NEDC) 10.1 l/100 km.

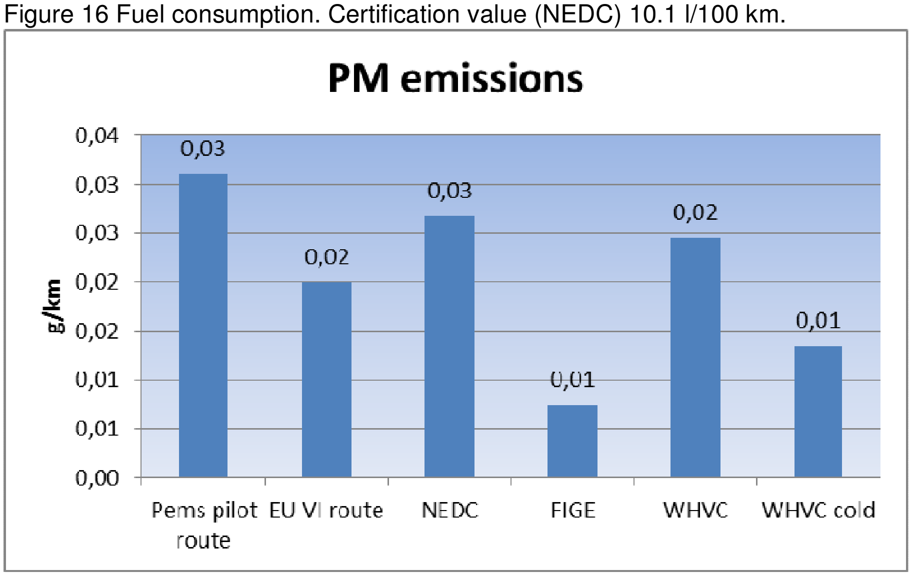


Figure 17. Emissions of soot (Pems and EU VI) and PM (NEDC, FIGE, WHVC). Certification value (NEDC) 0.028

The overall impression of the vehicle emission performance is good and no mil light indicated exhaust after treatment failure. Due to the lack of ECU signals no calculations of emissions in g/kWh were possible.

Vehicle C.

The vehicle was a medium sized destitution truck with an electric hybrid system equipped with a SCR system fulfilling the requirement of Euro V, EEV. The vehicle was tested with an extra load of 3000 kg during a Euro VI test route and a bus test route. Two test runs were carried out for each route and the average values are presented in this report.

Presentation of vehicle:

Table 8. Vehicle data.

Year model	2012
Mileage, km	15 400
Power, kW	120
Test weight, kg	11 300
Euro standard	V EEV

Test results

The results are presented as distance specific emissions in Figure 18 and 19. From the figures some general conclusions can be made. During the Euro VI test the exhaust temperature were well above the light off temperature of the catalyst i.e. 250 °C, thus giving a high reduction of CO, HC and NOx. The start/stop driving in the bus cycle generates temperatures ranging from 190 °C to 250 °C which increases the emission with a factor of approximately 2.5. The driving pattern in the bus test route also increases the fuel consumption with 15%. High standard deviation from the measurements of soot for both test cycles makes it impossible to distinguish the two cycles significantly.

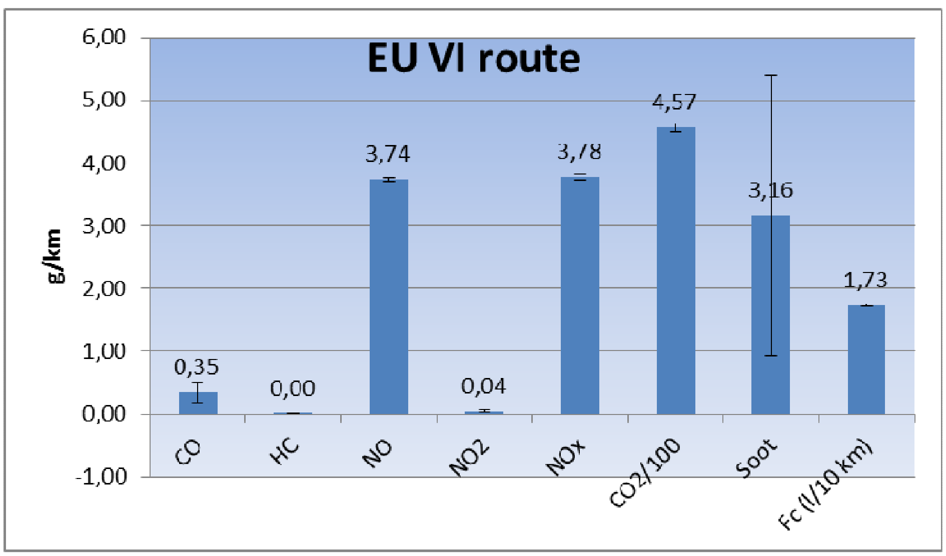


Figure 18. Distance specific CO mass emission.

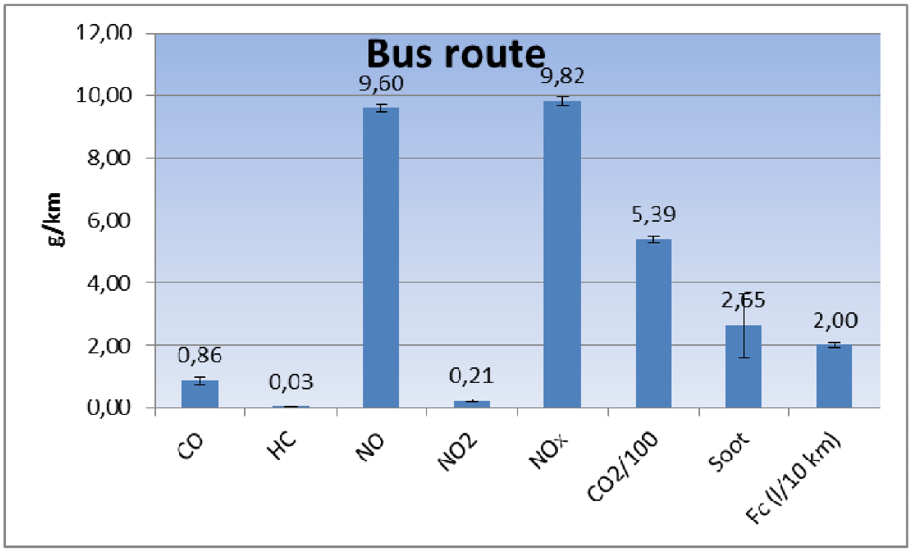


Figure 19. Brake specific CO mass emission.

The overall impression of the vehicle emission performance is good and no mil light indicated exhaust after treatment failure. Due to the lack of ECU signals no calculations of emissions in g/kWh were possible.

Vehicle D.

The vehicle type chosen was a distribution van, equipped with an EGR and a particulate filter system. The vehicle was tested both on roads and on cassis dynamometer with a cargo load of approximately 2 500. The tests were carried out with commercially available Environmental class 1 diesel (MK1). The vehicle was served in accordance to the manufacturer specification.

Table 9. Test vehicle data.

Year model	2010
Mileage, km	21800
Power, kW	140
After treatment system	EGR, DPF
Test weight, kg	5000
Euro standard	V

The Chassis dynamometer tests were:

- 2 FIGE (chassis dynamometer version of ETC – European Transient Cycle) warm start
- 2 WHVC (World harmonized vehicle chassis dynamometer test - warm start)
- 1 WHVC (World harmonized vehicle chassis dynamometer test - cold start)
- 2 NEDC (New European Driving Cycle chassis dynamometer test for light duty vehicles)

The on-board measurement cycles were:
- 2 Euro VI pems test routes
- 2 Pems pilot study test routes

The Euro VI test route is designed in order to carry out 5 times the power during the engine certification test procedure and at specified percentage of urban, rural and highway driving while the Pems pilot test route do not take the power into account.

Test results

The results are presented in Figure 20 – 24. From the figures some general conclusions can be made. The emissions of CO and CO2 are generally higher when driving on road compared to chassisdynamometer. In the case of CO the on road emission are 40 times higher compared to the chassis test. The emissions of HC were below the detection limit, i.e. 1 mg/km, during the on-board testing. The NO_x emissions are approximately 10% higher on the chassis dynamometer test compared to on road testing. The NOx include 10 to 30% NO2. The fuel consumption is on average 15% lower during the chassis dynamometer test.

In addition to presented results particulate matter (PM) and soot were measured. However, all results were below the detection limit i.e. 1 mg/km.

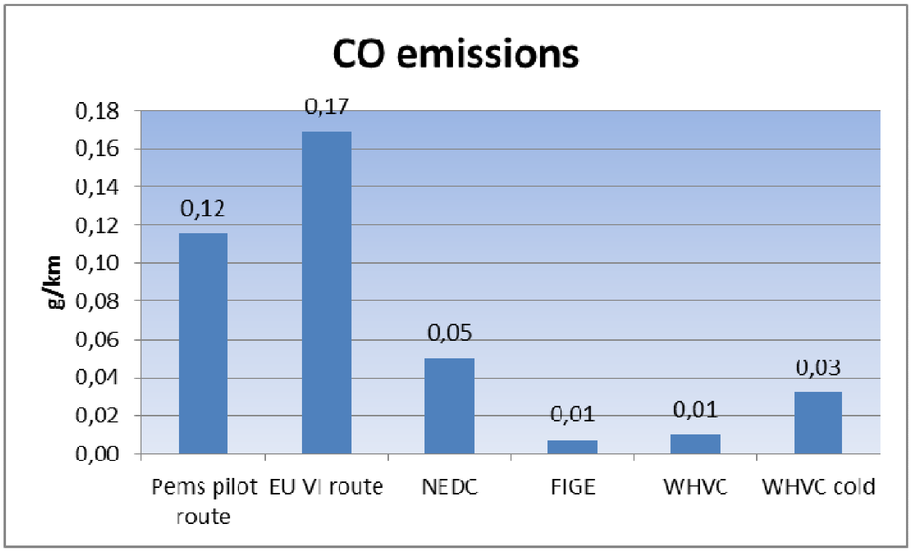


Figure 20. Emissions of CO.

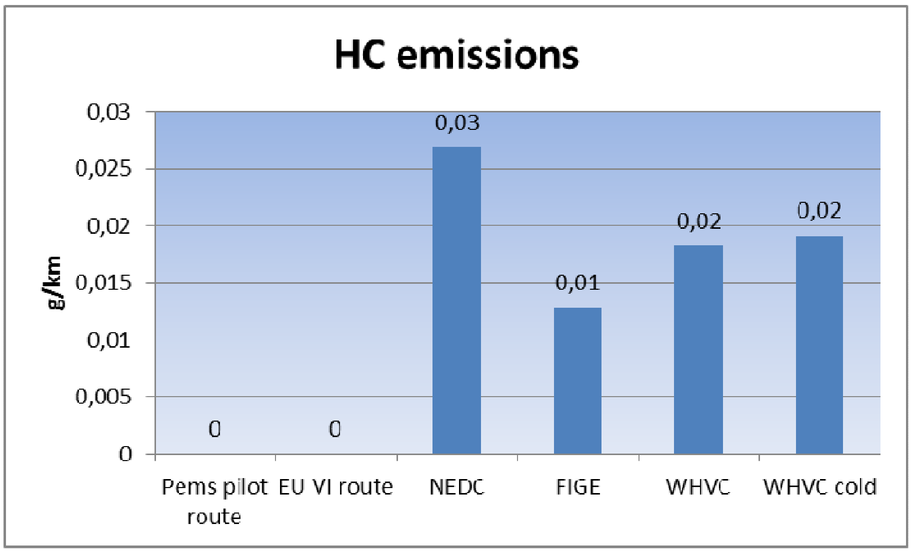


Figure 21. Emissions of HC.

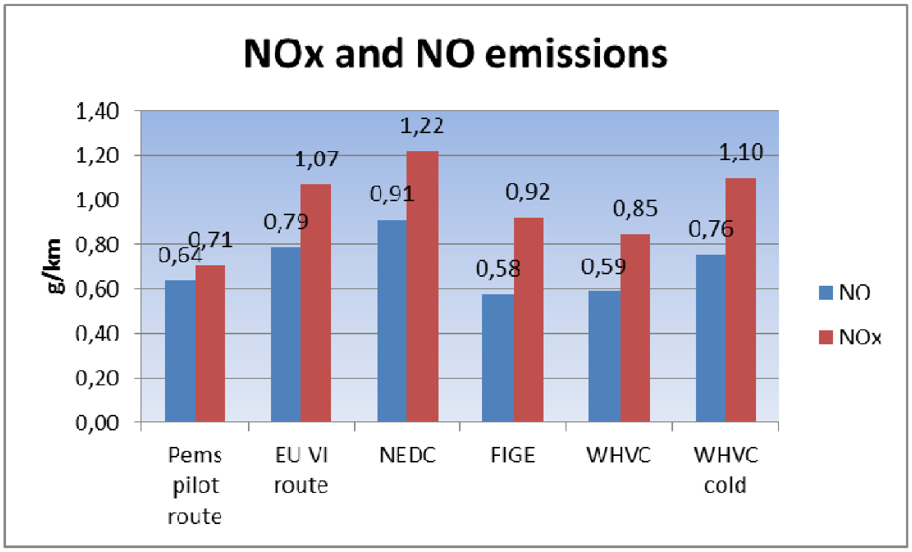


Figure 22. Emissions of NOx.

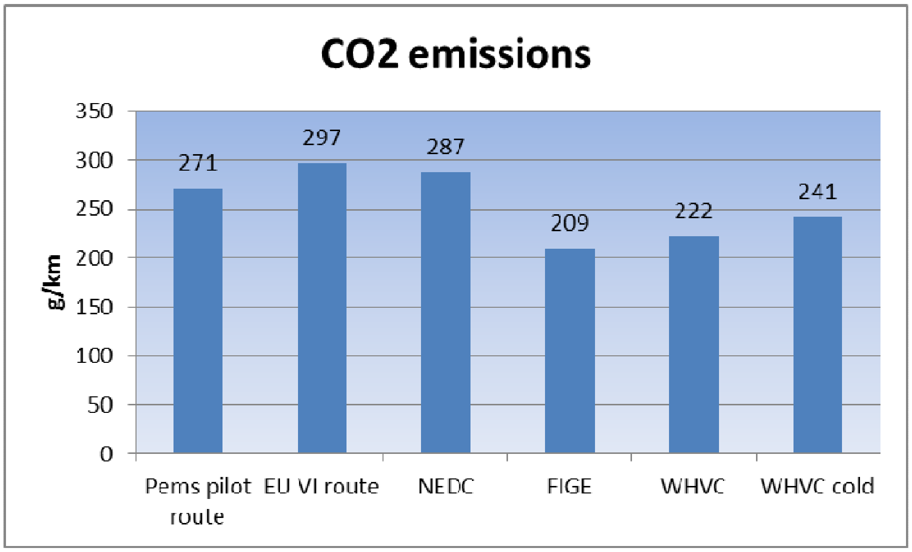


Figure 23. Emissions of CO_2. Certification value 272 g/km.

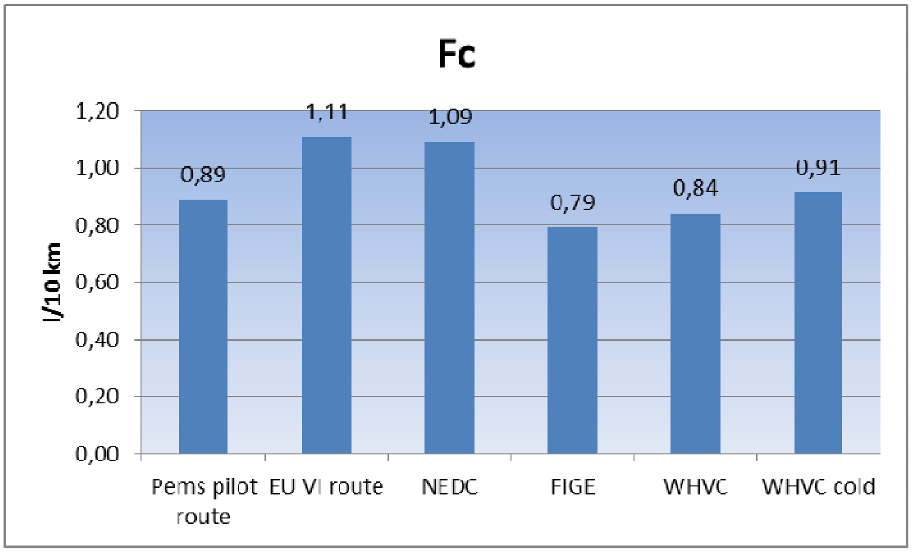


Figure 24. Fuel consumption. Certification value 1.03 L/10 km.

The overall impression of the vehicle emission performance is good and no mil light indicated exhaust after treatment failure. Due to the lack of ECU signals no calculations of emissions in g/kWh were possible.

Vehicle E.

The vehicle type chosen was a garbage truck with an electric hybrid system, equipped with a SCR. The vehicle was tested with during a Euro VI test route and a bus test route. Two test runs were carried out for each route and the average values are presented in this report. In addition data from a test run 2012 during a normal working day are presented.

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The tests were carried out with commercially available Environmental class 1 diesel (Mk1). The vehicle was served in accordance to the manufacturer specification.

Table 10. Vehicle data.

Year model	2011
Mileage, km	46 000 (25 000 in 2012)
Power, kW	250
Test weight, kg	17 500
Euro standard	V

The results are presented as distance specific emissions in Figure 25 and 30. From the figures some general conclusions can be made. During the Euro VI test the exhaust temperature were well above the light off temperature of the catalyst i.e. 250 °C, thus giving a high reduction of CO, soot and NOx. The start/stop driving in the bus cycle and the normal working day for a garbage truck generates temperatures ranging from 190 °C to 250 °C which increases the emission compared to the Euro VI route. The driving pattern in the bus and normal working day test routes also increases the fuel consumption, 30%. The emissions of HC were close to the detection limit, thus giving a high standard deviation.

Comparing the brake specific emissions with Euro V certification limits all regulated components were higher than the limit value, except CO and on the Euro VI route. However, it must be emphasised that PEMS measurement differs from the certification test procedure and can thus not be used as a pass or fail criteria for Euro V vehicles. Pass/fail criteria will be implemented in the Euro VI regulations.
In addition, on board results are soot measurements and the limit value are set for particulate matter (PM). Generally PM consist of 80% soot.

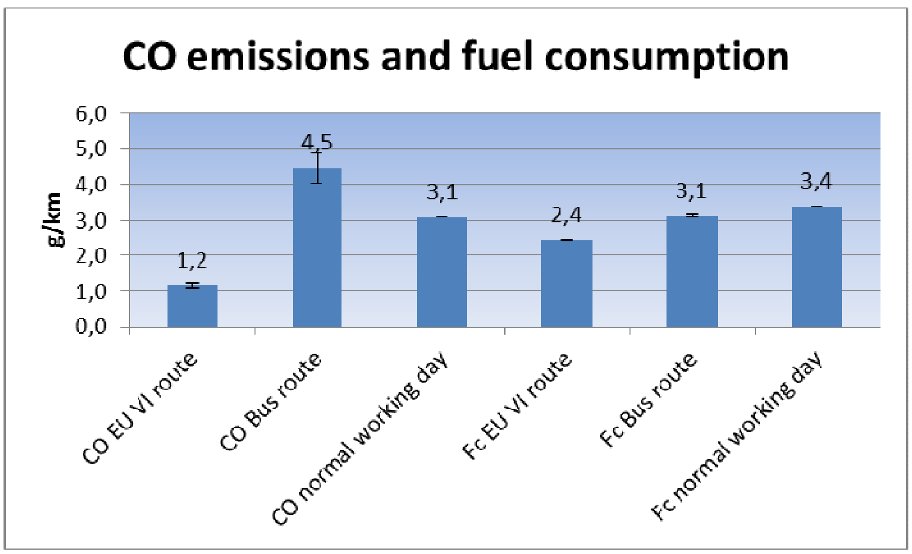

Figure 25. Distance specific CO mass emission and fuel consumption.

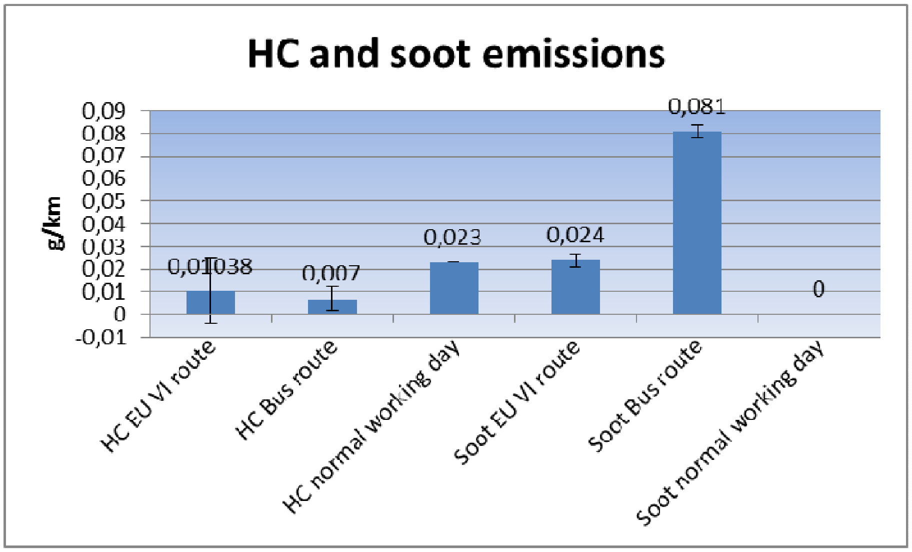

Figure 26. Distance specific HC and soot emissions.

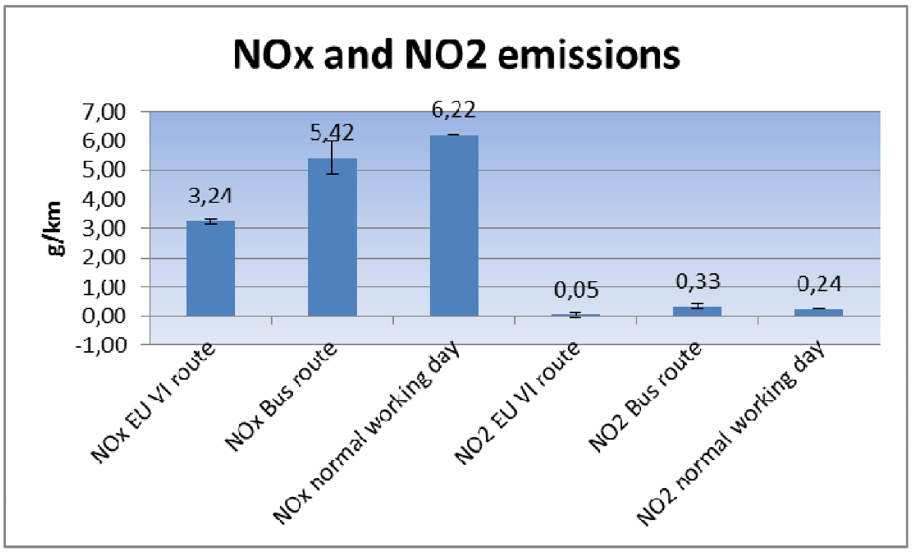

Figure 27. Distance specific NOx and NO2 emissions.

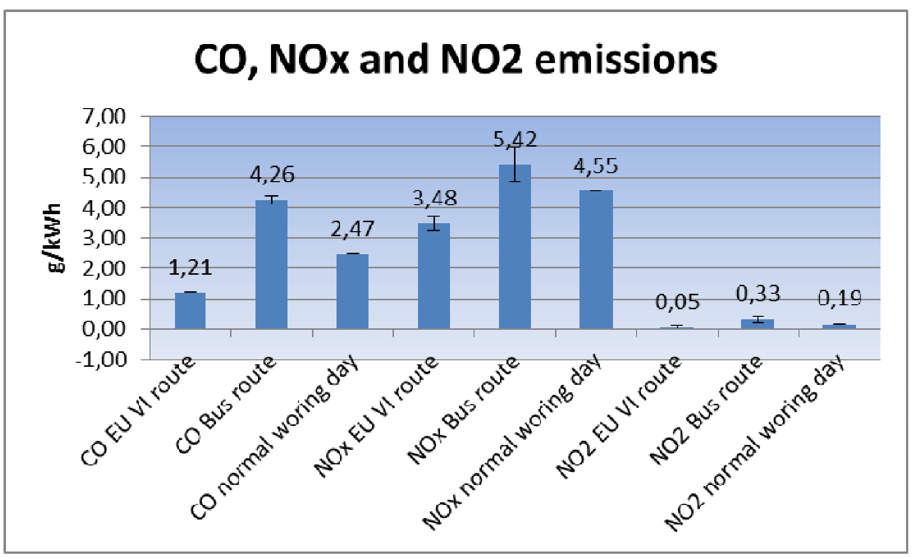

Figure 28. Brake specific CO, NOx and NO2 emissions.

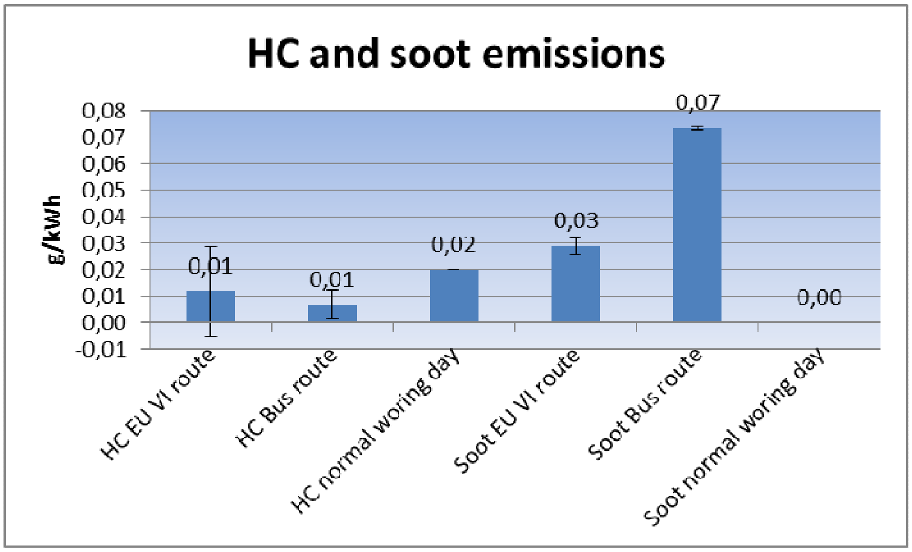

Figure 29. Brake specific HC and soot emissions (soot were not measured 2012).

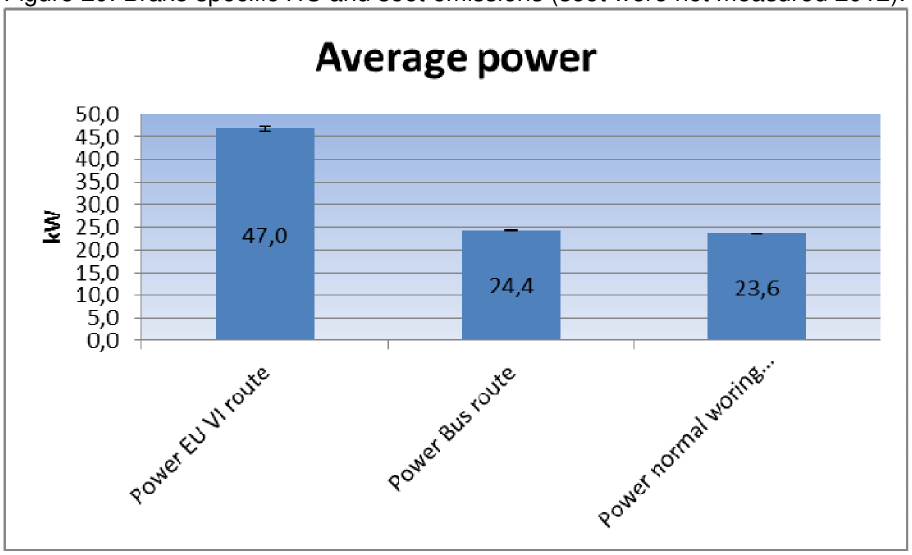

Figure 30 .Average power.

The overall impression of the vehicle emission performance is good and no mil light indicated exhaust after treatment failure.

Appendix 1.

Complete report from testing of Vehicle F, G.

Emission effects from Diesel Fuels and ED95 – Heavy Duty Vehicles

AVL MTC
Charlotte Sandström-Dahl

AVL MTC 2013/12

A Report for

The Swedish Transport Administration
and
The Swedish Transport Agency

SUMMARY

In order to reduce the climate impact from the transport sector, there is an ambition in the European Union to increase the share of alternative fuels. Since the transport sector is very diverse, there are multiple ways to deal with this. The vehicles can be dedicated towards a certain fuel, or accepting different types of fuel blends where at least part of the fuel consists of conventional types (i.e. diesel or petrol).

In recent years, new fuels and blends have been introduced on the market. In Europe, the Commission has presented a road map towards a low carbon economy 2050, a white paper on transport and a proposal for alternative fuel infrastructure. The main focus in these strategies is to reduce the oil dependency and the negative climate impact from the transport sector. In combination with the climate impact, it is important to also involve other aspects of new fuels, such as parameters affecting environment or health.

In this study vehicle tests have been performed with five different diesel fuels and the ethanol fuel ED95 used for compression ignited vehicles. Two heavy duty trucks have been used, one diesel truck and one dedicated for ED95, both of EEV emission standard. The tests have been performed on chassis dynamometer, where the vehicles have been driven according to the Worldwide Harmonized Vehicle Cycle (chassis dynamometer version of WHTC).

The following fuels were used – B7 (conventional diesel fuel), B7+HVO30, HVO100, synthetic diesel (GTL), B100 and ED95. The B7+HVO30, HVO100 and the synthetic diesel were so-called drop-in fuels, i.e. fuels that can be used in existing engines. The B100 can be used in existing vehicles with some adjustments, whereas the ED95 fuel can be used in dedicated vehicles.

The regulated components and CO2 have been measured. In addition, some unregulated components were also investigated:

- Aldehydes: sampled in DNPH-cartridges;
- Ethanol emissions: sampled with FTIR during the tests with the ED95 fuel;
- Particle number: Condensed Particle Counter (CPC);
- Particle size distribution: Electrical Low Pressure Impactor (ELPI);
- Particles: PAH (Polycyclic Aromatic Hydrocarbons) content.

Svensk sammanfattning

För att minska klimatpåverkan från transportsektorn finns det en ambition inom EU att öka andelen förnybara bränslen. Eftersom transportsektorn inte är homogen kommer det att krävas en rad åtgärder för att lyckas med detta.

De allt strängare emissionskrav som ställs på nya motorer och fordon kommer på sikt att leda till reducerad klimat- och miljöpåverkan från transportsektorn. Det tar dock tid att byta ut en befintlig fordonsflotta, framför allt när det gäller tunga fordon som har en stor miljöpåverkan. De bränslen som fordonen använder är dock en faktor som kan ge en förändring även på kort sikt.

Under senare tid har flera bränslen som kan användas i befintliga motorer introducerats på den europeiska marknaden. Transportsektorn består till stor del av tunga fordon, där motorer med kompressionständning dominerar på grund av dess höga verkningsgrad. I denna studie har två tunga fordon testats med sex olika bränslen, där samtliga bränslen är avsedda för motorer med kompressionständning. De bränslen som använts är B7 (konventionellt dieselbränsle), B7 med 30% HVO, 100% HVO, syntetisk diesel (GTL), B100 och ED95.

I studien har fordonen körts på chassidynamometer enligt den transienta körcykeln WHVC. Reglerade avgaskomponenter, CO2, aldehyder och etanol (för ED95-bränslet) har mätts. Partiklar har analyserat med avseende på massa, antal, storleksfördelning och PAH (Polycykliska Aromatiska Kolväten).

Table of contents

Abbreviations

B7	7% FAME (conventional diesel fuel, containing 7% FAME)
B100	100% FAME
CO	Carbon monoxide
CO2	Carbon dioxide
CPC	Condensation Particle Counter
ECU	Electronic Control Unit
EEV	Enhanced Environmentally friendly Vehicles
ELPI	Electrical Low Pressure Impactor
Fc	Fuel consumption
FTIR	Fourier Transform Infrared Spectroscopy
GTL	Gas-To-Liquid
HC	Hydrocarbon
HFID	Heated Flame Ionization Detector
HVO	Hydrotreated Vegetable Oil
Mk1	"Miljöklass 1" (environmental class 1)
NDIR	Non-Dispersive Infrared detector
NOx	Nitrogen oxides
OC	Oxidation catalyst
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PN	Particle number
SCR	Selective Catalytic Reduction
WHTC	Worldwide Harmonized Transient Cycle
WHVC	Worldwide Harmonized Vehicle Cycle

Introduction

In order to reduce the climate impact from the transport sector, there is an ambition in the European Union to increase the share of alternative fuels. Since the transport sector is very diverse, there are multiple ways to deal with this. The vehicles can be dedicated towards a certain fuel, or accepting different types of fuel blends where at least part of the fuel consists of conventional types (i.e. diesel or petrol).

In recent years, new fuels and blends have been introduced on the market. It is however important to look beyond the climate impact and thereby also involve other aspects of new fuels, such as parameters affecting environment or health.

In this study vehicle tests have been performed with five different diesel fuels and the ethanol fuel ED95 used for compression ignited vehicles. Two heavy duty trucks have been used, one diesel truck and one dedicated for ED95, both of EEV emission standard. The tests have been performed on chassis dynamometer, where the vehicles have been driven according to the Worldwide Harmonized Vehicle Cycle (chassis dynamometer version of WHTC).

The following fuels were used – B7 (conventional diesel fuel), B7+HVO30, HVO100, synthetic diesel (GTL), B100 and ED95. The B7+HVO30, HVO100 and the synthetic diesel (GTL) are so-called drop-in fuels, i.e. fuels that can be used in existing engines. The B100 can be used in existing vehicles, but adjustments of fuel system and ECU should be performed before permanent use. In the tests performed in this project, no adjustments were made. The ED95 fuel can only be used in dedicated vehicles.

The regulated components and CO2 have been measured. In addition, some unregulated components were also investigated: Aldehydes were sampled in DNPH-cartridges; ethanol emissions were measured with FTIR during the tests with the ED95 fuel; particle numbers were counted with a CPC; particle size distribution was analyzed with an ELPI instrument and the PAH content in the particles were analyzed.

Test vehicles

Two vehicles were used in the test program. One was a diesel truck, which were used for the testing with the diesel drop-in fuels. The other vehicle was a dedicated ED95 vehicle. The diesel truck is presented in Table 1 and the ED95 truck is presented in Table 2.

Table 1: Vehicle data – diesel truck.

Vehicle Make	Iveco
Vehicle Model	Truck
Model Year	2012
Chassis Number	ZCFA1EJ0402595831
Mileage (km)	29124
Gross vehicle weight (kg)	11990
Unladen weight (kg)	7535
Emission standard	Euro V (EEV)
Engine displacement (cm3)	5880
Max engine power (kW)	185
Aftertreatment	SCR
Test weight/inertia (kg)	9732

Table 2: Vehicle data – ED95 truck.

Vehicle Make	Scania
Vehicle Model	P270DA4X2MLA
Model Year	2012
Chassis Number	YS2P4X20002074109
Mileage (km)	24049
Gross vehicle weight (kg)	18000
Unladen weight (kg)	6590
Emission standard	Euro V (EEV)
Engine displacement (cm3)	8867
Max engine power (kW)	199
Aftertreatment	EGR
Test weight/inertia (kg)	12670

Test fuels

The diesel truck was tested with five different fuels:

- B7 (conventional diesel fuel);
- B7+HVO30;
- HVO100;
- B100;
- Synthetic diesel (GTL).

The B7, B7+HVO30, HVO100 and B100 were delivered from oil companies. The synthetic diesel was a GTL fuel which is commercially available, and was fuelled at a tank station.

The B7 fuel is a conventional diesel fuel ("Mk1" – environmental class 1) with 7% FAME. B7+HVO30 fuel is a conventional diesel fuel ("Mk1") with the addition of 7% FAME and 30% HVO.

B7, B7+HVO30, HVO100 and synthetic diesel (GTL) are so-called drop-in fuels, i.e. fuels which can be used in existing engines.
B100 can be used in existing vehicles, but adjustments of fuel system and ECU should be performed before permanent usage. No adjustments were performed prior to the tests in this project.

ED95 can only be used in dedicated vehicles. The fuel consists of 95% ethanol with the addition of ignition improver, lubricant and corrosion protection. Today, there is one fuel producer. ED95 is commercially available at one location in Stockholm, and the fuel is therefore primarily used in fleets. In this project the vehicle was tested by using the fuel from the vehicle fuel tank.

The fuels used in the test program are described in Table 3 and Table 4. The fuel specifications for the diesel fuels can be found in the Appendix.

Table 3: Fuel data: B7, B7+HVO30 and HVO100.

	Units	B7	B7 + HVO30	HVO100
Density	kg/m3	822,0	822,5	778,6
Total aromatic content	% V/V	4,7	4,7	0,2
Sulfur content	mg/kg	< 3	< 3	< 1
Cetane index	-	50,7	56,5	> 56,5
FAME and/or HVO content	% V/V	7,0	27,1+7,0	100

Table 4: Fuel data: B100, GTL and ED95.

	Units	B100 (RME)	GTL (Synthetic diesel)	ED95
Density	kg/m3	882,0	802,4	824
Total aromatic content	% V/V	-	< 0,5	0
Sulfur content	mg/kg	4	< 3,0	< 10
Cetane index	-	52,6 (number)	66,7	
FAME and/or HVO content	% V/V	98,4	< 0,05	0

Experimental

Chassis dynamometer test cell

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

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

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

A schematic description of the test cell is included in Appendix.

Engine power

The engine power was estimated by adding the integrated signals from measured acceleration force of the inertia used and the road load. No fan correction has been applied to the calculations. The integrated power is then used to calculate the total estimated work (kWh) during the test cycle which is used to calculate emissions in g/kWh. The estimation methodology is thorougly described in Appendix.

Measuring methods

Regulated and unregulated components were investigated in this study. The measuring methods for the gaseous components are presented in the first part of this chapter, followed by the methods for the particulate measurements.

Regulated gaseous emissions and CO2

The sampling- and analysing equipment are based on full flow dilution systems, i.e. the total exhaust is diluted using the CVS (Constant Volume Sampling) concept. The total volume of the mixture of exhaust and dilution air is measured by a CFV (Critical Flow Venturi) system. For the subsequent collection of particulates, a sample of the diluted exhaust is passed to the particulate sampling system. The sample is here diluted once more in the secondary dilution tunnel, a system referred to as full flow double dilution.

According to the regulations for transient tests the diluted exhaust gases are both bagsampled and sent for further analysis *and* on-line sampled. Through the CVS system a proportional sampling is guaranteed.

The equipment used for analysing the gaseous regulated emissions consist of double Horiba 9400D systems. Hereby exists the possibility to measure both diluted and raw exhaust emissions on-line simultaneously. The sampling system fulfils the requirements of Regulation (EU) 582/2011 in terms of sampling probes and heated lines etc.

The measured components and measurement principles are specified in Table 5.

Table 5: Measured components and measurement principles.

Component	**Measurement principle**
Total hydrocarbons (THC)	HFID (heated flame ionization detector) (190°C)
Carbon monoxide (CO)	NDIR (non-dispersive infrared analyzer)
Carbon dioxide (CO_2)	NDIR
Nitrogen oxides (NO_x)	CL (chemiluminescence)
Fuel consumption (FC)	Carbon balance of HC, CO and CO_2

Measurement of ethanol

Measurement of alcohols with FTIR (Fourier Transform Infrared Spectroscopy) is not a standard procedure, and is used mainly for research purposes. Different measurement principles for ethanol are thorougly described in [1].

The FTIR uses the fact that different substances absorb different frequencies of infrared light unequally. The FTIR analysis produces absorption peaks corresponding to the frequencies of vibrations between the bonds of the atoms in a molecule. Since different molecules are consisting of different combinations of atoms, the infrared spectrum is unique for a specific substance. This makes FTIR very useful for analyzing many different compounds. The size of the peaks is also corresponding to the amount of the substance.

The infrared beam from the source is divided by a beamsplitter, dividing the beam into two optical beams. One of the beams is reflected off of a non-mobile mirror back to the beamsplitter. The other beam is reflected off of a flat mirror which is mobile (only a few millimeters) back to the beamsplitter. The mobile mirror makes it possible to differentiate the beams. The two reflected beams are recombined at the beamsplitter, and the signal exiting the “interferometer” is a result of these two beams “interfering” with each other. The resulting signal is called an interferogram, which has the unique property that every data point (a function of the moving mirror position) which makes up the signal has information about every infrared frequency which comes from the source. This means that as the interferogram is measured, all frequencies are being measured simultaneously.

The analyzer requires a frequency spectrum in order to make an identification. This means that the individual frequencies need to be “decoded”, which is accomplished via a well-known mathematical technique called the Fourier transformation.

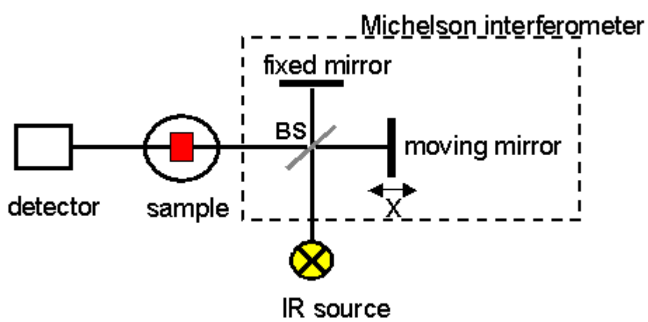

Figure 3: Schematic view of the principles of the FTIR (Source: *www.uni-ulm.de*).

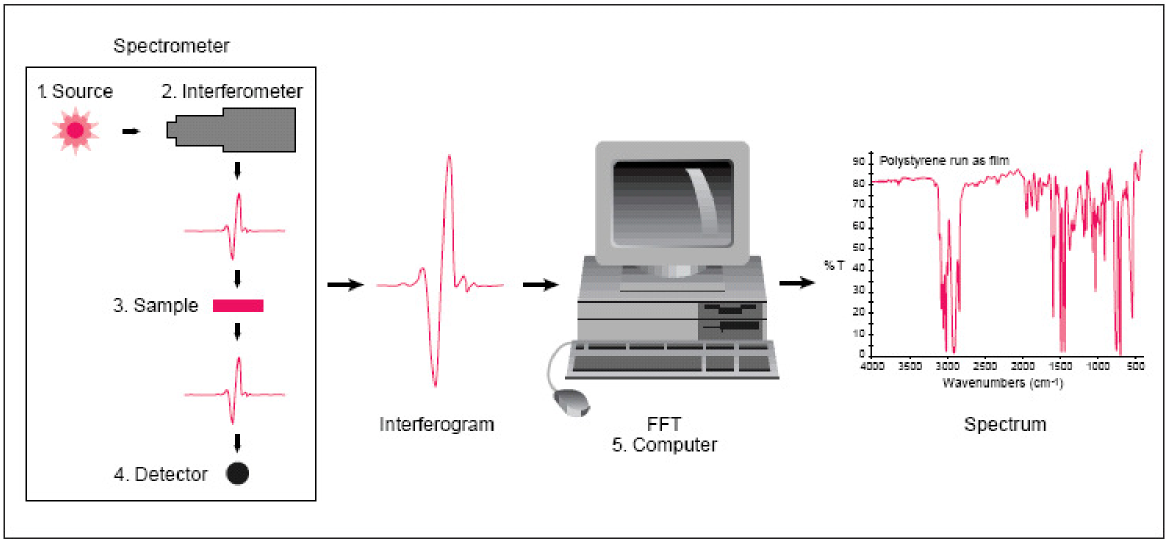

Figure 4: The working principle of the FTIR (Source: *www.mmrc.caltech.edu*).

The FTIR measurement is performed on raw exhaust emissions.

One advantage with the FTIR instrument is that it is possible to measure many substances at the same time, with a fast response.

Measurement of aldehydes

Analysis of aldehydes was carried out using 2.4-di nitro phenyl hydrazine (DNPH) coated filter cartridges. This method is in accordance with Method 1004 approved by US EPA and California ARB.

The DNPH-cartridges were, after sampling, extracted with distilled acetonitrile and analyzed on a C-18 silica column with a methanol/water gradient and HPLC/UV detection. Quantification was carried out with corresponding hydrazone as external standard.

Particulate emissions

The particulate emissions were analyzed gravimetrically, by number and by size distribution. The polycyclic aromatic hydrocarbons were sampled on large filters and polyurethane foam (PUF).

Particulate mass

The particulate mass was measured gravimetrically by the use of glass fibre filters. For the collection of particle matter (PM), a sample of the diluted exhaust is passed to the particulate sampling system. The sample is then diluted once more in the secondary dilution tunnel, a system referred to as full flow double dilution. The particles are collected on Teflon-coated Pallflex™ filter and measured gravimetrically. The sampling of particle matter is in accordance with Directive 2005/55/EEC.

Particle number

The particle number is measured in a Condensation Particle Counter (CPC) with a size range of 23nm to 2.5µm. The particle number is limited for heavy duty diesel engines from emission standard Euro VI (limits for positive ignited engines are not yet decided).

In the counter, the particles are enlarged by condensation of butanol and are thereafter detected and counted using a light-scattering method. A schematic description of the detector is presented in Figure 5.

In order to count non-volatile particles, a special sampling method has been developed. A pump draws the exhaust gas into a sampling probe which eliminates all particles >2.5 µm due to its special shape. The sampled exhaust gas is then diluted with cleaned hot air at a temperature of 150°C. This stabilizes the particle number concentration and reduces the concentration so that agglomerations and particle deposits are largely prevented.

After the hot primary dilution, the diluted exhaust gas is further heated up to a temperature of 300°C to 400°C in an evaporation tube in order to convert all volatile particles into gaseous phase. A secondary dilution is then performed to prevent further condensation or adsorption of volatile substances and to ensure that the maximum inlet temperature of 35°C is not exceeded. The particle number concentration is measured in the Condensation Particle Counter (with a size range of 23nm to 2.5µm according to UNECE-R83 specifications). The particles are enlarged due to the condensation of butanol and are detected and counted using the lightscattering.method.

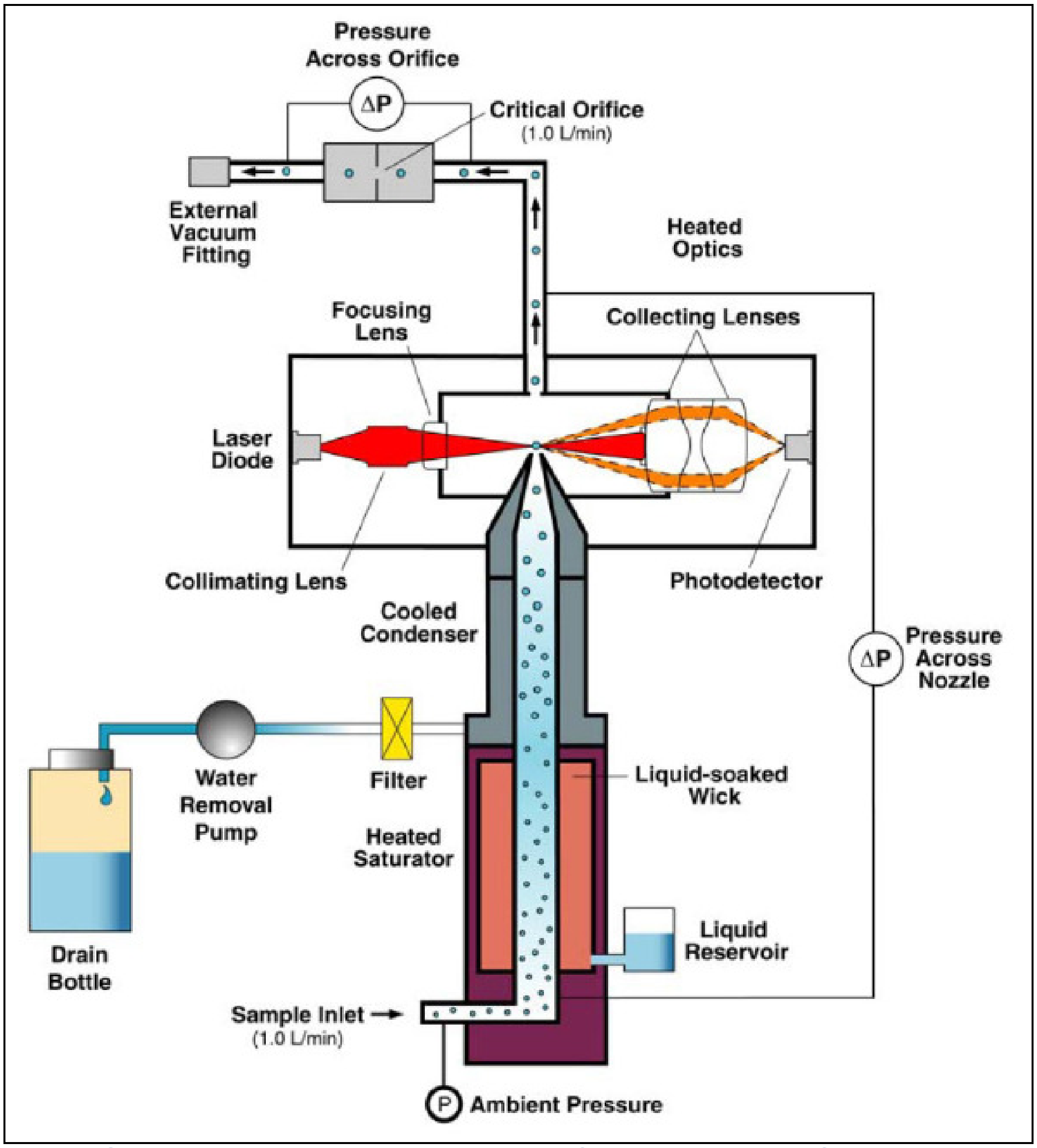

Figure 5: Schematic description of the detector in the Condensation Particle Counter.

Particulate size distribution

An Electrical Low Pressure Impactor (ELPI) was used for particle size distribution. In an impactor, the particles are classified according to their aerodynamic diameter. The ELPI impactor has 12 stages ranging from 7 nm to 10µm. The instrument was manufactured by Dekati Ltd. in Finland. The principle of the ELPI instrument is described below and a schematic description is presented in Figure 6.

Before entering the ELPI instrument, the exhaust gases are diluted in order to reduce their concentration. In this case, sampling was carried out from the full flow primary dilution tunnel.

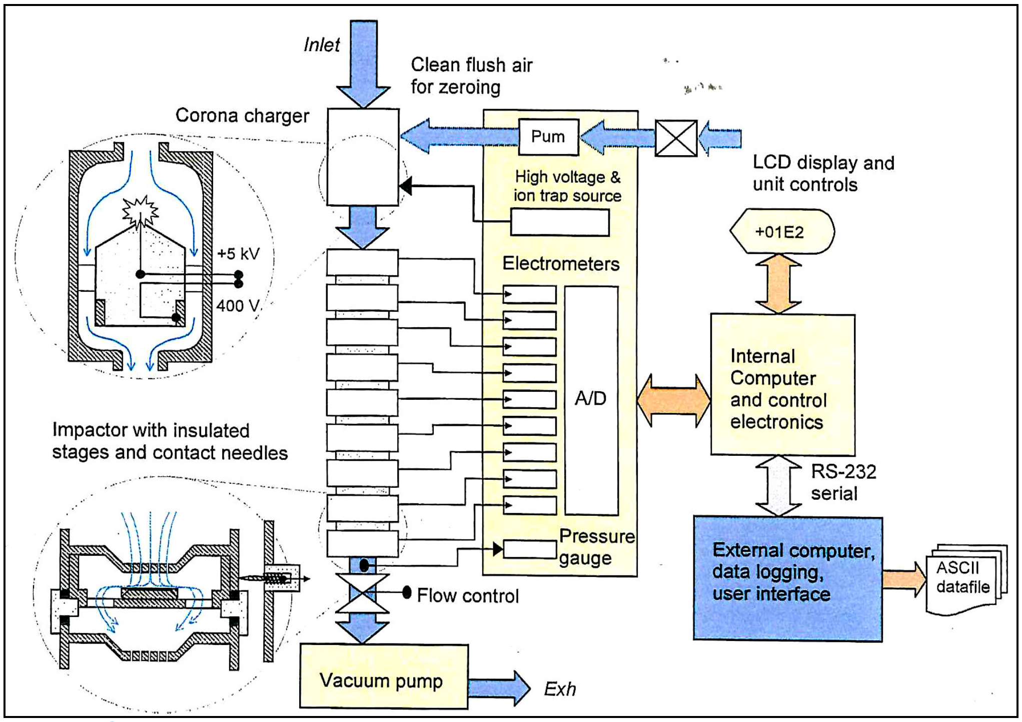

Figure 6: Schematic description of the operating principles in an ELPI instrument.

The ELPI™ operating principle can be divided into three major parts; particle charging in a unipolar corona charger, size classification in a cascade impactor and electrical detection with sensitive electrometers. The particles are first charged into a known charge level in the charger. After charging the particles enter a cascade low pressure impactor with electrically insulated collection stages. The particles are collected in the different impactor stages according to their aerodynamic diameter, and the electric charge carried by particles into each impactor stage is measured in real time by sensitive multichannel electrometers. This measured current signal is directly proportional to particle number concentration and size. The operating principle for the impactor is schematically described in Figure 7.

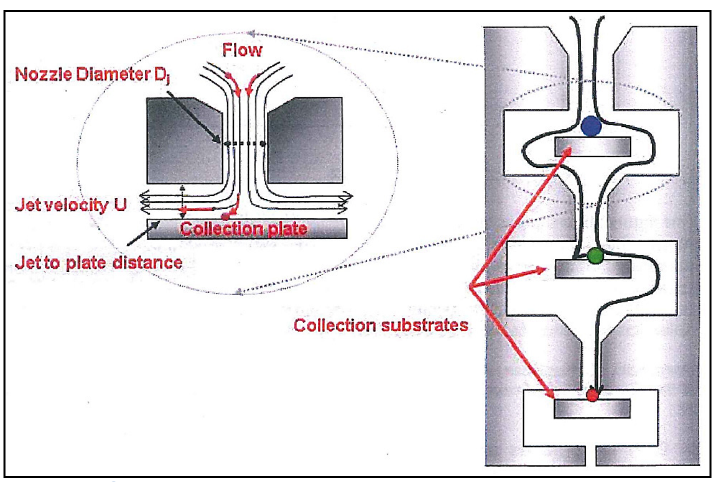

Figure 7: Operating principle for the impactor in ELPI.

The particle collection into each impactor stage is dependent on the aerodynamic size of the particles. Measured current signals are converted to (aerodynamic) size distribution using particle size dependent relations describing the properties of the charger and the impactor stages. The result is particle number concentration and size distribution in real-time.

PAH analysis

PAH are compounds with relatively high molecular weight. These compounds can be found condensed on particles and in gaseous phase. The particle associated compounds were collected on a large filter and the PAH in gaseous phase were collected in polyurethane foam (PUF) plugs. The dominating part of the PAH collected in the semivolatile phase are comparatively lighter PAH compounds (up to molecular weights of approximately 200 g/mole), whereas the PAH collected on the filters consists of both lighter and heavier PAH compounds. The filters and foam plugs were extracted before analysis. The extracts were chemically characterized and different types of PAH could be identified.

Hexane, toluene and methanol (all of HPLC-grade) were obtained from Rathburn Ltd, Scotland, UK. Dodecane (> 99 %) was obtained from Sigma-Aldrich, St. Louis, MO, USA and dimethyl sulfoxide (> 99.8 %) was from Merck Chemicals, Darmstadt, Germany.
A standard mixture of the PAHs determined in the present study and the deuterated PAHs phenanthrene-D_{10}, pyrene-D_{10}, benzo[a]anthracene-D_{12}, benzo[a]pyrene-D_{12}, benzo[ghi]perylene-D_{12} and dibenzo[a,i]pyrene-D_{14} was used for identification and quantification purposes.
A solution containing the deuterated PAHs phenanthrene-D_{10}, pyrene-D_{10}, benzo[a]anthracene-D_{12}, benzo[a]pyrene-D_{12} and benzo[ghi]perylene-D_{12} was used along with a solution of dibenzo[a,i]pyrene-D_{14} in toluene as internal standards. The manufacturer and purity of the PAH standards used in the present study have been published in detail elsewhere [2].

The PUF and filter samples were extracted with pressurized fluid extraction using an ASE 200 accelerated solvent extraction system (Dionex Corporation, Sunnyvale, CA, USA).
The filter samples were extracted in 5 ml extraction cells with an ASE method recently developed and validated for analysis of PAHs in diesel particulate matter using standard reference materials from the US National Institute of Standards and Technology (NIST) [2] [3]. Extractions were performed with a mixture of toluene and methanol (9:1; v/v) at elevated temperature and pressure (200 °C and 3000 psi). The extraction consisted of five 30 min extraction cycles.
The PUF samples were extracted in 33 ml extraction cells with acetone at 110 °C and 500 psi using two extraction cycles of 5 min. A 20 % flush was used and the purge time was set to 60 seconds.

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

The extracts were concentrated to about 5 mL using a TurboVap® LV evaporator (Zymark Corp., Hopkinton, MA, USA) under a gentle stream of nitrogen gas. The extracts were then transferred to glass vials with screw caps and stored in a freezer at -20 °C.
For analysis of PAH content in the filter and PUF extracts aliquots were transferred from the glass vials containing the extracts to disposable test tubes. Internal standards were added and the filter extracts were evaporated to approximately 0.5 ml while 0.5 ml toluene was added to the PUF extracts before reducing the volume to about 0.5 ml. The samples were then cleaned-up using a solid phase extraction (SPE) protocol described in detail elsewhere [4].

The analysis of PAHs was performed using a hyphenated High Performance Liquid Chromatography- Gas Chromatography/Mass Spectrometry (HPLC-GC/MS) system, which was constructed in house as previously described in detail [5]. Detailed description on the method used is available elsewhere [2] and will only be briefly recapitulated. The HPLC system consisted of an autosampler (CMA/200 Microsampler; CMA Microdialysis AB, Sweden), a Varian 9012 Inert solvent delivery system (Varian Inc., Palo Alto, CA, USA), a UV detector (SPD-6A; Shimadzu, Japan) and a nitrophenylpropylsilica column (4.0 mm i.d. x 125 mm, 5 µm particle size; Phenomenex, Torrance, CA, USA). Isocratic separation was performed using hexane with 0.1% dodecane (v/v) as the mobile phase. The HPLC part was connected to a GC (6890N; Agilent Technologies, Palo Alto, CA, USA) through a fused silica capillary inserted into the Programmed Temperature Vaporizer injector (CIS-3; Gerstel, Germany), which was operated in the solvent vent mode. The GC separation was carried out on a DB-17MS capillary column (60 m × 0.25 mm i.d. with 0.15 µm film thickness; J & W Scientific, Folsom, CA, USA) equipped with a retention gap (5 m x 250 µm i.d., J&W Scientific). Mass selective detection was performed using a quadrupole mass spectrometer (MSD 5973N; Agilent Technologies) operated in the electron ionization (EI) mode. Data acquisition was performed operating the quadrupole mass analyzer in selected ion monitoring (SIM) mode.

Test cycle

The vehicle was driven according to the WHVC (Worldwide Harmonized Vehicle Cycle) test cycle (Figure 8), which is a chassis dynamometer version of the WHTC (Worldwide Harmonized Transient Cycle) engine test cycle. The WHTC cycle is applicable for certification from Euro VI, where the engine will be tested both with cold start and hot start.

For each fuel, the tests consisted of one cold start and two hot starts. In order to achieve good repeatability for the two hot started tests, the vehicle was preconditioned prior to each test by driving at constant speed on the chassisdynamometer until the engine oil reached a stabilized temperature of approximately 90 °C. The vehicle was then idling in order to prepare and load necessary data parameters.

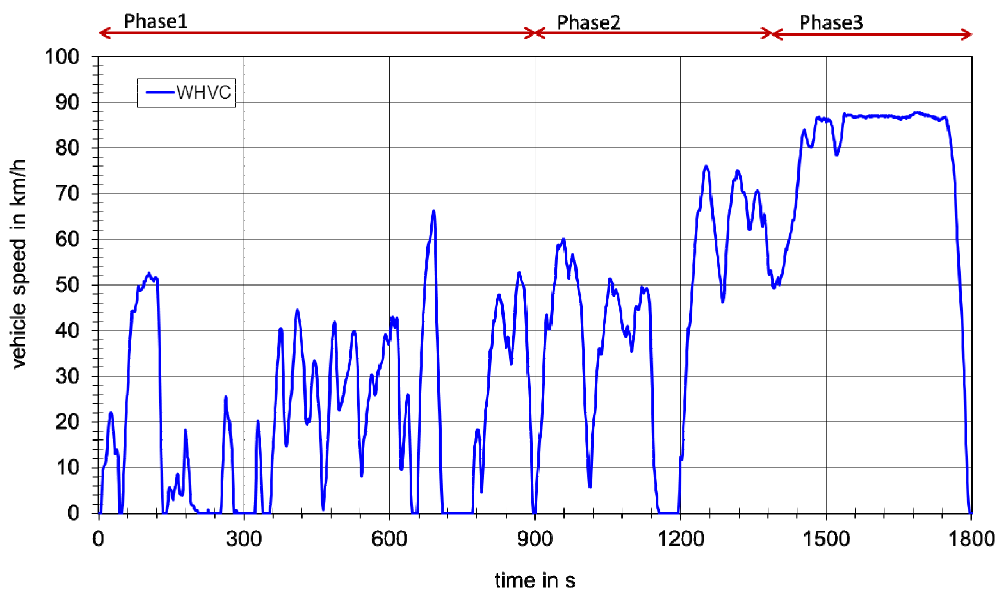

Figure 8: The WHVC test cycle – chassis dynamometer version of the WHTC cycle.

The WHVC driving cycle can be divided into three subcycles, each representing different driving patterns:

Phase 1: Urban driving (5,3 km)

Phase 2: Rural driving (5,6 km)

Phase 3: Motorway driving (9,1 km)

The test cycle has a total duration of 1800 seconds.

Test program

Two heavy duty trucks were used in the emission tests – one diesel truck, and one dedicated ED95 truck. The diesel truck was tested with five different fuels – B7 (conventional diesel fuel), B7+HVO30, HVO100, B100 and synthetic diesel (GTL).

For each of the fuels, the following tests were performed:

- 1 WHVC cold start
- 2 WHVC hot start

In connection to the fuel change, engine oil and oil filter were changed.

In order to ascertain a good adaptation to the respective fuel, the diesel vehicle was prepared by driving three WHVC after each fuel change.

The tests were performed with 50% load. For the B7 fuel the test program was extended with the addition of measurement of regulated emissions at 100% load.

Test results

The test results are presented in this chapter. In the first section, the regulated components are presented, followed by the unregulated measurements. The cold start emissions are presented first, followed by the hot start emissions and the weighted results.

The vehicles used in the test program are of emission standard Euro V. The test cycles used in this project are applicable for legislative testing of the engine, on engine test bench, from Euro VI. The test results presented in this report should not be compared with the Euro V limits.

Please observe that different y-scales are used in the diagrams.

Regulated emissions – cold start

The cold start test was performed once for each fuel, except for the B7 fuel where the fuel was used for one test with 50% load and one with 100% load. The results are presented in Table 6 and Figure 9.

Table 6: Emission test results in g/km, cold start.

		B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
CO	g/km	0,96	1,11	1,04	1,05	1,19	0,84	1,34
HC	g/km	0,02	0,01	0,01	0,00	0,00	0,00	1,52
NOx	g/km	3,61	3,47	3,29	3,29	3,18	3,58	3,62
PM	g/km	0,035	0,027	0,028	0,023	0,027	0,012	0,026

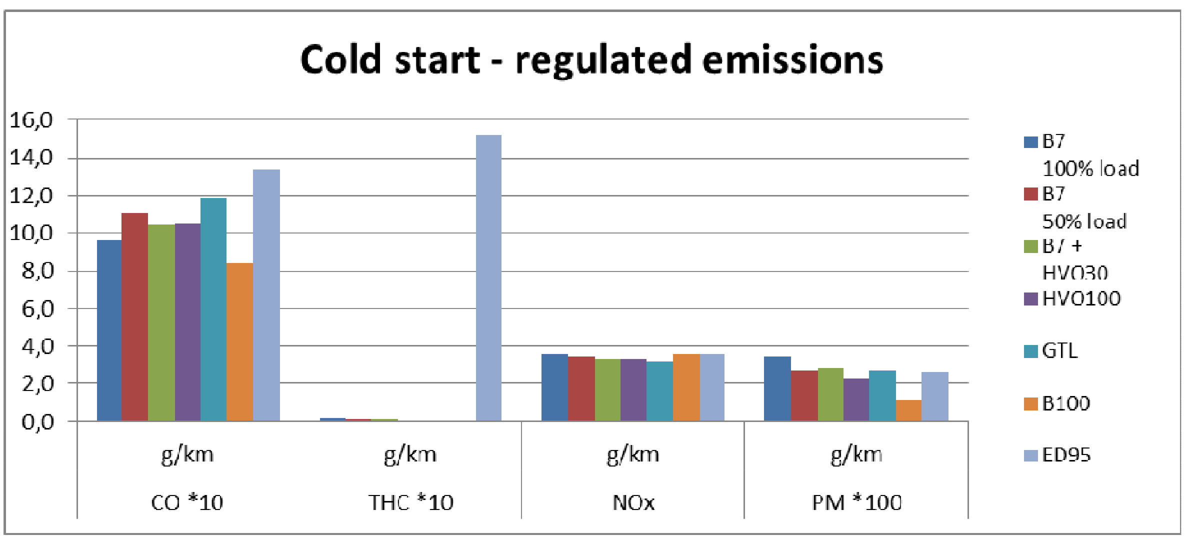

Figure 9: Regulated emissions from cold start test.

The THC emissions from the ED95 consist primarily of ethanol.

Regulated emissions – hot start

The hot start tests were performed twice for each fuel. For the B7 fuel, two tests with 50% load and with 100% load was performed. In the tables and diagrams presented in this chapter, the averaged results from the two tests are presented. The results are presented in Table 7 and Figure 10.

Table 7: Emission test results in g/km, averaged results from two hot start tests.

		B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
CO	g/km	0,88	0,82	0,80	0,77	0,88	0,66	0,11
HC	g/km	0,01	0,01	0,00	0,00	0,00	0,01	0,25
NOx	g/km	3,00	2,63	2,29	2,51	2,84	3,16	3,35
PM	g/km	0,023	0,017	0,018	0,012	0,018	0,007	0,004

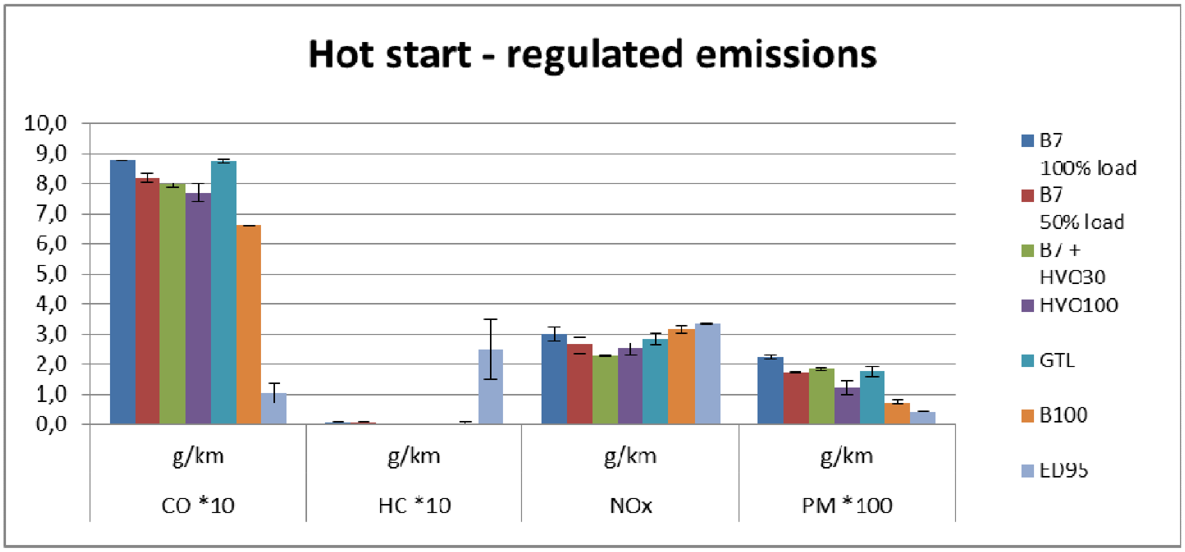

Figure 10: Regulated emissions from hot start tests, averaged from two tests.

The THC emissions from the ED95 consist primarily of ethanol.

The PM emissions from B100 are lower compared to the other fuels (with the exception of ED95). This can be explained by the increased amount of oxygen in the fuel, which can lead to more complete combustion and thereby reduce the PM emissions [6]. This explanation could probably also be applicable for the low PM emissions for the ED95 fuel.

The higher NOx emissions for B100 and ED95 can also be explained by the oxygen content in the fuel. A more complete combustion, in combination with the oxygen present, can lead to higher exhaust emissions of NOx. For B100, it can also be of relevance that no adaptation had been performed on the fuel system, such as injection timing and fuel pressure adjustments, prior to the tests [6].

Regulated emissions – weighted results

According to Regulation (EU) No 582/2011, applicable for Euro VI, the engine should be tested according to the transient cycle WHTC with one cold and one hot start. The results should be presented for the cold start, hot start and the weighted results for the two cycles.

The weighted result is calculated according to the following equation:

$$e = \frac{(0{,}14 \text{ x } m_{cold}) + (0{,}86 \text{ x } m_{hot})}{(0{,}14 \text{ x } W_{act\ cold}) + (0{,}86 \text{ x } W_{act\ hot})}$$

where:

e	specific emission, in g/kWh
m_{cold}	is the mass emission of the component in the cold start test, g/test
m_{hot}	is the mass emission of the component on the hot start test, g/test
$W_{act,cold}$	is the actual cycle work on the cold start test, kWh
$W_{act,hot}$	is the actual cycle work on the hot start test, kWh

In this study the hot start tests were repeated twice. The weighted results have therefore been counted for each of the two cycles, i.e. cold start together with hot start no 1, and cold start together with hot start no 2. The averaged results from these calculations are presented in Table 8 and Figure 11.

In the presented results, the total estimated work calculated through the method presented in Appendix has been applied.

Table 8: Weighted results for the regulated components, average from two hot start tests. Total estimated work (calculated) has been used.

		B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
CO	g/kWh	1,09	1,11	1,07	1,04	1,19	0,89	0,32
HC	g/kWh	0,01	0,01	0,01	0,00	0,01	0,01	0,69
NOx	g/kWh	3,78	3,53	3,13	3,35	3,75	4,15	3,86
PM	g/kWh	0,030	0,024	0,025	0,018	0,025	0,010	0,008

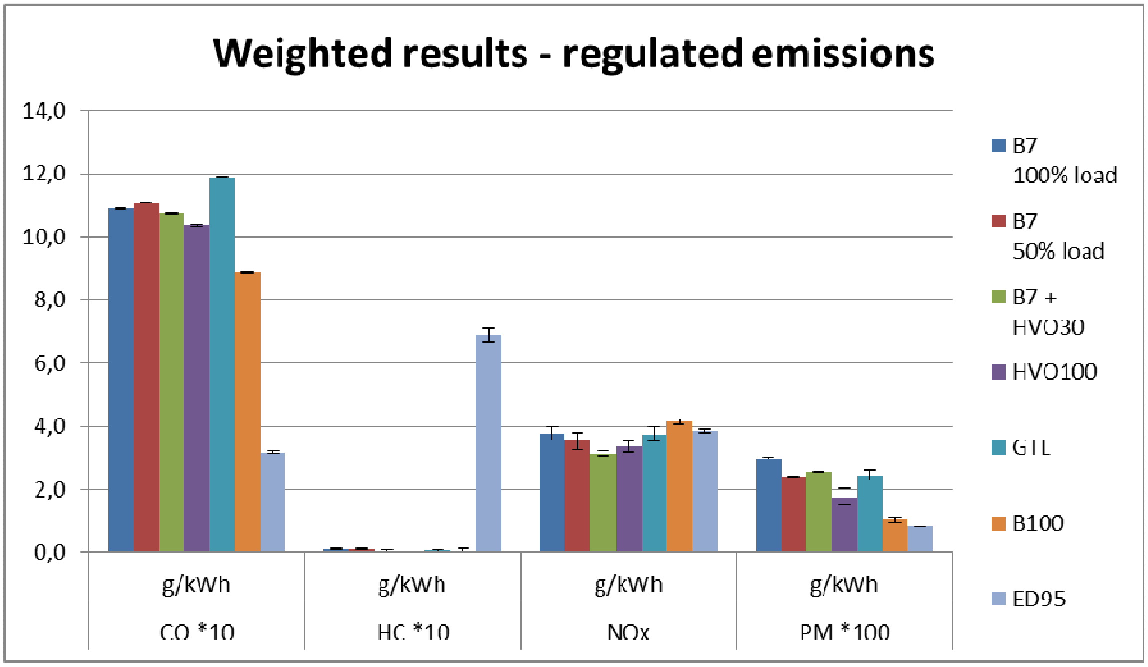

Figure 11: Weighted results for the regulated components, average from two hot start tests. Total estimated work (calculated) has been used.

CO2 emissions and fuel consumption

Cold start

The cold start test was performed once for each fuel, except for the B7 fuel where the fuel was used for one test with 50% load and one with 100% load. The test was performed once for each fuel, and the CO2 results and fuel consumption are presented in Table 9 and
Figure 12.

Table 9: CO2 and fuel consumption – cold start tests.

		B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
CO2	g/km	659,1	641,3	659,3	625,1	632,1	645,6	759,4
Fc	l/100km	24,63	23,88	24,42	25,86	25,50	23,03	51,41

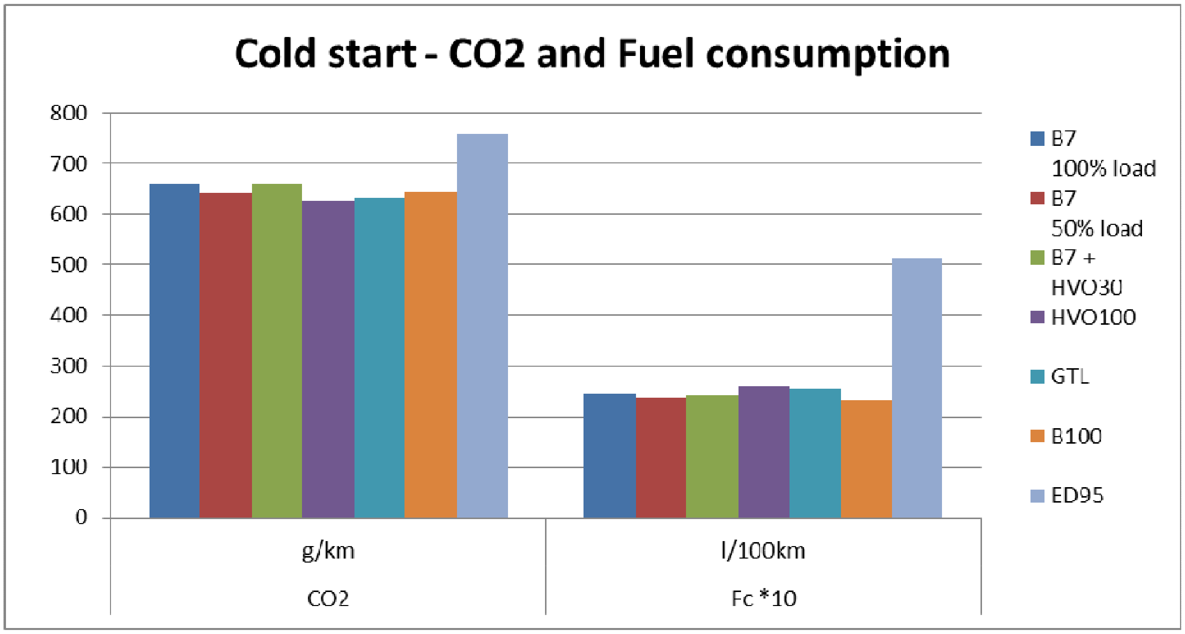

Figure 12: CO2 and fuel consumption – cold start tests.

Hot start

The hot start tests were performed twice for each fuel. For the B7 fuel, two tests with 50% load and with 100% load was performed. In the tables and diagrams presented in this chapter, the averaged results of CO2 and fuel consumption from the two tests are presented in Table 7 and Figure 13.

Table 10: CO2 and fuel consumption – hot start tests. Averaged results from two tests.

		B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
CO2	g/km	622,2	602,5	596,5	570,6	583,5	611,8	669,4
Fc	l/100km	23,76	23,01	23,30	24,74	24,14	22,53	45,84

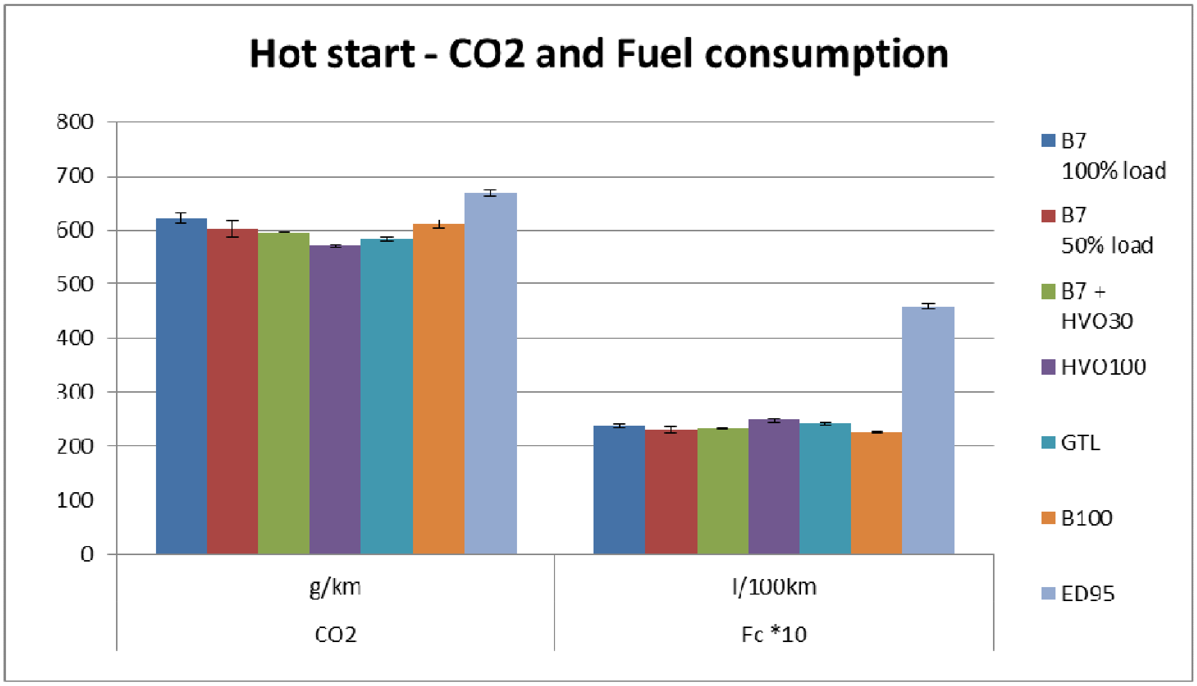

Figure 13: CO2 and fuel consumption – hot start tests. Averaged results from two tests.

Weighted results

According to Regulation (EU) No 582/2011, applicable for Euro VI, the weighted results from the cold start and the hot start WHTC should be used. The emissions of CO2 and fuel consumption should be presented in g/kWh. For the calculation, g/test is used.

In this study the hot start tests were repeated twice. The weighted results have therefore been counted for each of the two cycles, i.e. cold start together with hot start no 1, and cold start together with hot start no 2. The averaged results from these calculations are presented in Table 11 and Figure 14.

In the presented results, the total estimated work calculated through the method presented in Appendix has been applied.

Table 11: Weighted results for CO2 and fuel consumption, average from two hot start tests. Total estimated work (calculated) has been used.

		B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
CO2	g/kWh	766,6	779,5	777,0	737,7	763,2	791,5	776,1
Fc	g/kWh	244,4	248,4	247,6	235,1	243,3	252,0	427,8

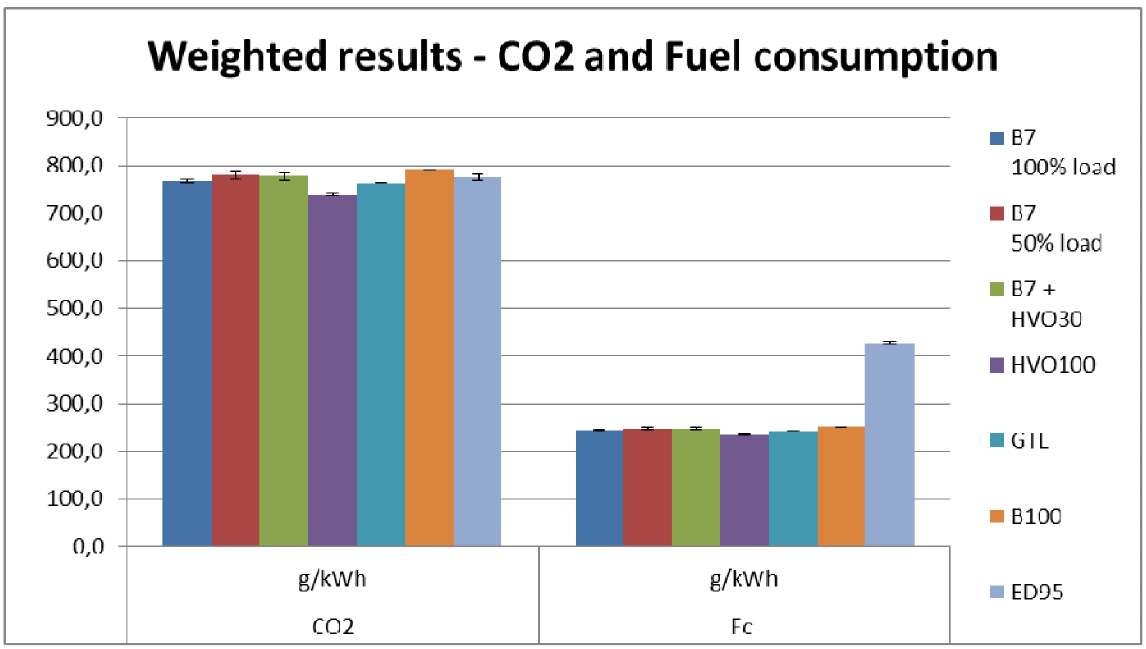

Figure 14: Weighted results for CO2 and fuel consumption, average from two hot start tests. Total estimated work (calculated) has been used.

Unregulated emissions

NO/NO2

The main components of NOx are NO and NO2. In the tests, the FTIR was used to measure NO and NO2. The test method is thorougly described in the Experimental chapter.

In Table 12 the NO and NO2 results are presented. NOx is calculated from the sum of NO and NO2. The calculated NO/NO2 ratio is presented in Table 12 and in Figure 15.

Table 12: NO and NO2 measured by FTIR. The calculated NO/NO2 ratio is presented in italic.

		WHVC	B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
NOx FTIR	g/km	Cold	3,449	3,284	3,165	3,119	3,042	3,424	3,480
NO FTIR	g/km	Cold	3,359	3,251	3,054	3,018	2,945	3,351	2,450
NO2 FTIR	g/km	Cold	0,093	0,036	0,112	0,104	0,099	0,075	1,030
Ratio NO/NO2		*Cold*	*36*	*90*	*27*	*29*	*30*	*45*	*2,4*
NOx FTIR, average	g/km	Hot	2,781	2,472	2,081	2,364	2,732	2,983	3,370
NO FTIR, average	g/km	Hot	2,768	2,465	2,070	2,346	2,713	2,967	1,920
NO2 FTIR, average	g/km	Hot	0,016	0,012	0,013	0,020	0,021	0,019	1,450
Ratio NO/NO2		*Hot*	*179*	*214*	*159*	*120*	*129*	*160*	*1,32*

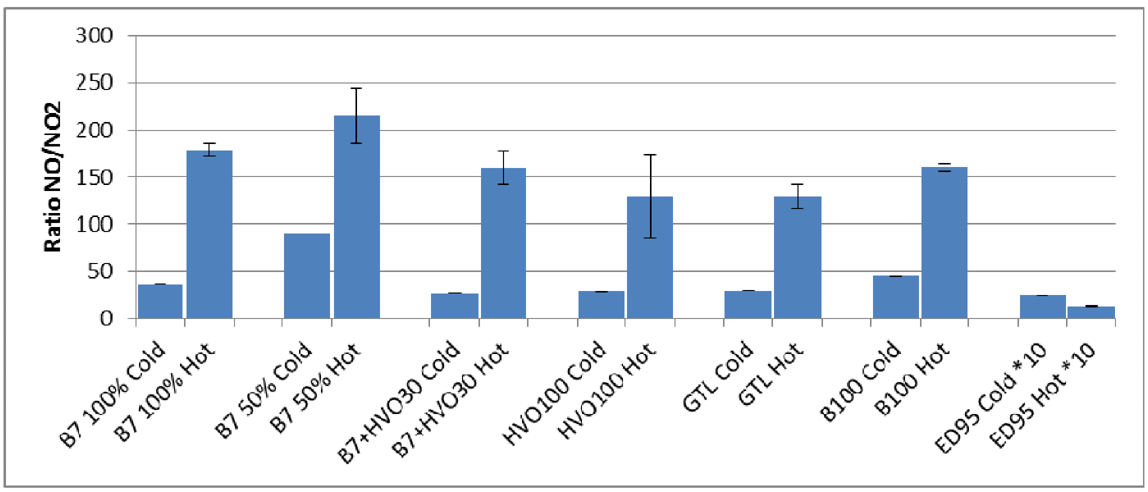

Figure 15: The calculated NO/NO2 ratio for hot and cold start tests.

Ethanol emissions

Ethanol emissions were measured with FTIR on the dedicated ED95 vehicle. The results presented in Figure 16 are from one cold start WHVC and averaged from two hot starts.

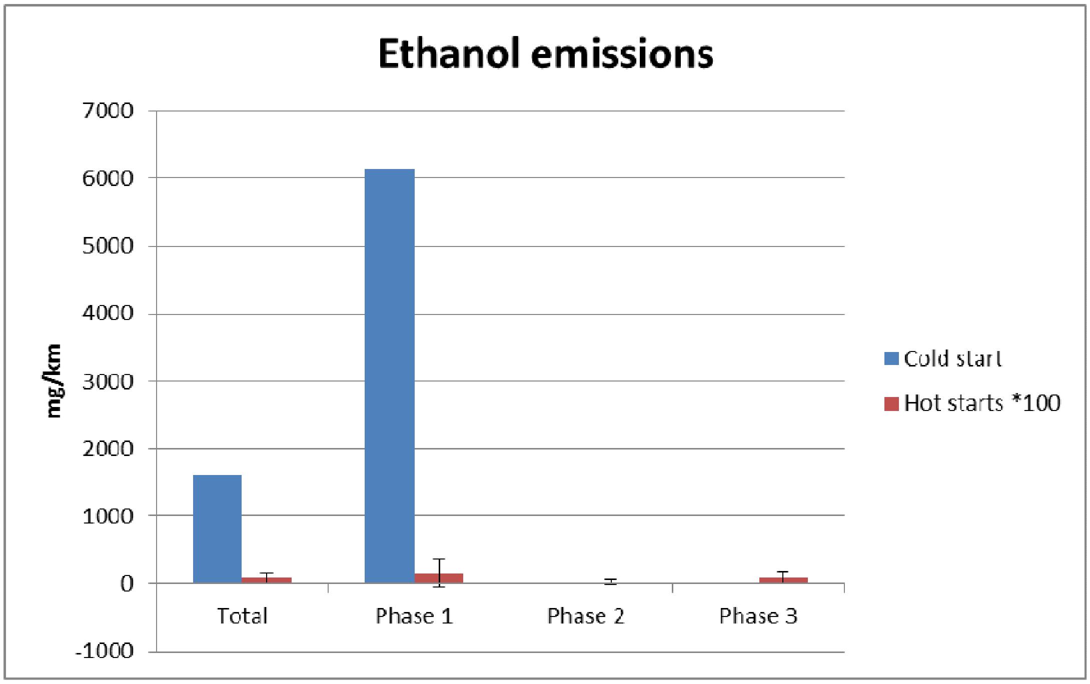

Figure 16: Ethanol emissions measured by FTIR on the ED95 vehicle. Please note the calculation factor for the hot start tests.

The cold started test yielded high ethanol emissions, where the first phase of the driving cycle dominates totally.

The ethanol emissions in the two hot started tests deviated, but the emissions were much lower compared to the cold started test.

Aldehydes

The following aldehydes were analyzed:

- Formaldehyde
- Acetaldehyde
- Acrolein
- Propionaldehyde
- Crotonaldehyde
- Metacrolein
- Butyraldehyde
- Bensaldehyde

The International Agency for Research on Cancer (IARC) [7] has classified Formaldehyde as carcinogenic to humans (Group 1), whereas Acetaldehyde has been classified as possibly carcinogenic to humans (Group 2B).

The aldehydes were sampled in DNPH-cartridges. The cartridges were analyzed at an external laboratory.

The diesel fuels are presented first, with separate diagram for cold (Figure 17 and Figure 18) and hot start (Figure 19 and Figure 20) tests. The ED95 tests are presented separately due to the higher levels of emitted aldehydes.

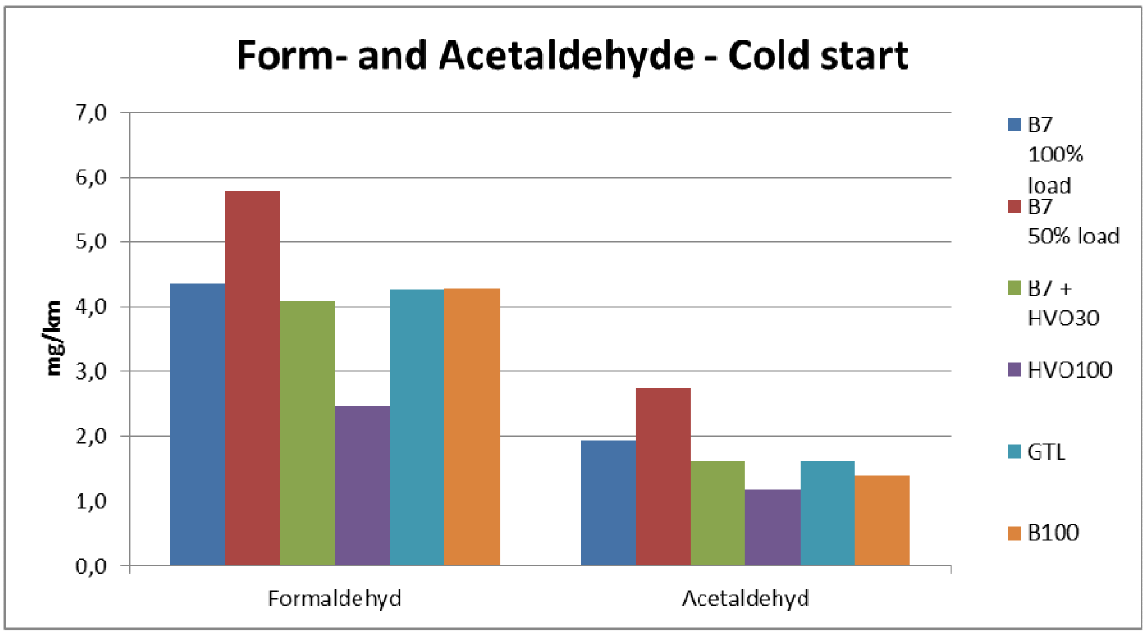

Figure 17: Formaldehyde and Acetaldehyde emissions, diesel fuels, cold start.

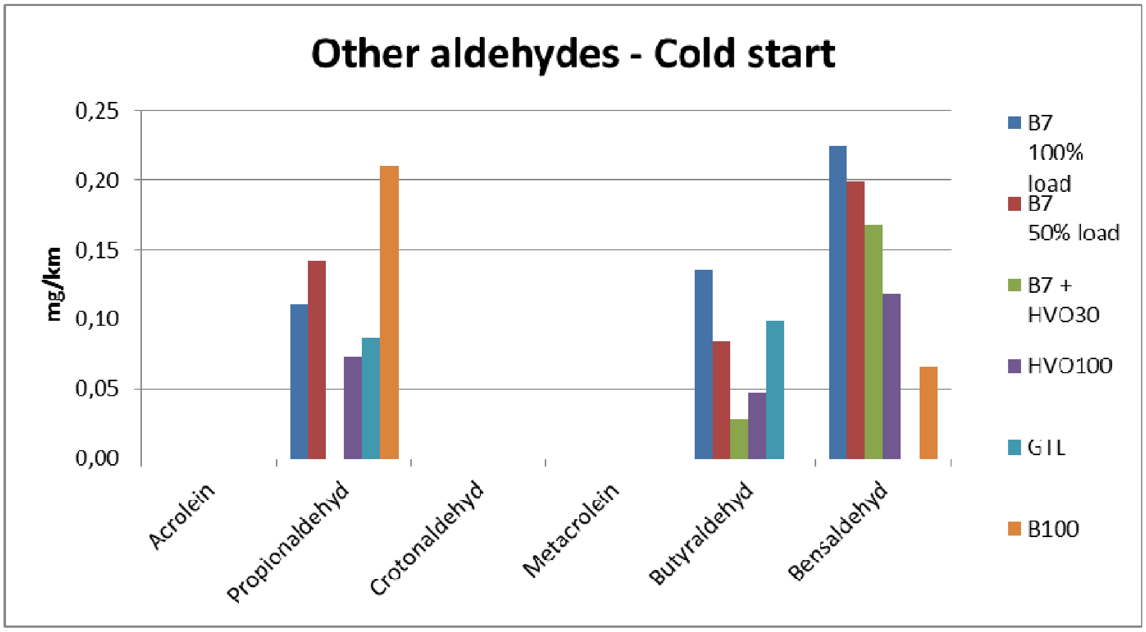

Figure 18: Emissions of other aldehydes, diesel fuels, cold start.

The aldehyde emissions from the cold start test are presented in Figure 17 and Figure 18. The aldehyde emissions are dominated by Formaldehyde and Acetaldehyde. The HVO100 generates the lowest aldehyde emissions of the compared fuels. Among the diesel fuels, the highest emissions of Formaldehyde and Acetaldehyde were from the 50% load test with B7 fuel. The results from the cold start test are generated from one emission test for each fuel. To be able to tell if the differences between the fuels are significant, the tests have to be repeated.

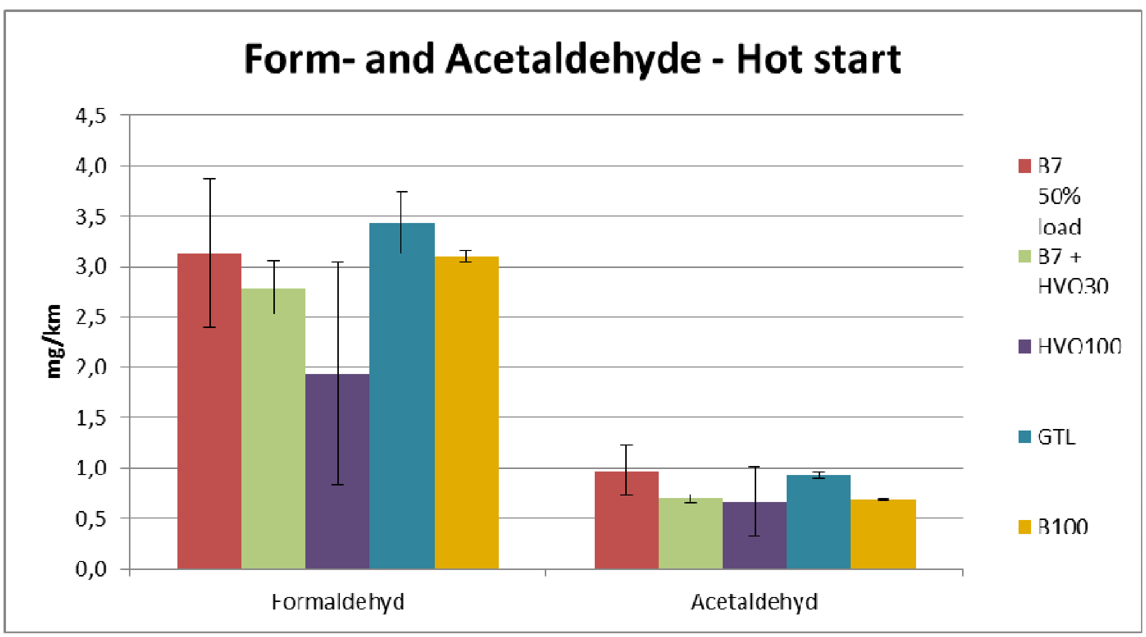

Figure 19: Formaldehyde and Acetaldehyde emissions, diesel fuels, averaged results from hot start tests.

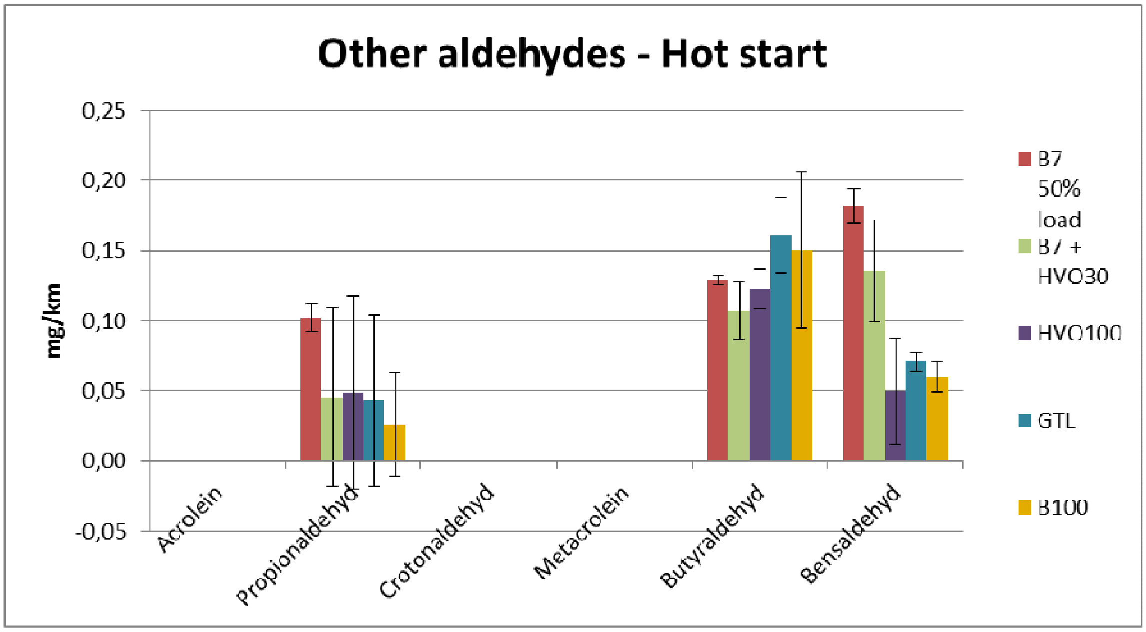

Figure 20: Emissions of other aldehydes, diesel fuels, averaged results from hot start tests.

The averaged results from the aldehyde emissions from the hot started tests are presented in Figure 19 and Figure 20. The pattern is similar to the cold start tests, with Formaldehyde and Acetaldehyde as dominating components, but the levels are decreased. In accordance to the cold start test, the HVO100 seems to generate lower emissions of Formaldehyde. The standard deviation is however large, so this difference can not be considered as significant.

The emissions of Bensaldehyde are significantly higher for the B7 50% and B7+HVO30 compared to the other fuels. These fuels have higher levels of aromatics in the fuel, and the higher levels of Bensaldehyde in the emissions are probably a reaction product from these aromatics.

Aldehydes are formed in an oxidation reaction of alcohols, such as ethanol. The levels of emitted aldehydes when the tests were performed on ED95 are therefore much higher compared to the diesel fuels. The results for the ED95 tests are presented in Figure 21 and Figure 22. Formaldehyde and Acetaldehyde are dominating and are therefore presented separately.

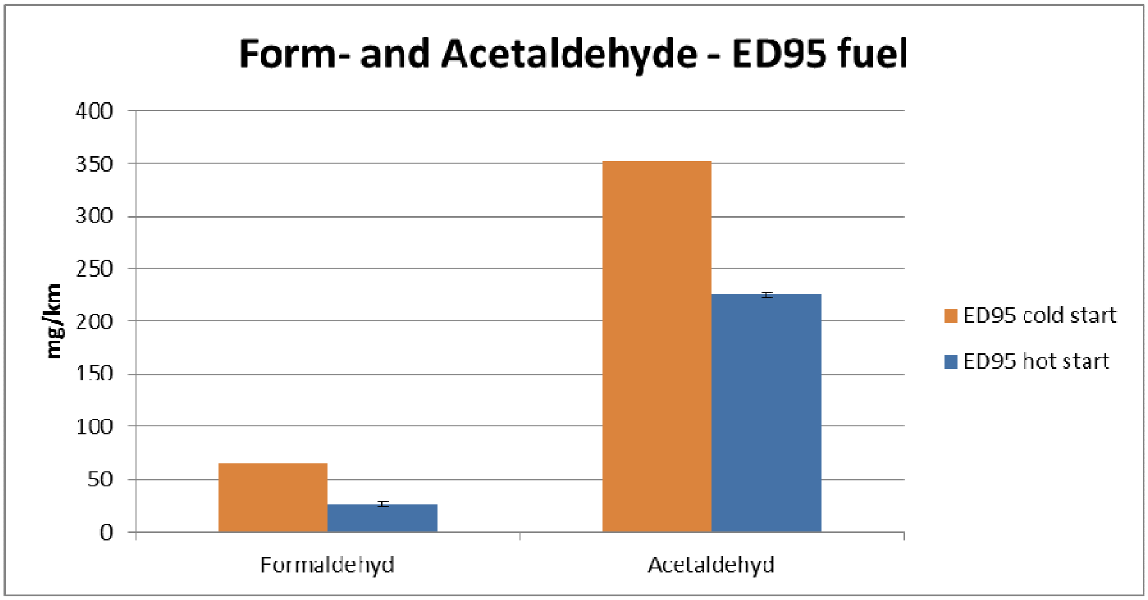

Figure 21: Formaldehyde and acetaldehyde emissions from tests using ED95 fuel – cold and hot started tests.

The aldehydes were sampled in DNPH-cartridges, two in series in order to prevent breakthrough. However, during the analysis of the cartridges from the ED95 tests, high levels of Acetaldehyde were observed also in the second cartridge. There is therefore a possibility that the actual Acetaldehyde emissions are higher than presented in this study.

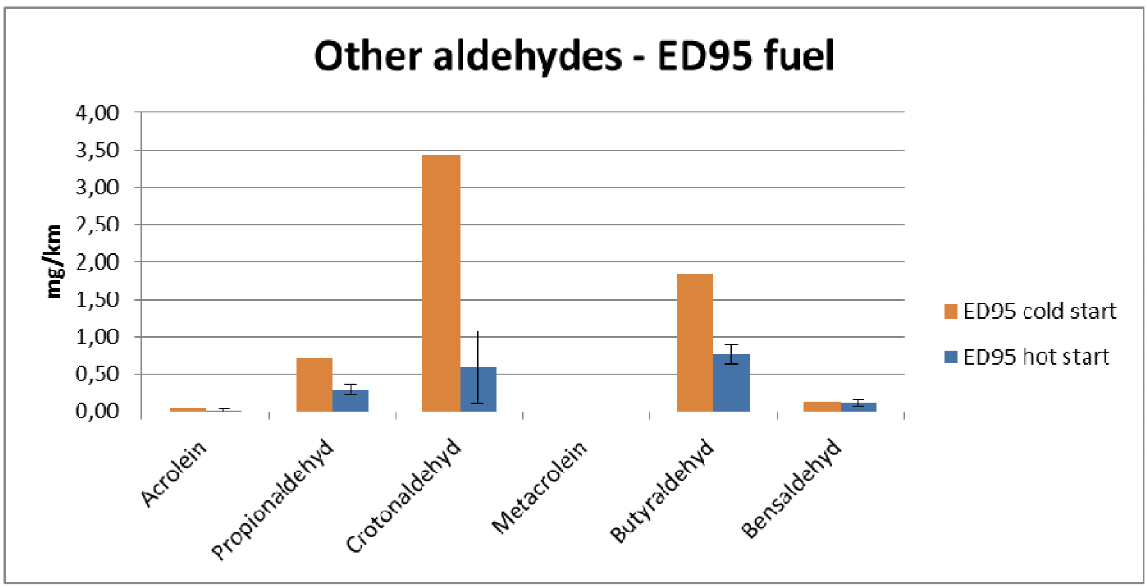

Figure 22: Other aldehydes from tests using ED95 fuel – cold and hot started tests.

In conformity with the emissions of Formaldehyde and Acetaldehyde from the ED95 testing, the other aldehydes analysed in this study are also at higher levels compared to the diesel fuel testing.

Metacrolein was not present in any of the tests.

Particle number

The particle number emissions were measured with CPC (Condensed Particle Counter). The CPC measures particles in the size span of 23 nm to 2,5 m. For further details, please see instrument description in the Experimental chapter.

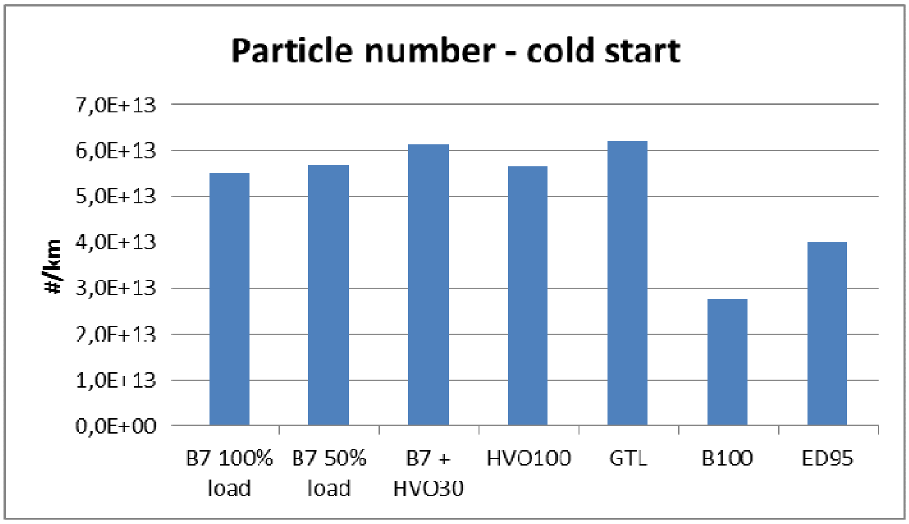

Figure 23: Particle number – cold start test.

The particle number from the cold start tests are presented in Figure 23. For the particle size span measured by the CPC, the B100 fuel generated the lowest number of particles. The particle number emissions from the ED95 fuel was lower compared to the diesel fuels, with the exception of the B100 fuel. The lower PN emissions for B100 and ED95 can probably be explained by the higher amount of oxygen in the fuel, which can lead to more complete combustion.

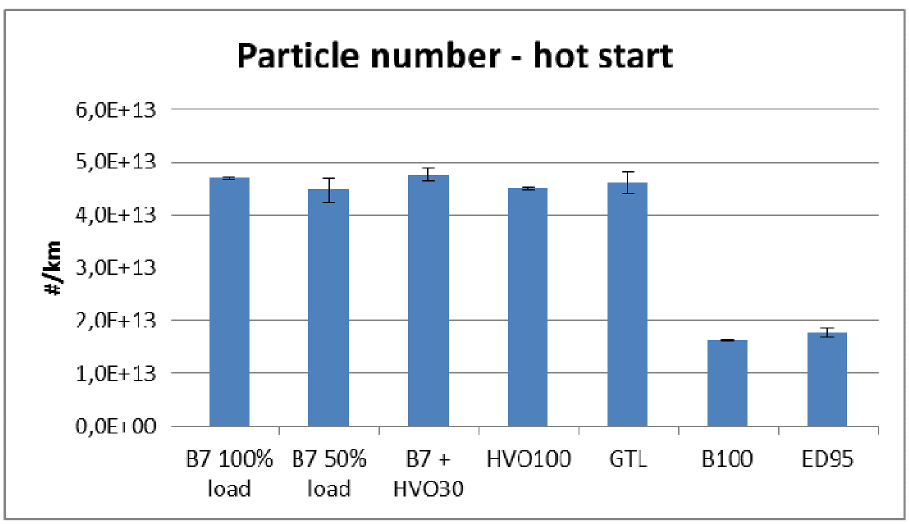

Figure 24: Particle number – averaged results from hot start tests.

The averaged results from particle number from the hot start tests are presented in Figure 24. The B100 and ED95 generated significantly lower levels of particles compared to the other fuels in this investigation.

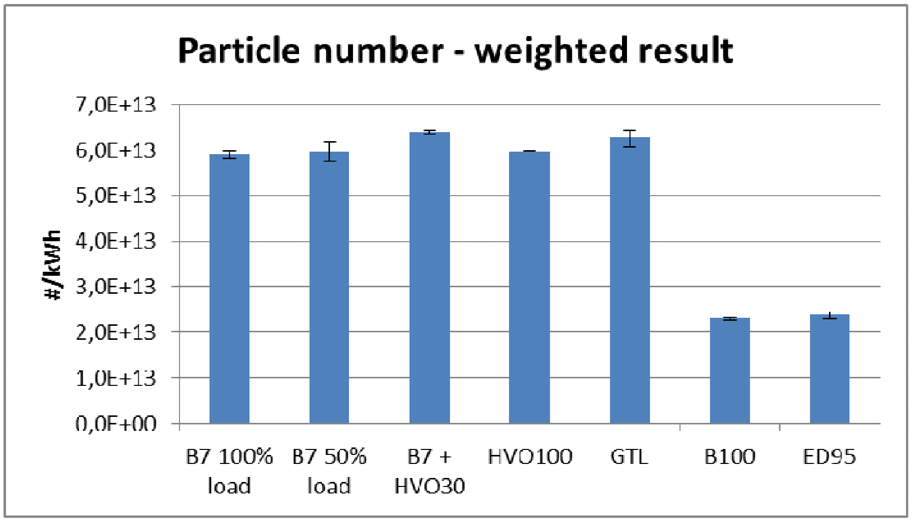

Figure 25: Particle number – average weighted results. Presented in #/kWh, where the total estimated work (calculated) has been used.

The average results from the weighted emissions of particle number are presented in Figure 25. The results are presented in #/kWh, where the total estimated work calculated through the method presented in Appendix has been applied.

Similar pattern can be observed as for the cold and hot starts, with significantly lower levels of particle numbers for the B100 and ED95 fuels.

The particle emissions are reduced for B100 and ED95 both regarding mass (PM) and number (PN). One explanation for the reduction of particles for B100 can be the increased amount of oxygen in the fuel, which can lead to more complete combustion and thereby reduce the particle emissions [6]. This explanation could probably also be applicable for the lower particle emissions for the ED95 fuel.

Particle size distribution

The particle size distribution was measured with an ELPI (Electrical Low Pressure Impactor) instrument. The particles are separated in the impactor in 12 stages according to their aerosol size. The lowest stage collects particles from 7 nm. The specification for the instrument is described in the Experimental chapter.

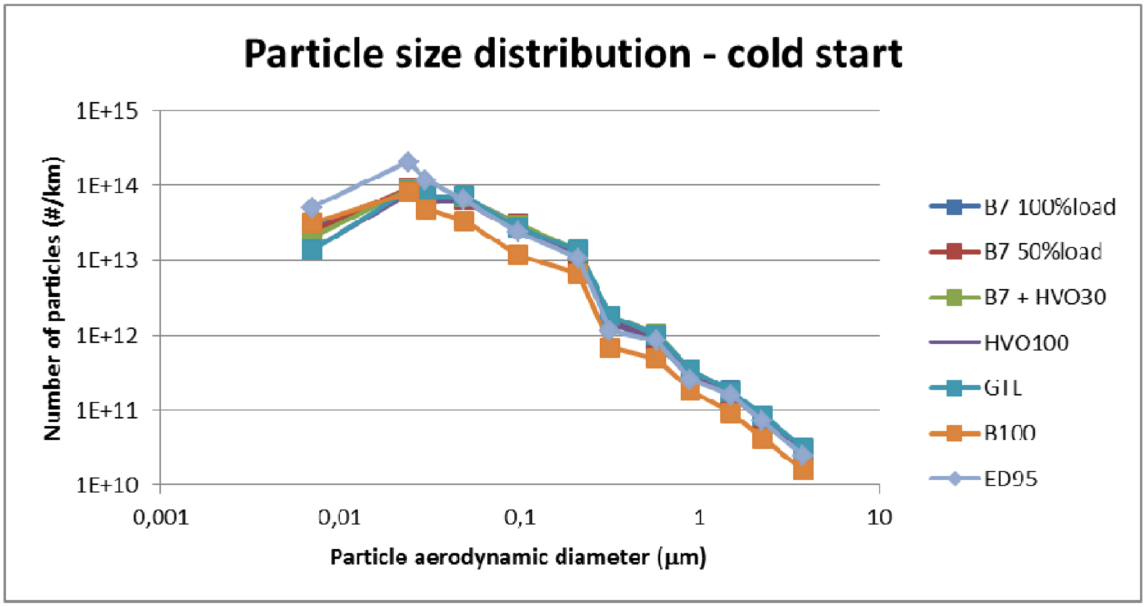

Figure 26: Particle size distribution – cold start. Number of particles per km.

The size distribution of particles emitted during the cold start test is presented in Figure 26. For the smallest particle sizes, the ED95 test had the highest amount. This is in agreement with the findings presented by VTT [8]. In the larger size stages the emitted particles are at the same level for all of the fuels, with the exception of B100 with lower emission levels.

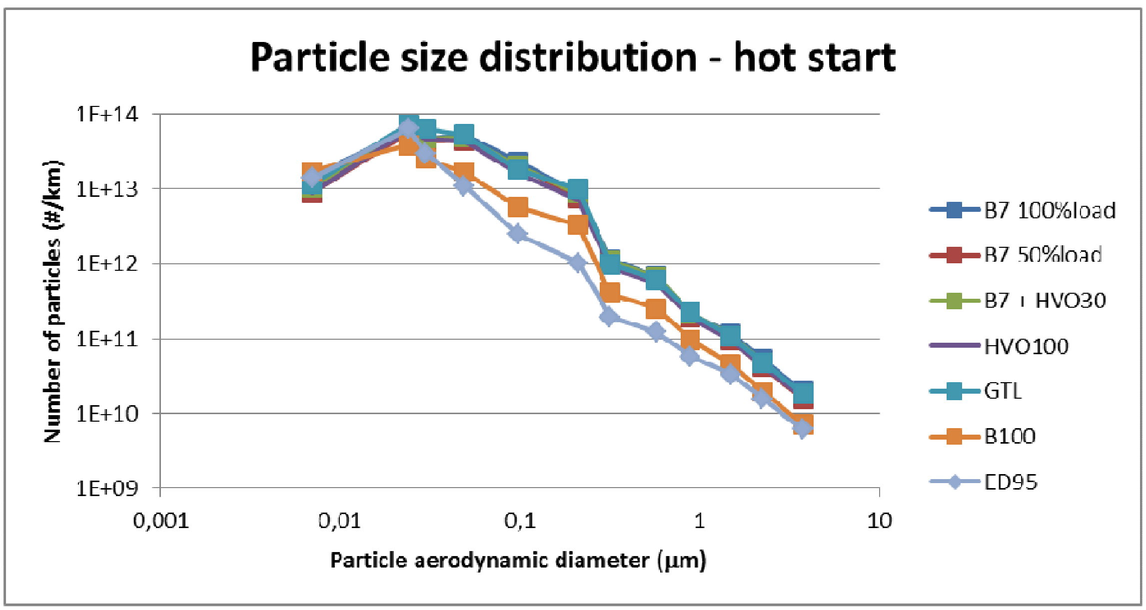

Figure 27: Particle size distribution – hot start tests. Number of particles per km.

The particle size distribution from the hot start tests are presented in Figure 27. The number of particles emitted during the hot start tests are reduced, compared to cold start. For the larger particles sizes, the B100 and ED95 tests are distinguished with lower levels of emitted particles. The reduction of particles for B100 can be explained by the higher amount of oxygen in the fuel, leading to improved combustion and reduction of particle emissions [6]. This explanation could probably also be applicable for the lower particle emissions for the ED95 fuel.

Polycyclic Aromatic Hydrocarbons (PAH)

PAH are compounds with relatively high molecular weight. These compounds can be found condensed on particles and in gaseous phase. The particle associated compounds were collected on a large filter and the PAH in gaseous phase were collected in polyurethane foam (PUF) plugs. The dominating part of the PAH collected in the semivolatile phase are comparatively lighter PAH compounds (up to molecular weights of approximately 200 g/mole), whereas the PAH collected on the filters consists of both lighter and heavier PAH compounds. The filters and foam plugs were extracted and analysed separately to distinguish between the different phases. The extracts were chemically characterized and different PAH compounds could be identified.

For an easier overview, the analyzed compounds have been summarized for the respective phase (filter and semivolatile). The total emissions of the analyzed PAH from the cold start test are presented in Figure 28 and Figure 30, whereas the total emissions from the hot start tests are presented in Figure 29 and Figure 31. In these overviews there has not been any distinction between the different PAH compounds. The characteristics differ, as well as the effect on environment and human health. Complete lists of the analyzed compounds can be found in Appendix.

The PAH in the emissions can be derived from unburned residues of fuel, as a byproduct from the combustion or from the engine oil. According to the fuel specifications, the diesel fuels denoted B7 and B7+HVO30 have higher total aromatic content. This is is also reflected in the filter phase of the particle extracts presented in Figure 28 (cold start) and Figure 29 (hot start), with somewhat elevated levels. The difference in the hot start tests is however not significant, due to the high standard deviations.

The B100 fuel shows the lowest emissions for summarized PAH in filter phase in the cold start test. In the hot start tests, the summarized PAH in filter phase for B100 is significantly lower compared to the B7 fuel.

With the exception of B100, the summarized PAH emissions in filter phase shows no major differences between the fuels.

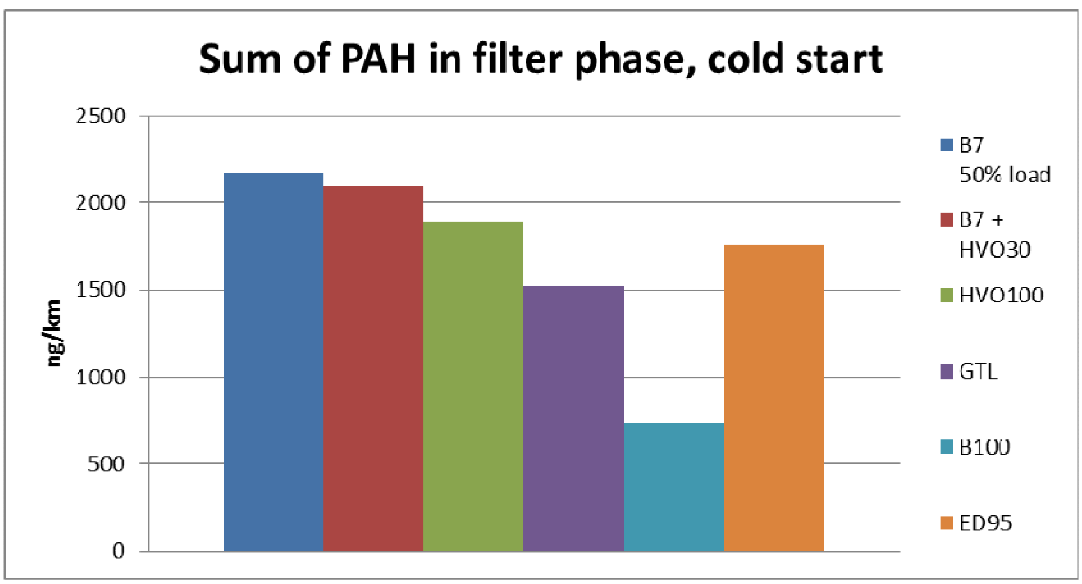

Figure 28: Total emissions of analyzed PAH in filter phase, cold start.

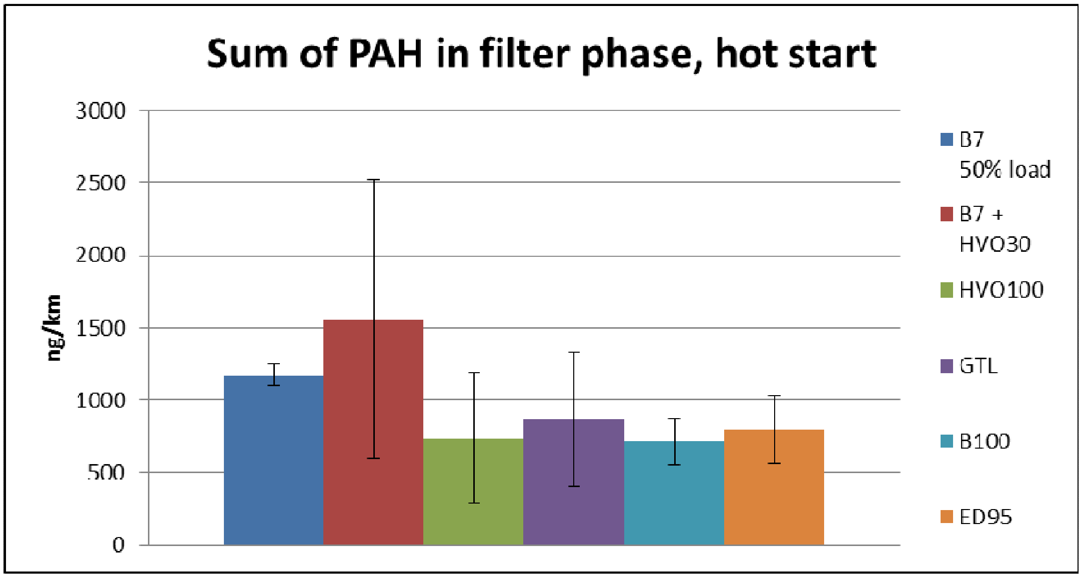

Figure 29: Total emissions of analyzed PAH in filter phase, averaged results from the hot start tests.

The summarized emissions of PAH in semivolatile phase is presented in Figure 30 (cold start) and Figure 31 (hot start). In the cold start test, the HVO100 and ED95 fuels show elevated levels compared to the other fuels.

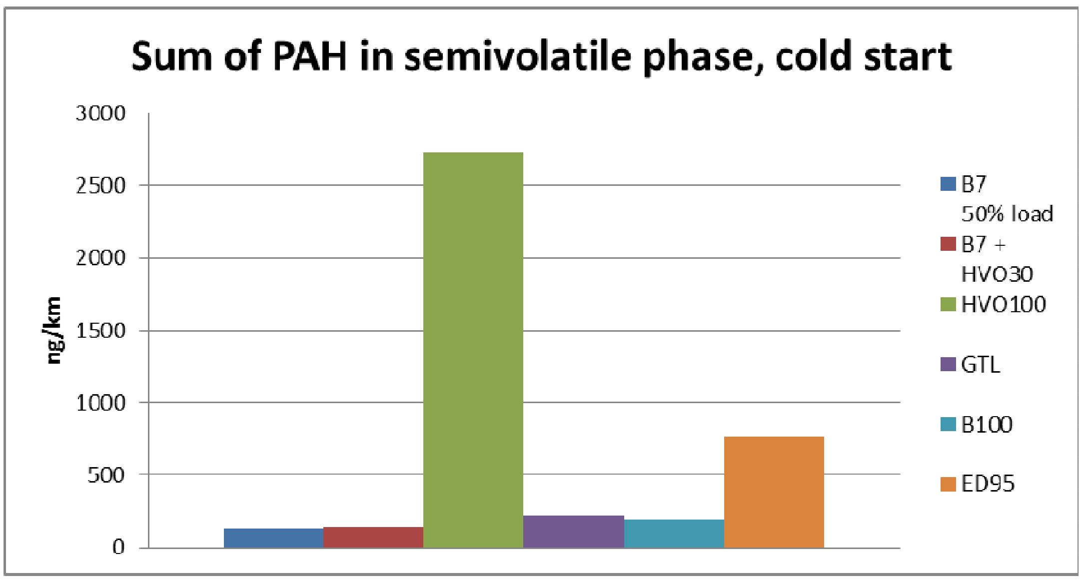

Figure 30: Total emissions of analyzed PAH in semivolatile phase, cold start.

For the HVO fuel test with cold start, the PAH emissions in semivolatile phase consists almost exclusively of Benzo(c)phenanthrene. A literature survey could not give any specific information on this PAH compound from emission measurement studies, and no conclusive evidence of mutagenic effect could be found.

In the hot start tests, the GTL and B7 fuels have the lowest levels of summarized PAH in semivolatile phase. The GTL fuel is significantly lower in these tests compared to HVO100 and ED95. No significant differences could be distinguished for the other fuels due to the high standard deviations.

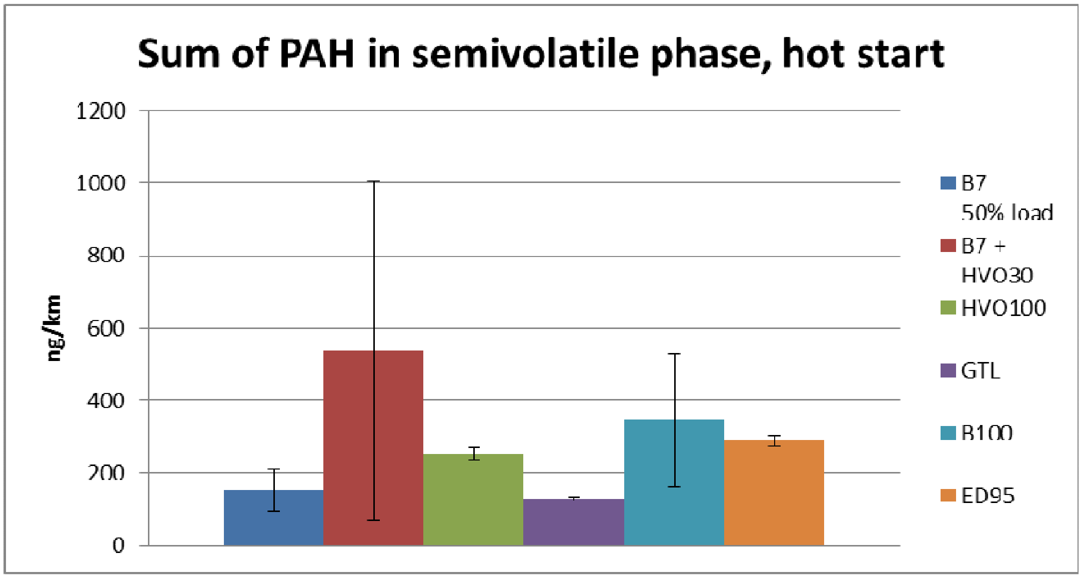

Figure 31: Total emissions of analyzed PAH in semivolatile phase, averaged results from the hot start tests.

PAH and Toxic Equivalence

The PAH group consists of many different compounds with varying characteristics. Some PAHs have been more thoroughly investigated regarding health effects.

The US EPA uses a theoretical method where the potential effects of some compounds have been translated into Toxic Equivalence Factors (TEF). The factor is established through toxicological studies. This method assumes that compounds have additive effect, and that the effect is linear. Some of the investigated PAHs are presented in Table 13 together with their TEF values. Please note that the list is not complete and the TEFs can be updated or changed.

Table 13: Toxic Equivalence Factors for some PAH [9].

PAH	TEF
Anthracene	0,01
Benzo(a)pyrene	1
Benzo(b)fluoranthene	0,1
Benzo(k)fluoranthene	0,05
Dibenzo(a,e)pyrene	0,2
Dibenzo(a,h)pyrene	1
Dibenzo(a,i)pyrene	1
Dibenzo(a,l)pyrene	100
Fluoranthene	0,05
Phenanthrene	0,0005
Pyrene	0,001

The TEF can be used to calculate TEQ (Toxic Equivalence) which is described as the potency to induce cancer. The factor for respective compound is multiplied by the emission in ng/km for the specific compound. The products are thereafter summarized to achieve the TEQ value for the emission test.

The TEQ values for the PAH compounds listed in Table 13 were calculated, and the results from the filter phase are presented in Figure 32 and Figure 33. The TEQ results from the semivolatile phase are presented in Figure 34 and Figure 35.

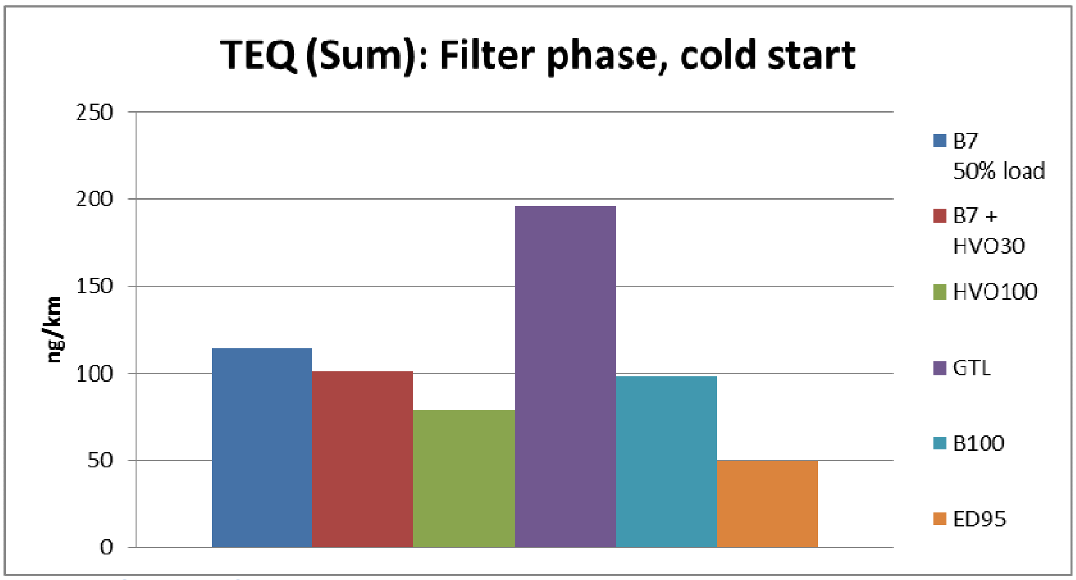

Figure 32: Sum of TEQ for the filter phase, cold start test.

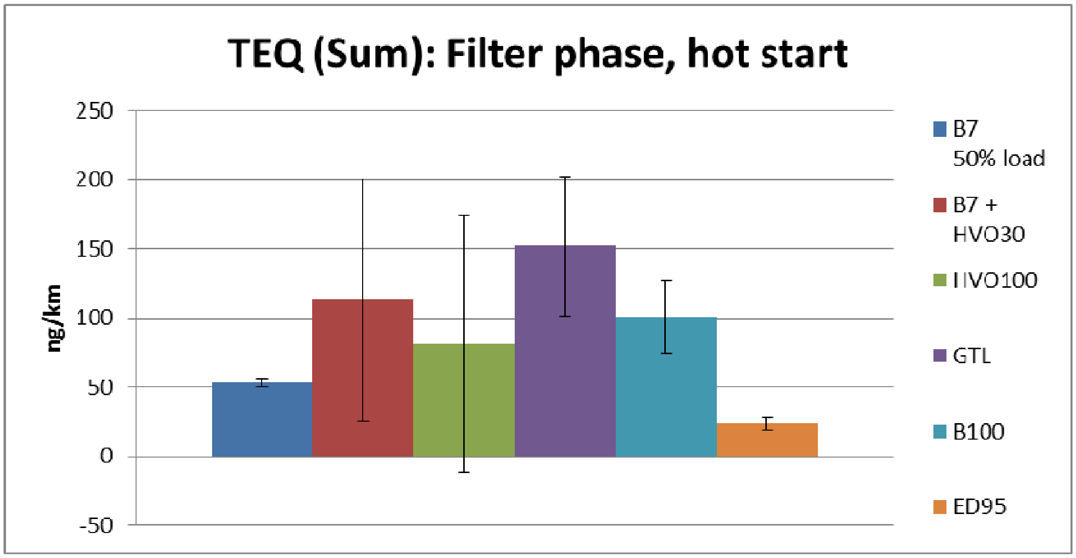

Figure 33: Sum of TEQ for filter phase, average of hot start tests.

For the filter phase, the summarized TEQ values in the cold start test are higher for the GTL fuel and lower for the ED95 fuel – compared to the other fuels. For the hot start tests, the ED95 is significantly lower than B7. For the other fuels, the standard deviations are too high to distinguish significant differences.

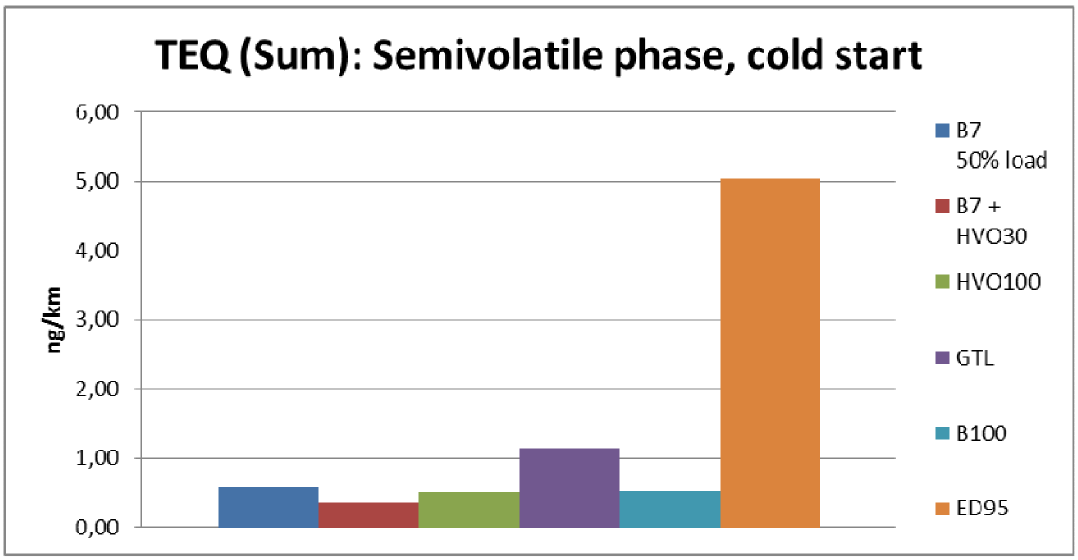

Figure 34: Sum of TEQ for semivolatile phase, cold start test.

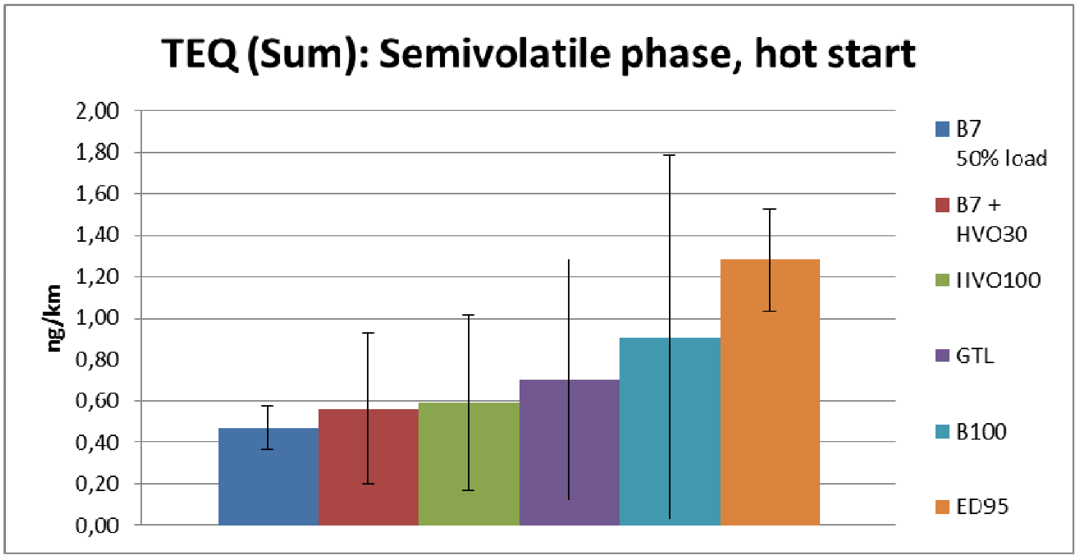

Figure 35: Sum of TEQ for semivolatile phase, average of hot start tests.

For the semivolatile phase, consisting of lighter PAHs, the summarized TEQ values are very low for all fuels. The ED95 shows comparatively high TEQ values both at cold start and hot start, and is significantly higher than B7.

Health effect studies are complex, and the results are dependent on the endpoints in the studies. It is not adviceable to draw conclusions regarding health effects only from TEQ results, but Toxic Equivalence Factors could be useful as a screening method. High TEQ values for exhaust emissions from a fuel should be followed up with more thorough health effect studies.

Discussion

The climate impact from the transport sector needs to be reduced. The sector is however diverse and there is a need to approach the problems in several ways. Stricter emission standards will reduce the regulated emissions in the future, but for the heavy duty sector, the fleet will consist of vehicles from different emissions standards. The fuels available on the market have however the potential to effect the emissions from the existing vehicle fleet.

The heavy duty sector is dominated by the compression ignited engine, due to its higher efficiency. By influencing the fuels used for these vehicles, the climate impact can be substantial. It is however important to investigate the climate impact in combination with other aspects affecting environment and health.
In this study, totally six fuels for compression ignited engines have been investigated. The following fuels were used – B7 (conventional diesel fuel), B7+HVO30, HVO100, synthetic diesel (GTL), B100 and ED95. The B7+HVO30, HVO100 and the synthetic diesel (GTL) are so-called drop-in fuels, i.e. fuels that can be used in existing engines. The B100 can be used in existing vehicles with some adjustments, whereas the ED95 fuel can be used in dedicated vehicles.

The regulated components and CO2 have been measured. In addition, some unregulated components were also investigated: Aldehydes were sampled in DNPH-cartridges; ethanol emissions were measured with FTIR during the tests with the ED95 fuel; particle numbers were counted with a CPC; particle size distribution was analyzed with an ELPI instrument and the PAH content in the particles were analyzed.

For the majority of the analyzed components, there are no major differences in emission levels compared to the conventional diesel fuel. Some exceptions are the higher levels of aldehydes (mainly Formaldehyde and Acetaldehyde) emitted by the ethanol fuelled vehicle, both during cold and hot started tests. The ethanol vehicle showed higher levels of ultrafine particles in the cold start test, but had lower levels than conventional diesel for the larger particles during hot start test. The B100 fuel had overall lower particle levels in all size stages.

The general conclusion is that none of the investigated fuels have any major negative impact on the components analyzed in this study. The included fuels contain components which have the possibility to come from renewable sources, and an increased usage can have a positive impact on the climate.

Regarding the emissions, it is however clear that the effects of fuel change are limited for the investigated fuels. To reduce the levels of regulated components, the introduction of engines which can meet more stringent emission legislation are needed. It will however still be important to analyze components which can have negative impact on health and environment, and which are not regulated in the emission legislations.

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Appendix

The diesel fuel specifications are included in Appendix. For the synthetic diesel, typical analysis data is presented.

Diesel fuel specification: B7

Properties	Results	Units	Ref. Test Methods
Appearance at 20°C	1	rating	ASTM D 4176-04
Appearance at 20°C	BRIGHT AND CLEAR		Visual inspection
Aromatic content	4,7	% V/V	SS 15 51 16:1993
Ash content	< 0,010	% m/m	SS-EN ISO 6245:2003
Carbon residue (on 10% dist res)	< 0,20	% m/m	SS-EN ISO 10370:1996
Cetane index	50,7	-	SS-EN ISO 4264:2007
Cetane number	55,0		SS-EN ISO 5165:1998
Cloud point	-30	°C	SS-EN 23015:1994
Cold Filter Plugging Point	-32	°C	SS-EN 116:1999
Colour (ASTM scale)	< 0,5		SS-ISO 2049:1997
Conductivity	800	pS/m	SS-ISO 6297:1998
Cu strip corrosion (3h at 50°C)	1A		SS-EN ISO 2160:1998
Density at 15°C	822,0	kg/m3	SS-EN ISO 12185 T1:99
Dist: IBP	182,0	°C	SS-EN ISO 3405:2011
Dist: Temp. at 95% V/V rec.	318,5	°C	SS-EN ISO 3405:2011
FAME content	8,7	% V/V	SS-EN 14078:2009
FAME content	7,0	% V/V	SS-EN 14078:2009
Flash point	71,0	°C	SS-EN ISO 2719:2003
Lubricity (WSD 1.4) at 60°C	< 400	µm	SS-EN ISO 12156-1:06
Oxidation stability	< 25	g/m3	SS-EN ISO 12205:1996
PAH content	0,02	% V/V	SS 15 55 16:1993
Sulphur content	< 3	mg/kg	SS-EN ISO 20884:2011
Total contamination	< 24	mg/kg	SS-EN 12662:2008
Water content	58	mg/kg	SS-EN ISO 12937:2001
Viscosity at 40°C	2,151	mm2/s	SS-EN ISO 3104/AC:99

Results according to ISO 4259

Diesel fuel specification: B7+HVO30

Properties	Results	Units	Ref. Test Methods
Appearance at 20°C	1	rating	ASTM D 4176-04
Appearance at 20°C	BRIGHT AND CLEAR		Visual inspection
Aromatic content	4,7	% V/V	SS 15 51 16:1993
Ash content	< 0,010	% m/m	SS-EN ISO 6245:2003
Carbon residue (on 10% dist res)	< 0,20	% m/m	SS-EN ISO 10370:1996
Cetane index	56,5	-	SS-EN ISO 4264:2007
Cetane number	63,8		SS-EN ISO 5165:1998
Cloud point	-8	°C	SS-EN 23015:1994
Cold Filter Plugging Point	-13	°C	SS-EN 116:1999
Colour (ASTM scale)	< 1,0		SS-ISO 2049:1997
Conductivity	850	pS/m	SS-ISO 6297:1998
Cu strip corrosion (3h at 50°C)	1A		SS-EN ISO 2160:1998
Density at 15°C	822,5	kg/m3	SS-EN ISO 12185 T1:99
Dist: IBP	193,9	°C	SS-EN ISO 3405:2011
Dist: Temp. at 95% V/V rec.	326,6	°C	SS-EN ISO 3405:2011
FAME content	7,0	% V/V	SS-EN 14078:2009
Flash point	73,0	°C	SS-EN ISO 2719:2003
Lubricity (WSD 1.4) at 60°C	< 400	µm	SS-EN ISO 12156-1:06
Manganese content	NOT ADDED		--
Oxidation stability	< 25	g/m3	SS-EN ISO 12205:1996
PAH content	< 0,02	% V/V	SS 15 55 16:1993
Sulphur content	< 3	mg/kg	SS-EN ISO 20884:2011
Total contamination	< 24	mg/kg	SS-EN 12662:2008
Water content	52	mg/kg	SS-EN ISO 12937:2001
Viscosity at 40°C	2,520	mm2/s	SS-EN ISO 3104/AC:99
Renewable content	27,1 *	% V/V	Intern
* innan tillsatt 7% FAME			

Results according to ISO 4259

Diesel fuel specification: HVO100

Physical property	Method	Unit	Sample 1.
Density at 15°C	ENISO12185	kg/m3	778,6
Cloud point with the ISL mini automatic device	ASTMD7689	°C	-37
Cold filter plugging point	EN116	°C	-40
Viscosity at 20 °C	ENISO3104	mm2/s	4,360
Viscosity at 40 °C	ENISO3104	mm2/s	2,831
Sulphur, UV	ENISO20846	mg/kg	<1
Water colouometric	ENISO12937	mg/kg	17
Flash point, Pensky Martens	ENISO2719	°C	83,0
Copper Corrosion 3 h 50 °C	ENISO2160	no	1a
Contamination	EN12662	mg/kg	3
Ash, 775°C	ENISO6245	wt-%	<0,001
Aniline point	ISO2977	°C	96,3
Cetane index	ENISO4264		>56,5
Micro Carbon Residue 10% bottom	ENISO10370	wt-%	<0,01
Acidity Total (TAN)	ASTMD3242	mg KOH/g	0,001
Monoaromatics	EN12916	wt-%	0,2
Diaromatics	EN12916	wt-%	<0,1
Tri+-aromatics	EN12916	wt-%	<0,10
Polyaromatics	EN12916	wt-%	<0,1
Aromatics	EN12916	wt-%	0,2
Gross heat of comb. calor.	ASTMD4809	MJ/kg	47,169
Oxidation stability	ENISO12205	g/m3	24
Carbon, C	ASTMD5291	wt-%	84,5
Hydrogen	ASTMD5291	wt-%	15,1
High Frequency Reciprocating Rig	ENISO12156-1	µm/60°C	341
Cetane Number by IQT-analyser	ASTMD6890		77,0
Distillation IBP	ENISO3405	°C	186,8
Distillation 5 vol-%	ENISO3405	°C	237,8
Distillation 10 vol-%	ENISO3405	°C	254,6
Distillation 20 vol-%	ENISO3405	°C	267,0
Distillation 30 vol-%	ENISO3405	°C	272,2
Distillation 40 vol-%	ENISO3405	°C	275,2
Distillation 50 vol-%	ENISO3405	°C	277,4
Distillation 60 vol-%	ENISO3405	°C	279,8
Distillation 70 vol-%	ENISO3405	°C	282,2
Distillation 80 vol-%	ENISO3405	°C	285,3
Distillation 90 vol-%	ENISO3405	°C	289,7
Distillation 95 vol-%	ENISO3405	°C	293,9
Distillation FBP	ENISO3405	°C	302,1
Distillation Recovery	ENISO3405	vol-%	97,7
Distillation Residue	ENISO3405	vol-%	2,3

Diesel fuel: GTL

Analysis	Unit	Method	Result	Uncertainty
Density at 15°C	kg/m3	*SS-EN-ISO 12185-96	802,4	0,35
Aromatics	%mass	EN 12916-2000	<0,5	
Polyaromatics di and higher			<0,1	
Ash	%mass	*SS-EN-ISO 6245-2003	<0,001	0,0057
Carbon Residue on 10% residue	%mass	EN-ISO 10370-96	<0,03	0,041
Cetane index		*EN-ISO 4264	66,7	2,67
Cetane Number		*SS-EN-ISO 5165-98	52,2	
DFPP	°C	*EN 116-98	<-35	
Cloud Point	°C	SS-EN 23015-94m	<-35	
Copper corrosion 3h at 50°C		*EN-ISO 2160-98	1A	
Distillation		*EN-ISO 3405-11		
Recovered at 180°C	%vol			
Recovered at 250°C	%vol		43,6	
Recovered at 350°C	%vol		95,4	
95% Recovered at	°C		345,6	
Flash point (proc. A)	°C	*EN-ISO 2719-2002	97,0	3,00
Lubricating property at 60°C		EN-ISO 12156-00		
Wear scar diam. WS1.4 corr.	µm		262	
Fatty Acid Methylester (FAME)	%vol	SS-EN 14078:2004	<0,05	
Oxidation Stability	g/m3	SS-EN-ISO 12205-96	5	3,8
Total contamination	mg/kg	EN 12662/98	1	1,70
Sulphur content	mg/kg	*EN-ISO 20846-2011	<3,0	0,70
Viscosity at 40°C	mm3/s	*ASTM D7042-12	2,975	
Water Karl Fischer	mg/kg	EN-ISO 12937-01	24	10,2

Diesel fuel specification: B100 (RME)

Properties	Results	Units	Ref. Test Methods
Acid value	0,11	mg KOH/g	EN 14104:2004
Cetane number	52,6		EN ISO 5165:1998
Cloud point	-6	°C	EN 23015:1994
Cold Filter Plugging Point	-14	°C	EN 116:1997/AC:1999
Cu strip corrosion (3h at 50°C)	1A		EN ISO 2160:1998
Density at 15°C	882,0	kg/m3	EN ISO 12185:96/C1:01
Diglyceride content	0,03	% m/m	EN 14105:2003
Ester content	98,4	% m/m	EN 14103:2004
Free glycerol	0,01	% m/m	EN 14105:2003
Group 1 metals (Na + K)	< 2,0	mg/kg	EN 14538:2006
Group 2 metals (Ca + Mg)	< 2,0	mg/kg	EN 14538:2006
Iodine value	111	g I/100g	EN 14111:2003
Linolenic acid methyl ester	10	% m/m	EN 14103:2004
Methanol content	0,11	% m/m	EN 14110:2004
Monoglyceride content	0,34	% m/m	EN 14105:2003
Oxidation stability at 110°C	8,0	hours	EN 15751:2009
Phosphorus content	< 1,0	mg/kg	EN 14107:2007
Polyunsaturated methyl esters	< 1,00	% m/m	--
Sulfated ash content	< 0,020	% m/m	ISO 3987:2004
Sulphur content	4	mg/kg	EN ISO 20884:2011
Total contamination	9	mg/kg	EN 12662:2008
Total glycerol	0,09	% m/m	EN 14105:2003
Triglyceride content	0,02	% m/m	EN 14105:2003
Use of CFPP additive - name	no		--
Use of oxidation stabiliser - name	no		--
Water content	153	mg/kg	EN ISO 12937:2000
Viscosity at 40°C	4,355	mm2/s	EN ISO 3104:96/AC:99

Results according to ISO 4259

Dynamometer power vs. engine power

The engine power was estimated by adding the integrated signals from measured acceleration force of the inertia used and the road load. No fan correction has been applied to the calculations. The positive portions of the power is integrated and used to calculate the total estimated work (kWh) during the test cycle. This figure is then used to calculate emissions in g/kWh.

Instead of measuring the torque and speed of the crank shaft of the engine or the torque shaft close to the engine the estimation of work is here based on the power transferred via the traction of the tyres to the surface of the dynamometer roll and absorbed by the dynamometer. This power constitutes of two parts:

- P_{road} which is the power needed to overcome the road load curve, i.e. P_{road} = f(v) where v is the vehicle speed. The road load curve is the combination of frictional forces depending of road surface, tyres and vehicle load and vehicle air drag that the dynamometer is set to simulate. The road load is the sum of resistances when rolling the vehicle at constant speed on a straight and levelled road at 20°C and without metrological wind. When setting the dynamometer, the internal power absorption unit of the dynamometer is tuned to simulate the requested P_{road} = f(v) when the vehicle is run on the dynamometer with warm tyres. In reality this means that the internal power absorption usually is negative, i.e. power is transferred to the system at vehicle speeds below about 40 to 50 km/h (due to the high frictional forces of the tyres running on the dynamometer roll compared to running on a road). Only at vehicle speeds higher than this speed interval the internal power absorption actually absorbs power.

- $P_{inertia}$ which is the power needed to accelerate and decelerate the rotational inertia in the system. Apart from the simulated road load, the simulated vehicle mass or the vehicle inertia is crucial for the transient chassis testing. This power is simply the $P_{inertia} = dv/dt * m * v$, i.e. the measured acceleration of the system measured as the change in dynamometer roll speed times the simulated vehicle mass times the roll speed.

- So, the sum of $P_{road} + P_{inertia}$ is a measure of the instantaneous power transferred to the system. This power originates from the engine and is transferred via the gearbox through the drive shaft and rear axis and wheels to the surface of the dynamometer roll. In cases of retardation in the test cycle, either the engine is motoring or the exhaust brake or the wheel brakes are used. In those cases the sum of $P_{road} + P_{inertia}$ may become negative, i. e. power is transferred from the dynamometer system to the vehicle. All such portions should of cause not be included when integrating the work performed by the engine. Only events when the sum ($P_{road} + P_{inertia}$) is positive must be included in the integrated work.

- The boundary between the dynamometer system and the engine goes at the outgoing axis from the vehicle gear box, because this axis and the downstream drive train is included when road load setting is done for the vehicle. Going upstream from the outgoing axis of the gearbox will add also the frictional losses of the gearbox itself to the calculated number so far. Further on, when comparing to the power definition of the engine applied at engine bench test, specifically regarding the auxiliaries, where there should be no cooling fan fitted at test (or a fan running on maximum slip if the fan is of the proportional type). But running the vehicle on a chassis dynamometer comprises also the vehicle cooling fan which in turn also absorbs power originating from the engine.

The resulting used formula for calculating the work is the following:

$$\text{engine work} = \int [(P_{inerta} + P_{road} + P_{drivtrain} + P_{gearbox} + P_{fan}) + abs(P_{inerta} + P_{road} + P_{drivtrain} + P_{gearbox} + P_{fan})] / 2$$

where

$P_{inerta} + P_{road}$ is measured and explained as above
$P_{drivtrain}$ is the eventual difference in drivetrain frictional forces depending on the transferred torque (only the “idle” frictional forces are included in the road load figure)
$P_{gearbox}$ corresponds to the frictional losses in the gearbox (depending on used gear ratio)

P_{fan} corresponds to the power absorbed by the cooling fan during the chassis test

The trick in the formula to add the sums of power two times and divide the sum by 2 is made to eliminate the negative portions of sums from the integrated work. This is archived by the abs-function of the second sum.

This way to calculate the power also assumes that the P_{road} is unambiguously consistent throughout chassis test series. This may not be the case. Probably there is a considerate influence on P_{road} by temperature depending system friction such as those caused by the tyres and hence the instantaneous tyre temperature.

In our case we have chosen to approximate the $P_{drivtrain}$, $P_{gearbox}$ and P_{fan} to zero. So instead of being the work delivered by the engine, it is instead more or less the work delivered at the outgoing axis of the gear box. So the engine work defined according to the engine test methods regarding auxiliaries is most likely to be slightly underestimated by this calculation method.

B7 50% load: PAH filter phase

Unit: ng/km	B7 50% load	B7 50% load	B7 50% load
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	423,3	297,5	267,5
Anthracene	63,0	29,6	31,8
3-Methylphenanthrene	42,1	41,0	35,6
2-Methylphenanthrene	55,4	48,2	44,1
2-Methylanthracene	12,3	6,4	6,1
9-Methylphenanthrene	47,4	42,5	40,2
1-Methylphenanthrene	45,7	34,3	30,6
4H-cyclopenta(def)phenanthrene	20,2	8,9	7,3
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	42,4	22,2	21,5
3,6-Dimethylphenanthrene	0,0	3,8	3,4
3,9-Dimethylphenanthrene	27,9	35,2	35,0
Fluoranthene	178,6	85,6	76,9
Pyrene	211,8	90,5	83,9
9,10-Dimethylanthracene	79,5	69,2	67,8
1-Methylfluoranthene	18,8	6,4	6,0
Benz(a)fluorene	12,6	4,4	3,7
Benz(b)fluorene	8,1	2,4	5,8
2-Methylpyrene	11,9	5,3	4,0
4-Methylpyrene	14,7	6,0	5,2
1-Methylpyrene	18,8	5,6	0,0
Benzo(ghi)fluoranthene	83,9	30,2	28,5
Benzo(c)phenanthrene	5,2	4,4	2,4
Benzo(b)naphto(1,2-d)thiop	0,0	0,0	0,0
Cyclopenta(cd)pyrene	96,4	43,7	38,5
Benz(a)anthracene	89,4	31,7	29,8
Chrysene	121,5	48,0	44,0
3-Methylchrysene	2,1	0,0	0,0
2-Methylchrysene	7,7	5,9	5,3
6-Methylchrysene	5,5	0,0	0,0
1-Methylchrysene	15,8	5,4	0,0
Benzo(b)fluoranthene	79,7	32,9	31,3
Benzo(k)fluoranthene	39,4	16,2	16,4
Benzo(e)pyrene	79,1	29,4	28,1
Benzo(a)pyrene	94,7	45,8	42,9
Perylene	13,8	6,1	5,8
Indeno(1,2,3-cd)fluoranthe	0,0	0,0	0,0
Indeno(1,2,3-cd)pyrene	34,7	24,3	20,5
Dibenz(a,h)anthracene	0,0	3,6	3,5
Picene	5,4	2,9	2,7
Benzo(ghi)perylene	54,6	38,2	33,1
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	0,0	0,5	3,2
Coronene	11,3	12,1	11,5
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
Sum PAH ng/km	2175,1	1226,7	1124,1

B7 50% load: PAH semivolatile phase

Unit: ng/km	B7 50% load	B7 50% load	B7 50% load
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	49,4	31,7	49,1
Anthracene	9,0	4,3	6,7
3-Methylphenanthrene	5,6	5,0	6,8
2-Methylphenanthrene	5,2	5,3	6,2
2-Methylanthracene	0,0	1,1	1,8
9-Methylphenanthrene	5,5	5,1	5,8
1-Methylphenanthrene	5,2	5,1	6,4
4H-cyclopenta(def)phenanthrene	2,2	1,1	1,7
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	3,0	1,9	2,2
3,6-Dimethylphenanthrene	0,0	0,0	0,0
3,9-Dimethylphenanthrene	0,0	0,0	0,0
Fluoranthene	9,5	6,0	8,7
Pyrene	9,9	8,7	9,6
9,10-Dimethylanthracene	0,0	0,0	0,0
1-Methylfluoranthene	0,0	0,0	0,0
Benz(a)fluorene	0,0	0,0	0,0
Benz(b)fluorene	0,0	0,0	0,0
2-Methylpyrene	0,0	0,0	0,0
4-Methylpyrene	0,0	0,0	0,0
1-Methylpyrene	0,0	0,0	0,0
Benzo(ghi)fluoranthene	0,0	0,0	0,5
Benzo(c)phenanthrene	30,6	36,6	88,1
Benzo(b)naphto(1,2-d)thiop	0,0	0,0	0,0
Cyclopenta(cd)pyrene	0,0	0,0	0,0
Benz(a)anthracene	0,0	0,0	0,0
Chrysene	0,0	0,0	0,0
3-Methylchrysene	0,0	0,0	0,0
2-Methylchrysene	0,0	0,0	0,0
6-Methylchrysene	0,0	0,0	0,0
1-Methylchrysene	0,0	0,0	0,1
Benzo(b)fluoranthene	0,0	0,0	0,0
Benzo(k)fluoranthene	0,0	0,0	0,0
Benzo(e)pyrene	0,0	0,0	0,0
Benzo(a)pyrene	0,0	0,0	0,0
Perylene	0,0	0,0	0,0
Indeno(1,2,3-cd)fluoranthe	0,0	0,0	0,0
Indeno(1,2,3-cd)pyrene	0,0	0,0	0,0
Dibenz(a,h)anthracene	0,0	0,0	0,0
Picene	0,1	0,4	0,1
Benzo(ghi)perylene	0,0	0,0	0,0
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	0,4	0,4	0,3
Coronene	0,0	0,0	0,0
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
SumPAH ng/km	135,6	112,7	194,2

B7 + HVO30: PAH filter phase

Unit: ng/km	B7 + HVO30	B7 + HVO30	B7 + HVO30
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	437,5	324,0	195,5
Anthracene	69,7	79,4	22,6
3-Methylphenanthrene	40,1	212,3	19,3
2-Methylphenanthrene	50,1	249,5	24,3
2-Methylanthracene	13,5	68,1	5,9
9-Methylphenanthrene	39,4	278,1	20,8
1-Methylphenanthrene	43,1	245,8	19,4
4H-cyclopenta(def)phenanthrene	22,7	52,5	7,6
9-Methylanthracene	7,0	0,0	0,0
2-Phenylnaphthalene	44,3	16,6	16,9
3,6-Dimethylphenanthrene	4,3	3,6	2,1
3,9-Dimethylphenanthrene	34,0	34,7	18,9
Fluoranthene	173,1	73,5	62,8
Pyrene	212,7	92,1	68,7
9,10-Dimethylanthracene	65,2	70,4	34,9
1-Methylfluoranthene	16,1	10,7	4,6
Benz(a)fluorene	11,3	7,1	3,1
Benz(b)fluorene	8,0	5,0	3,9
2-Methylpyrene	9,3	7,3	2,9
4-Methylpyrene	12,9	9,8	3,4
1-Methylpyrene	17,8	10,6	3,7
Benzo(ghi)fluoranthene	75,0	25,8	20,8
Benzo(c)phenanthrene	16,6	4,8	4,2
Benzo(b)naphto(1,2-d)thiop	2,3	0,7	0,0
Cyclopenta(cd)pyrene	129,2	40,5	38,7
Benz(a)anthracene	77,8	36,1	26,3
Chrysene	99,3	44,9	33,8
3-Methylchrysene	1,8	1,4	0,7
2-Methylchrysene	7,1	3,0	2,4
6-Methylchrysene	4,9	2,4	1,6
1-Methylchrysene	14,1	1,8	3,9
Benzo(b)fluoranthene	60,3	35,8	25,7
Benzo(k)fluoranthene	29,6	18,8	13,2
Benzo(e)pyrene	58,9	27,5	22,3
Benzo(a)pyrene	84,6	50,8	43,8
Perylene	12,4	6,3	5,7
Indeno(1,2,3-cd)fluoranthe	0,0	1,7	2,4
Indeno(1,2,3-cd)pyrene	29,5	26,8	29,4
Dibenz(a,h)anthracene	4,6	4,5	0,0
Picene	4,1	3,2	0,2
Benzo(ghi)perylene	51,1	38,0	43,4
Dibenzo(a,l)pyrene	0,0	1,1	0,0
Dibenzo(a,e)pyrene	0,4	2,8	4,6
Coronene	0,3	10,4	19,7
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
Sum PAH ng/km	2095,9	2240,5	884,0

B7 + HVO30: PAH semivolatile phase

Unit: ng/km	B7 + HVO30	B7 + HVO30	B7 + HVO30
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	38,9	63,0	20,0
Anthracene	4,1	6,5	5,9
3-Methylphenanthrene	4,9	11,8	2,8
2-Methylphenanthrene	5,2	11,2	2,7
2-Methylanthracene	1,0	1,9	0,3
9-Methylphenanthrene	4,5	0,0	2,5
1-Methylphenanthrene	4,2	0,0	2,4
4H-cyclopenta(def)phenanthrene	1,6	2,9	0,7
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	2,4	4,2	1,4
3,6-Dimethylphenanthrene	0,0	0,0	0,0
3,9-Dimethylphenanthrene	0,0	0,0	0,0
Fluoranthene	6,3	11,4	5,0
Pyrene	7,9	11,1	4,4
9,10-Dimethylanthracene	0,0	0,0	0,0
1-Methylfluoranthene	0,0	0,0	0,0
Benz(a)fluorene	0,0	0,0	0,0
Benz(b)fluorene	0,0	0,0	0,0
2-Methylpyrene	0,0	0,0	0,0
4-Methylpyrene	0,0	0,0	0,0
1-Methylpyrene	0,0	0,0	0,0
Benzo(ghi)fluoranthene	0,0	0,0	0,6
Benzo(c)phenanthrene	65,4	82,1	813,9
Benzo(b)naphto(1,2-d)thiop	0,0	0,0	0,0
Cyclopenta(cd)pyrene	0,0	0,0	0,0
Benz(a)anthracene	0,0	0,0	0,0
Chrysene	0,0	0,0	2,6
3-Methylchrysene	0,0	0,0	0,0
2-Methylchrysene	0,0	0,0	0,0
6-Methylchrysene	0,1	0,0	0,0
1-Methylchrysene	0,0	0,0	0,0
Benzo(b)fluoranthene	0,0	0,0	0,1
Benzo(k)fluoranthene	0,0	0,0	2,8
Benzo(e)pyrene	0,0	0,0	0,0
Benzo(a)pyrene	0,0	0,0	0,0
Perylene	0,0	0,0	0,0
Indeno(1,2,3-cd)fluoranthe	0,0	0,0	0,0
Indeno(1,2,3-cd)pyrene	0,0	0,0	0,0
Dibenz(a,h)anthracene	0,0	0,0	0,0
Picene	0,1	0,0	0,0
Benzo(ghi)perylene	0,0	0,0	0,0
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	0,1	0,3	0,2
Coronene	0,0	0,0	0,0
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
SumPAH ng/km	146,7	206,4	868,3

HVO100: PAH filter phase

Unit: ng/km	HVO100	HVO100	HVO100
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	456,5	122,2	233,2
Anthracene	48,2	12,7	24,8
3-Methylphenanthrene	36,5	11,3	29,4
2-Methylphenanthrene	46,1	12,6	35,9
2-Methylanthracene	10,7	2,9	5,8
9-Methylphenanthrene	36,6	12,7	31,5
1-Methylphenanthrene	36,3	9,9	27,3
4H-cyclopenta(def)phenanthrene	22,9	4,9	9,8
9-Methylanthracene	0,0	0,0	5,2
2-Phenylnaphthalene	37,0	8,0	21,9
3,6-Dimethylphenanthrene	3,7	1,3	2,8
3,9-Dimethylphenanthrene	30,9	10,6	24,8
Fluoranthene	160,4	33,4	78,2
Pyrene	199,1	34,8	87,8
9,10-Dimethylanthracene	0,0	17,5	51,3
1-Methylfluoranthene	13,7	2,1	6,4
Benz(a)fluorene	10,1	1,1	4,0
Benz(b)fluorene	7,7	0,6	2,7
2-Methylpyrene	8,2	1,4	3,6
4-Methylpyrene	10,0	1,5	4,7
1-Methylpyrene	13,5	1,5	5,3
Benzo(ghi)fluoranthene	63,7	10,6	24,3
Benzo(c)phenanthrene	25,1	2,0	5,5
Benzo(b)naphto(1,2-d)thiop	0,0	0,0	0,8
Cyclopenta(cd)pyrene	109,5	16,9	44,5
Benz(a)anthracene	63,4	8,5	26,3
Chrysene	97,6	16,4	38,0
3-Methylchrysene	2,2	0,2	0,8
2-Methylchrysene	6,2	0,8	2,5
6-Methylchrysene	4,2	0,5	1,6
1-Methylchrysene	10,4	2,0	1,6
Benzo(b)fluoranthene	54,9	8,7	30,8
Benzo(k)fluoranthene	29,6	4,3	14,7
Benzo(e)pyrene	53,9	8,3	26,7
Benzo(a)pyrene	63,2	12,6	45,3
Perylene	10,0	1,9	5,6
Indeno(1,2,3-cd)fluoranthe	2,2	0,6	1,6
Indeno(1,2,3-cd)pyrene	30,6	7,0	26,3
Dibenz(a,h)anthracene	4,4	0,0	3,3
Picene	4,1	1,3	2,2
Benzo(ghi)perylene	49,1	12,5	45,5
Dibenzo(a,l)pyrene	0,0	0,0	0,9
Dibenzo(a,e)pyrene	2,8	0,1	2,4
Coronene	15,3	4,9	14,2
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
Sum PAH ng/km	1890,4	423,3	1061,8

HVO100: PAH semivolatile phase

Unit: ng/km	HVO100	HVO100	HVO100
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	37,3	18,0	37,7
Anthracene	4,4	1,6	5,0
3-Methylphenanthrene	4,7	2,7	5,4
2-Methylphenanthrene	4,4	2,6	5,0
2-Methylanthracene	0,8	0,1	0,9
9-Methylphenanthrene	4,6	2,4	4,7
1-Methylphenanthrene	2,3	1,8	3,7
4H-cyclopenta(def)phenanthrene	1,7	0,8	1,8
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	2,3	1,4	3,6
3,6-Dimethylphenanthrene	0,0	0,0	0,0
3,9-Dimethylphenanthrene	0,0	0,0	0,0
Fluoranthene	7,8	5,4	13,2
Pyrene	7,9	5,1	11,3
9,10-Dimethylanthracene	0,0	0,0	0,0
1-Methylfluoranthene	0,0	0,0	0,0
Benz(a)fluorene	0,0	0,0	0,0
Benz(b)fluorene	0,0	0,0	0,0
2-Methylpyrene	0,0	0,0	0,0
4-Methylpyrene	0,0	0,0	0,0
1-Methylpyrene	0,0	0,0	0,0
Benzo(ghi)fluoranthene	1,0	0,4	0,5
Benzo(c)phenanthrene	2605,3	195,0	170,6
Benzo(b)naphto(1,2-d)thiop	0,0	0,0	0,0
Cyclopenta(cd)pyrene	8,4	0,0	0,0
Benz(a)anthracene	0,0	0,0	0,0
Chrysene	5,1	1,5	0,0
3-Methylchrysene	24,2	0,0	0,0
2-Methylchrysene	0,0	0,0	0,0
6-Methylchrysene	0,0	0,0	0,0
1-Methylchrysene	0,0	0,0	0,0
Benzo(b)fluoranthene	0,3	0,0	0,0
Benzo(k)fluoranthene	0,2	0,0	0,0
Benzo(e)pyrene	0,0	0,1	0,5
Benzo(a)pyrene	0,0	0,0	0,0
Perylene	0,0	0,0	0,0
Indeno(1,2,3-cd)fluoranthe	0,0	0,0	0,0
Indeno(1,2,3-cd)pyrene	0,0	0,0	0,0
Dibenz(a,h)anthracene	0,0	0,0	0,0
Picene	0,1	0,1	0,2
Benzo(ghi)perylene	0,0	0,0	0,0
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	0,2	0,0	1,0
Coronene	0,0	0,0	0,0
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
SumPAH ng/km	2723,0	239,1	265,2

GTL: PAH filter phase

Unit: ng/km	GTL	GTL	GTL
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	330,6	297,3	115,3
Anthracene	42,5	34,8	16,0
3-Methylphenanthrene	33,6	29,5	11,1
2-Methylphenanthrene	41,6	35,4	13,7
2-Methylanthracene	6,4	4,4	2,6
9-Methylphenanthrene	34,5	31,7	12,5
1-Methylphenanthrene	31,6	25,9	10,2
4H-cyclopenta(def)phenanthrene	18,1	9,4	3,9
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	37,9	24,0	10,3
3,6-Dimethylphenanthrene	2,6	2,9	1,2
3,9-Dimethylphenanthrene	24,1	24,6	9,2
Fluoranthene	133,7	85,3	36,5
Pyrene	157,7	95,8	43,7
9,10-Dimethylanthracene	49,6	44,5	16,3
1-Methylfluoranthene	12,9	6,3	2,9
Benz(a)fluorene	8,8	4,1	2,0
Benz(b)fluorene	5,9	2,9	1,4
2-Methylpyrene	6,2	4,2	1,9
4-Methylpyrene	8,3	4,9	2,3
1-Methylpyrene	11,2	5,6	2,8
Benzo(ghi)fluoranthene	47,5	35,1	13,9
Benzo(c)phenanthrene	13,9	10,4	3,3
Benzo(b)naphto(1,2-d)thiop	1,3	1,0	0,5
Cyclopenta(cd)pyrene	77,7	53,3	27,7
Benz(a)anthracene	51,4	35,1	18,1
Chrysene	64,7	50,0	24,8
3-Methylchrysene	5,7	0,0	0,5
2-Methylchrysene	6,0	0,0	1,6
6-Methylchrysene	0,0	0,0	1,1
1-Methylchrysene	3,1	0,0	3,1
Benzo(b)fluoranthene	44,6	35,8	19,2
Benzo(k)fluoranthene	22,1	17,3	10,0
Benzo(e)pyrene	39,8	33,1	18,0
Benzo(a)pyrene	63,2	51,2	28,1
Perylene	9,3	7,3	3,9
Indeno(1,2,3-cd)fluoranthe	1,8	1,8	1,0
Indeno(1,2,3-cd)pyrene	22,1	24,6	13,3
Dibenz(a,h)anthracene	3,7	3,7	1,8
Picene	2,5	2,7	1,4
Benzo(ghi)perylene	35,8	43,0	23,5
Dibenzo(a,l)pyrene	1,2	1,3	0,8
Dibenzo(a,e)pyrene	2,2	3,9	2,0
Coronene	7,4	15,0	7,2
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
Sum PAH ng/km	1524,8	1198,9	540,6

GTL: PAH semivolatile phase

Unit: ng/km	GTL	GTL	GTL
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	78,7	45,6	20,6
Anthracene	7,4	3,1	1,8
3-Methylphenanthrene	10,5	5,8	2,4
2-Methylphenanthrene	12,2	6,3	2,8
2-Methylanthracene	1,6	0,8	0,6
9-Methylphenanthrene	11,7	5,2	2,2
1-Methylphenanthrene	11,3	4,1	2,0
4H-cyclopenta(def)phenanthrene	3,5	1,6	1,1
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	5,0	2,5	1,5
3,6-Dimethylphenanthrene	0,0	0,0	0,0
3,9-Dimethylphenanthrene	0,0	0,0	0,0
Fluoranthene	17,9	8,0	5,3
Pyrene	16,1	6,8	4,4
9,10-Dimethylanthracene	0,0	0,0	0,0
1-Methylfluoranthene	0,0	0,0	0,0
Benz(a)fluorene	0,0	0,0	0,0
Benz(b)fluorene	0,3	0,0	0,0
2-Methylpyrene	0,0	0,0	0,0
4-Methylpyrene	0,0	0,0	0,3
1-Methylpyrene	0,0	0,0	2,4
Benzo(ghi)fluoranthene	0,0	0,0	0,0
Benzo(c)phenanthrene	43,8	26,8	64,9
Benzo(b)naphto(1,2-d)thiop	0,0	0,1	0,2
Cyclopenta(cd)pyrene	0,0	0,0	0,0
Benz(a)anthracene	0,0	0,0	0,0
Chrysene	0,0	2,6	3,5
3-Methylchrysene	0,0	0,0	3,1
2-Methylchrysene	0,0	0,0	0,0
6-Methylchrysene	0,0	0,0	0,0
1-Methylchrysene	0,0	9,0	0,2
Benzo(b)fluoranthene	0,0	6,5	0,0
Benzo(k)fluoranthene	0,0	0,0	0,0
Benzo(e)pyrene	0,0	0,4	0,8
Benzo(a)pyrene	0,0	0,0	0,0
Perylene	0,0	0,0	5,8
Indeno(1,2,3-cd)fluoranthe	0,0	0,0	2,0
Indeno(1,2,3-cd)pyrene	0,0	0,0	0,0
Dibenz(a,h)anthracene	0,0	0,0	0,0
Picene	0,2	0,0	0,1
Benzo(ghi)perylene	0,0	0,0	0,0
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	0,9	0,1	0,2
Coronene	0,0	0,0	0,0
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
SumPAH ng/km	221,2	135,3	127,9

B100: PAH filter phase

Unit: ng/km	B100	B100	B100
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	123,9	129,8	91,0
Anthracene	76,8	14,0	87,2
3-Methylphenanthrene	13,7	19,7	15,8
2-Methylphenanthrene	16,9	25,1	21,2
2-Methylanthracene	2,4	2,2	16,2
9-Methylphenanthrene	15,2	23,1	19,1
1-Methylphenanthrene	12,9	17,5	15,5
4H-cyclopenta(def)phenanthrene	7,4	3,9	3,9
9-Methylanthracene	1,4	0,0	0,0
2-Phenylnaphthalene	14,5	10,9	13,6
3,6-Dimethylphenanthrene	1,7	2,0	1,7
3,9-Dimethylphenanthrene	13,7	16,4	17,8
Fluoranthene	55,1	38,3	41,5
Pyrene	62,7	39,7	42,5
9,10-Dimethylanthracene	25,3	31,3	32,7
1-Methylfluoranthene	4,5	2,5	2,7
Benz(a)fluorene	3,3	1,6	2,0
Benz(b)fluorene	2,4	0,8	1,1
2-Methylpyrene	2,4	1,7	1,9
4-Methylpyrene	3,2	2,0	2,0
1-Methylpyrene	5,1	2,3	2,3
Benzo(ghi)fluoranthene	19,9	9,8	12,2
Benzo(c)phenanthrene	3,7	10,5	119,8
Benzo(b)naphto(1,2-d)thiop	0,5	0,3	0,3
Cyclopenta(cd)pyrene	40,3	14,4	22,8
Benz(a)anthracene	18,5	13,0	14,9
Chrysene	27,4	19,9	23,3
3-Methylchrysene	0,5	0,3	0,4
2-Methylchrysene	1,5	0,9	1,1
6-Methylchrysene	1,2	1,0	1,2
1-Methylchrysene	5,6	1,1	2,1
Benzo(b)fluoranthene	20,0	13,8	17,1
Benzo(k)fluoranthene	9,9	7,5	9,0
Benzo(e)pyrene	20,2	11,8	15,2
Benzo(a)pyrene	31,1	23,5	30,6
Perylene	4,3	3,0	3,9
Indeno(1,2,3-cd)fluoranthe	1,3	1,7	2,3
Indeno(1,2,3-cd)pyrene	17,2	22,0	29,3
Dibenz(a,h)anthracene	2,2	2,9	3,5
Picene	1,4	2,2	2,5
Benzo(ghi)perylene	28,9	28,2	40,4
Dibenzo(a,l)pyrene	0,6	0,5	0,8
Dibenzo(a,e)pyrene	1,2	4,1	5,7
Coronene	15,4	24,6	34,3
Dibenzo(a,i)pyrene	0,0	1,4	1,9
Dibenzo(a,h)pyrene	0,0	1,1	1,6
Sum PAH ng/km	737,6	604,3	828,0

B100: PAH semivolatile phase

Unit: ng/km	B100	B100	B100
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	49,1	90,8	78,0
Anthracene	6,7	8,4	7,3
3-Methylphenanthrene	6,8	7,8	5,3
2-Methylphenanthrene	6,2	7,8	4,7
2-Methylanthracene	1,8	1,4	1,0
9-Methylphenanthrene	5,8	8,8	5,7
1-Methylphenanthrene	6,4	5,8	3,9
4H-cyclopenta(def)phenanthrene	1,7	3,0	2,4
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	2,2	2,3	1,5
3,6-Dimethylphenanthrene	0,0	0,0	0,0
3,9-Dimethylphenanthrene	0,0	6,9	0,0
Fluoranthene	8,7	7,9	4,3
Pyrene	9,6	11,1	13,2
9,10-Dimethylanthracene	0,0	22,1	0,0
1-Methylfluoranthene	0,0	0,0	0,0
Benz(a)fluorene	0,0	0,0	0,0
Benz(b)fluorene	0,0	0,0	0,0
2-Methylpyrene	0,0	0,0	0,0
4-Methylpyrene	0,0	0,0	0,0
1-Methylpyrene	0,0	0,0	0,0
Benzo(ghi)fluoranthene	0,5	0,4	0,4
Benzo(c)phenanthrene	88,1	0,4	345,3
Benzo(b)naphto(1,2-d)thiop	0,0	1,1	0,1
Cyclopenta(cd)pyrene	0,0	0,6	0,1
Benz(a)anthracene	0,0	0,0	0,0
Chrysene	0,0	2,5	3,0
3-Methylchrysene	0,0	2,1	0,1
2-Methylchrysene	0,0	1,1	0,0
6-Methylchrysene	0,0	0,0	0,0
1-Methylchrysene	0,1	0,2	0,1
Benzo(b)fluoranthene	0,0	7,0	0,0
Benzo(k)fluoranthene	0,0	7,1	0,0
Benzo(e)pyrene	0,0	0,5	0,0
Benzo(a)pyrene	0,0	0,0	0,0
Perylene	0,0	6,7	0,0
Indeno(1,2,3-cd)fluoranthe	0,0	2,9	0,0
Indeno(1,2,3-cd)pyrene	0,0	0,0	0,0
Dibenz(a,h)anthracene	0,0	0,0	0,0
Picene	0,1	0,1	0,1
Benzo(ghi)perylene	0,0	0,0	0,0
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	0,3	0,1	0,1
Coronene	0,0	0,0	0,0
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
SumPAH ng/km	194,2	216,9	476,6

ED95: PAH filter phase

Unit: ng/km	ED95	ED95	ED95
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	39,1	52,0	74,2
Anthracene	5,2	7,8	7,4
3-Methylphenanthrene	9,3	9,4	10,8
2-Methylphenanthrene	10,8	11,3	14,7
2-Methylanthracene	1,6	1,3	1,2
9-Methylphenanthrene	7,2	10,1	10,8
1-Methylphenanthrene	7,5	9,5	8,6
4H-cyclopenta(def)phenanthrene	4,6	2,5	4,0
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	10,7	3,7	7,8
3,6-Dimethylphenanthrene	2,3	1,4	1,6
3,9-Dimethylphenanthrene	10,8	6,3	10,3
Fluoranthene	68,6	39,4	70,3
Pyrene	91,5	50,8	87,9
9,10-Dimethylanthracene	28,3	18,5	34,3
1-Methylfluoranthene	5,9	3,4	6,6
Benz(a)fluorene	5,4	2,3	3,5
Benz(b)fluorene	3,9	1,1	1,5
2-Methylpyrene	3,7	2,6	4,3
4-Methylpyrene	4,8	2,9	4,7
1-Methylpyrene	4,4	2,3	3,1
Benzo(ghi)fluoranthene	36,5	8,2	10,9
Benzo(c)phenanthrene	21,6	2,7	23,2
Benzo(b)naphto(1,2-d)thiop	0,9	0,5	0,5
Cyclopenta(cd)pyrene	30,5	11,9	14,9
Benz(a)anthracene	28,7	8,4	7,8
Chrysene	52,2	17,6	18,1
3-Methylchrysene	1,1	0,5	0,5
2-Methylchrysene	2,6	1,2	1,1
6-Methylchrysene	1,6	1,0	1,3
1-Methylchrysene	1,6	0,9	1,0
Benzo(b)fluoranthene	40,7	13,8	15,4
Benzo(k)fluoranthene	20,8	6,2	6,6
Benzo(e)pyrene	62,4	16,2	18,4
Benzo(a)pyrene	40,3	16,4	21,0
Perylene	7,4	2,9	3,4
Indeno(1,2,3-cd)fluoranthe	2,3	0,9	1,5
Indeno(1,2,3-cd)pyrene	64,2	17,5	28,6
Dibenz(a,h)anthracene	4,3	1,6	2,2
Picene	2,7	1,4	1,7
Benzo(ghi)perylene	311,6	74,7	121,8
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	4,6	2,3	3,2
Coronene	694,7	185,9	297,5
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
Sum PAH ng/km	1758,4	631,3	968,1

ED95: PAH semivolatile phase

Unit: ng/km	ED95	ED95	ED95
Driving cycle: WHVC	Cold start	Hot start 1	Hot start 2
0 = < 0,1			
Phenanthrene	246,8	127,4	123,3
Anthracene	9,8	8,2	6,9
3-Methylphenanthrene	24,2	12,1	10,8
2-Methylphenanthrene	27,4	12,7	11,8
2-Methylanthracene	2,6	1,2	1,2
9-Methylphenanthrene	23,9	10,4	9,9
1-Methylphenanthrene	21,9	10,9	9,7
4H-cyclopenta(def)phenanthrene	26,9	7,9	8,5
9-Methylanthracene	0,0	0,0	0,0
2-Phenylnaphthalene	12,9	8,0	7,2
3,6-Dimethylphenanthrene	3,2	0,0	0,0
3,9-Dimethylphenanthrene	15,6	7,5	6,9
Fluoranthene	91,5	20,3	21,7
Pyrene	163,5	20,2	22,5
9,10-Dimethylanthracene	49,7	21,8	20,2
1-Methylfluoranthene	2,8	0,0	0,0
Benz(a)fluorene	1,3	0,0	0,0
Benz(b)fluorene	0,0	0,0	0,0
2-Methylpyrene	0,0	0,0	0,0
4-Methylpyrene	4,1	0,0	0,0
1-Methylpyrene	2,6	0,0	0,0
Benzo(ghi)fluoranthene	6,0	0,0	0,7
Benzo(c)phenanthrene	17,2	26,3	9,7
Benzo(b)naphto(1,2-d)thiop	0,4	0,2	0,3
Cyclopenta(cd)pyrene	3,3	0,0	0,0
Benz(a)anthracene	0,0	0,0	0,2
Chrysene	1,9	1,7	1,7
3-Methylchrysene	0,0	1,4	0,0
2-Methylchrysene	0,0	0,0	0,0
6-Methylchrysene	0,0	0,0	0,0
1-Methylchrysene	0,2	0,2	0,0
Benzo(b)fluoranthene	0,1	0,0	1,4
Benzo(k)fluoranthene	3,3	0,0	2,6
Benzo(e)pyrene	0,3	0,3	0,3
Benzo(a)pyrene	0,0	0,0	0,0
Perylene	0,0	0,0	0,0
Indeno(1,2,3-cd)fluoranthe	0,0	0,0	0,0
Indeno(1,2,3-cd)pyrene	0,0	0,0	0,0
Dibenz(a,h)anthracene	0,0	0,0	0,0
Picene	0,0	0,1	0,1
Benzo(ghi)perylene	1,9	0,0	0,0
Dibenzo(a,l)pyrene	0,0	0,0	0,0
Dibenzo(a,e)pyrene	0,0	0,1	0,1
Coronene	0,0	0,0	0,0
Dibenzo(a,i)pyrene	0,0	0,0	0,0
Dibenzo(a,h)pyrene	0,0	0,0	0,0
SumPAH ng/km	765,6	298,8	277,7

Appendix 2.

Complete report from testing of Vehicle H.

TEST REPORT

Emission Measurement on a Heavy Duty Euro VI truck. On road with PEMS and on chassis dynamometer

Kristina Willner

AVL SWEDEN

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Summary

AVL Motortestcenter AB (AVL) has on commission by the Swedish Transport Agency carried out extensive testing of a Euro VI heavy-duty truck. The aim of the tests was to learn more about the emission performance of a vehicle of the newest emission standard and to see if the manufacturers have managed to reduce the emission levels sufficiently also during real-world operation. Another aim of the testing was to evaluate the robustness of the new in-service conformity pass-fail method. The vehicle was tested under laboratory conditions on a chassis dynamometer as well as with a Portable Emissions Measurement System (PEMS) on the road in normal traffic.

On chassis dynamometer, measurement of all emission components regulated by Euro VI emission standards (CO, THC, NOx, PM, PN, NH_3) was carried out in order to enable a comparison to the engine type approval emission limits of a Euro VI HD engine. In addition, particle size distribution was measured.

PEMS is the current procedure to evaluate the in-service emission conformity of Heavy Duty Vehicles. PEMS can measure the gaseous emissions CO, THC, NOx, CO_2, NO and NO_2. In addition to the gas analyzing equipment there are also a possibilities to measure PM and/or soot.
For the PEMS tests performed, the gaseous emissions where measured and in some tests also PM/soot.

The influence of the emission performance, by a wide range of different driving conditions, was investigated.

- Influence of different aspects of test route composition on the emission levels and conformity factor
- Influence of speed variations within the legal boundaries on the emission levels and conformity factor
- Influence of different ambient temperatures on the emission levels and conformity factor
- Influence of different payloads
- How a Euro VI vehicle performs at cold start during start at different ambient temperatures

In addition, tests were carried out in order to:

- Produce test results comparable to test results previously obtained within the program

The tests were evaluated with the data evaluation tool EMROAD to calculate the emission levels and conformity factor for each regulated emission component. Some tests were calculated with the evaluation tool Concerto PEMS, whose conformity with EMROAD has been verified by TÜV.

The influence of trip composition on the emission levels and the conformity factor seems to be limited, but a trip designed to a faster warm up of the SCR system may result in lower NOx emissions. The 20% threshold may also influence the conformity factor by excluding data from the urban part of the trip.

The aftertreatment systems of a Euro VI vehicle are sensitive to changes and test preconditions may need special attention. Conditioning prior to the test can have a large influence on the test result. Even if the coolant temperature at test start is the same for all tests, may differences in exhaust gas temperature influence the test result.

Cold starts have a large influence on the NOx emission result when looking at the “all event result” (Described in chapter “Test information”) but, due to variances of data exclusions, not necessarily on the conformity factor.

Different ambient temperatures do not influence the NOx emission levels once the vehicle has reached its optimal operating temperature.

Different payloads do affect the results but not significantly. The lowest conformity factor was achieved with a 50% (of 40 tons) payload.

Introduction

During the past years, measurement of emission performance on road with vehicles in normal operation has been more of interest partly because experience show big differences in exhaust emissions when an engine is tested in a laboratory according to the set requirements and when the same engine is installed in a vehicle operating under normal conditions. Further, questions have been raised why ambient air quality is not improved in the same pace as emission limits are becoming more stringent. Measurement of vehicles in use by PEMS (Portable Emissions Measurement System) has become more important and the method is now prescribed in European legislation (Regulation no 49) which will be valid for all HD vehicles of environmental class Euro VI and later.

AVL has on commission by the Swedish Transport Agency carried out emission validation tests on a Heavy Duty truck of emission standard Euro VI. The purpose of the testing was to evaluate the emission performance of a Euro VI vehicle and to investigate how the emission performance is influenced by temperature (start and ambient), different loads, variations of driving pattern, variations of speed within the legislative boundaries and variations of test route aggressiveness (amount of altitude changes).

The on-road tests of the vehicle in this project have been carried out in accordance with the requirements. Calculation has been carried out according to the EMROAD method. The results are presented according to the work base window method and the CO_2 reference mass method described in the regulation as well as “all events” (Described in chapter “Test information”).

Test object

Table 14 Vehicle information

Vehicle category (2007/46/EC):	N_3
Mileage at test start [km]:	7570
Vehicle curb weight [ton]:	9.6
Vehicle total weight [ton]:	27
Maximum trailer weight [ton]:	60
Payload [ton]:	3-20
Total test weight [ton]:	22.5-39.5

Table 15 Engine information

Emission Standard:	Euro VI
Engine displacement [liters]:	13
Number of cylinders:	6
Engine rated power (kW):	350
Idle speed [rpm]:	600
Aftertreatment:	DOC, SCR, DPF, Ammonia slip cat, EGR

Test information

The vehicle has been tested with PEMS on road and on a chassis dynamometer. More information about test equipment can be found in Appendix 2: Test equipment.

For chassis dynamometer test the WHVC (World Harmonized Vehicle Cycle) test cycle have been used (warm and cold start) as well as the FIGE test cycle (warm start).

Table 16 Test program on chassis dynamometer

3	WHVC cold start (start with cold engine at approx. 22°C)
4	WHVC warm start (start with warm engine, oil temperature approx. 80°C)
1	FIGE (start with warm engine, oil temperature approx. 80°C)

The on-road tests of the vehicle and the test result calculation have been carried out in accordance with the requirements. More detailed information of the test cycles can be found in Appendix 3: Test cycles.

There are two different methods for calculation of emitted exhaust emissions:

- One method is to calculate total emissions when a vehicle is moving from a point A to a point B and include all measurements during the trip including all transient conditions, low load and periods of idle, cold engine operation and high altitudes (called "**all events**"). This method can be used to present "real-life emissions".

- The other method is to verify whether engines mounted in heavy duty vehicles meet set emission requirements for European type approval. The method for calculation only account for those measuring points (area) in the engine map (rpm/torque) that corresponds to those measuring points (area) subjected to the engine tests for European type approval. The purpose of this approach is that the engine should be tested as identical as possible for type approval as for in service conformity. The result of this pass-fail-evaluation method is a **Conformity Factor** (CF) which is the fraction between calculated emission value according to the given data-evaluation method and the applicable type approval emission limit; i.e. vehicles are not allowed to emit more than 1.5 times the emission limit value under the prescribed test procedure and data-evaluation rules.

For the calculation of Conformity Factors, first, data points not meeting the applicable ambient and altitude conditions are excluded (invalid data). In addition are either the emissions emitted before the engine coolant temp has reached 70°C eliminated or the emissions emitted before the coolant temperature has been stable at least 5 minutes, maximum 20 minutes after engine start. Whatever criterion is reached first will be effective. Once the invalid data is removed from the test, calculation of moving and averaging windows can be performed. Next, data belonging to windows whose power is below 20% of the maximum engine power ("invalid windows") is excluded. Last, valid windows with the 10% highest emission results are eliminated and the results of the remaining windows (the 90% criterion) are used for the calculation of Conformity Factors.

According to the regulation the PEMS test run shall be designed in order to carry out five times the work performed or produce five times the CO_2 reference mass in kg/cycle during the engine certification test procedure. The test cycle shall consist of urban, rural and motorway driving and each share of operation shall be expressed as a percentage of the total trip duration.

Table 17 Vehicle speed characteristics and trip composition for N3 vehicles

	Urban	Rural	Motorway
Velocity (km/h)	0 - 50	50 - 75	75 -
Percentage of trip (%)	20 ± 5	25 ± 5	55 ± 5

Although the requirements are met, there are still possibilities to interpret the requirement in different ways. During the tests two different routes fulfilling the requirements for Euro VI have been used. It has been investigated to what extent the conformity factors are influenced by driving the test routes with lowest possible speed, i.e. as close as possible to the lower limit for urban, rural and motorway driving respectively. Other aspects studied is how the emissions are influenced by driving with different payloads (10%, 50% and 90% of European maximum allowed payload (40 ton). 50% and 90% maximum allowed EU payload corresponds to 10% and 50% maximum allowed Swedish payload (60 ton)), by starting with different engine temperatures and by performing the test at different ambient temperatures.

Tests have also been performed on a shorter test route not fulfilling the requirements for Euro VI. This test route has previously been extensively used within the Swedish In-Service Compliance program, and data have been collected for correlation purposes as well as additional investigation of test routes.

On the request of Joint Research Center (JRC) was a test route designed which repeated a shorter trip consisting of urban, rural and motorway driving numerous times (Random cycle).

The vehicle was also tested in an ordinary “real world distribution route” in the suburban parts of Stockholm.

Table 18 Test program PEMS

EU VI route 2	10 °C	10 ton	normal speed
EU VI route 2	10 °C	10 ton	low speed
EU VI route 2 counter clockwise	10 °C	10 ton	normal speed
EU VI route 1	20 °C	3 ton (~10% of max payload 40/60 tons)	normal speed
EU VI route 1	20 °C	10 ton (~50% of max payload 40 tons)	normal speed
EU VI route 1	20 °C	20 ton (~90% of max payload 40 tons and ~50% of max payload 60 tons)	normal speed
EU VI route 2	Cold start, 0 °C	10 ton	normal speed
EU VI route 2	Cold start, 10 °C	10 ton	normal speed
EU VI route 2	Cold start, 20 °C	10 ton	normal speed
EU VI route 2	warm start, 0 °C	10 ton	normal speed
EU VI route 2	warm start, 10 °C	10 ton	normal speed
EU VI route 2	warm start, 20 °C	10 ton	normal speed
PEMS-Pilot-route	10 °C	10 ton	normal speed
PEMS-Pilot-route, counter clockwise	10 °C	10 ton	normal speed
Random cycle	20 °C	10 ton	normal speed
Real world route (distribution test route)	10 °C	10 ton	normal speed

Zeroing (pre-test, auto, and post-test) been performed with nitrogen gas. The zero-span results have been saved within the test data files and the results are presented as drift corrected.

Test fuel specifications characteristics: All tests were performed with commercially available Diesel (MK1), fuel data used for the calculations; Table 19

Table 19 Fuel Data

MK1	
Assumption	
Density at 15°C:	815 kg/m^3 (average of SIS 800-830 kg/m^3)
Sulphur content:	2 ppm (approximately, standard data from Preem)
Carbon [% of weight]:	86.2248
Hydrogen [% of weight]:	13.775
Sulphur [% of weight]:	0.0002

ECU Protocol for PEMS logging: ISO 15765-4

Test evaluation

Certification limits used for the evaluation: **Table 20**

Limits used for calculation of EU conformity factors: **Table 20**

Table 20 EU emission standard for Euro VI vehicles, and proposal for maximum allowed EU conformity factors

	NOx	CO	THC	PM
Emission limit (g/kWh)	0.46	4.0	0.16	0.01
Maximum allowed conformity factor	1.5	1.5	1.5	1.5*

***CF for PM is not yet established**

Test results

Results from Chassis Dynamometer

The chassis dynamometer inertia during the tests was 20 tons (max load for the dynamometer), which is approximately 10 % of maximum vehicle load and corresponds to a lower load compared to the engine load applied during a WHTC or an ETC. The simulated load on chassis dynamometer is also lower than most road tests.

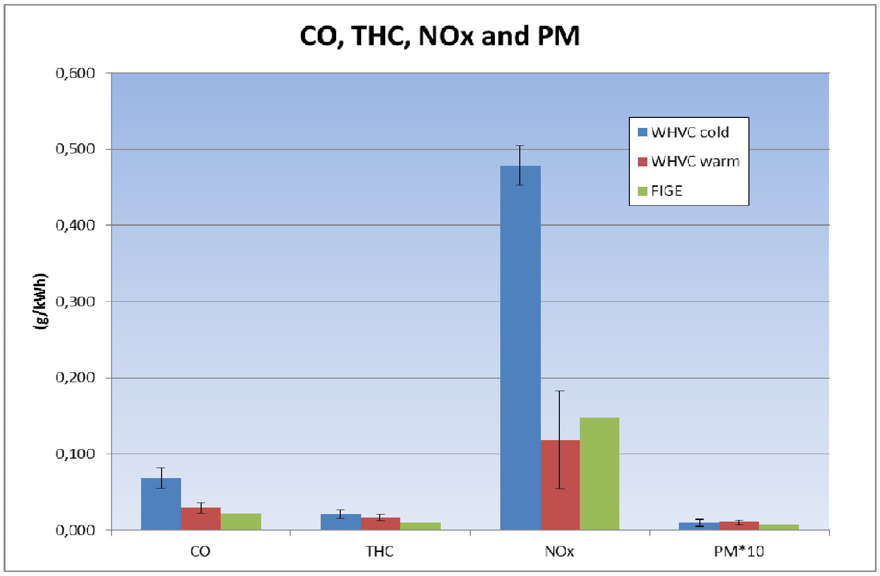

Figure 36 Test results regulated emissions, Chassis dynamometer

Emissions of NOx are higher during the cold start test, still well below the Euro VI emission limit for WHTC test. The particulate emissions are very low during all tests. The CO emissions are a little higher during the cold start test, but both CO and THC emissions are close to the detection limit.

The emissions during the chassis dynamometer test are in the same range as for the PEMS test.

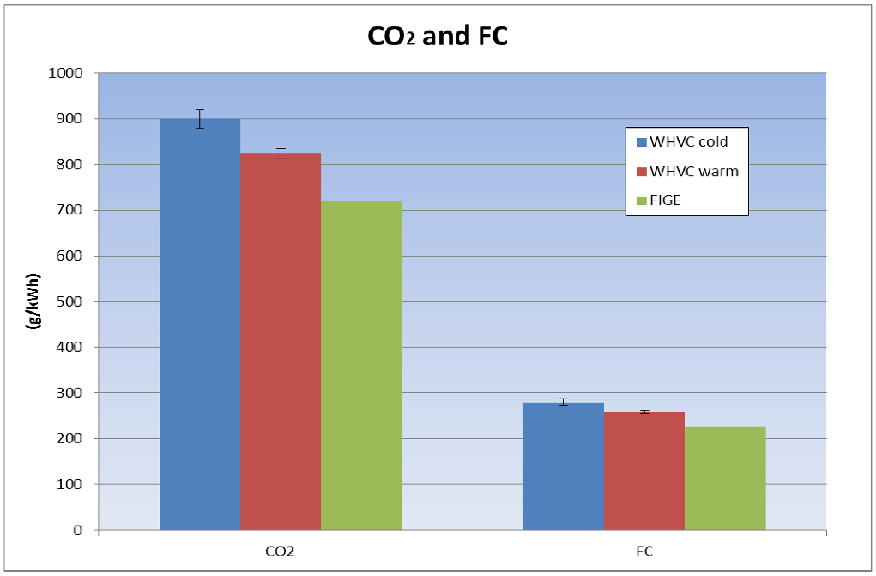

Figure 37 Test results CO2 and Fuel Consumption, Chassis dynamometer

Also the CO_2 and fuel consumption during the chassis dynamometer test are in the same range as for the PEMS test.

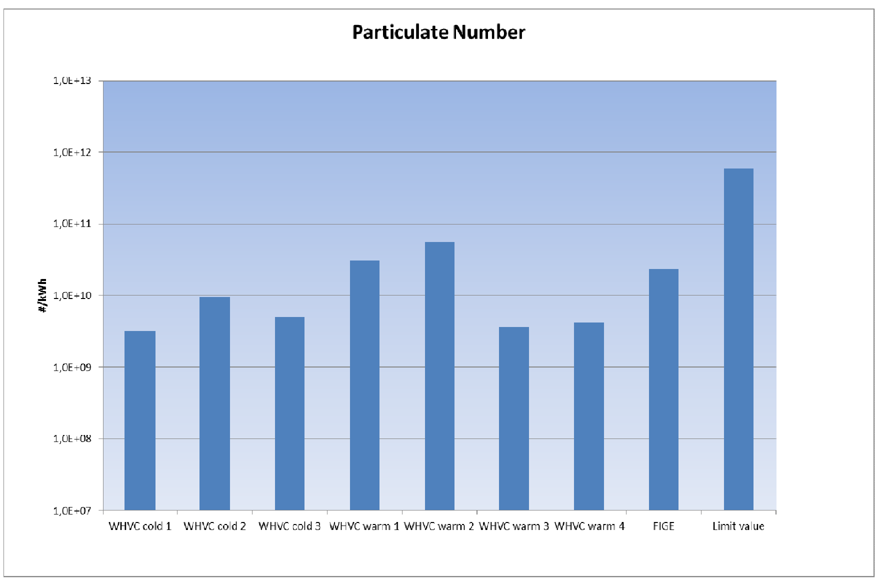

Figure 38 Particulate number, Chassis dynamometer

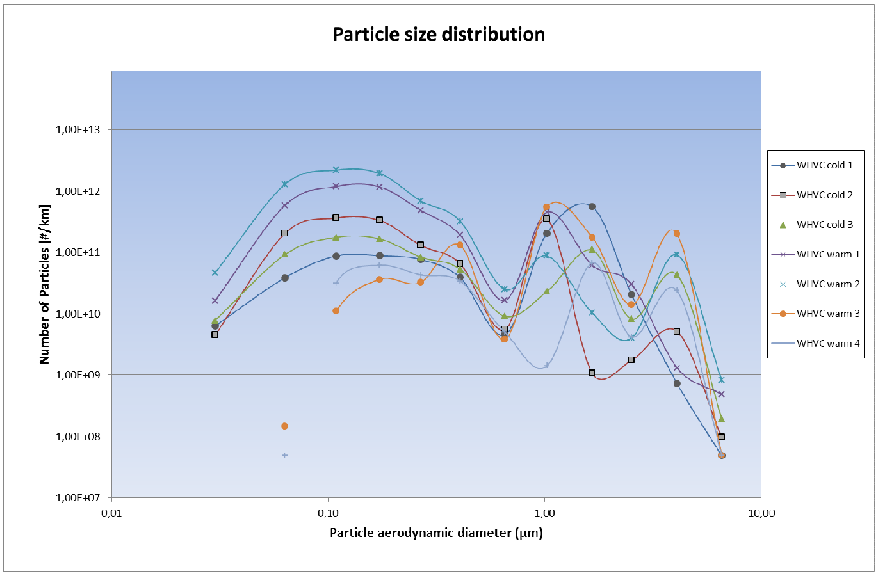

Figure 39 Particulate size distribution, Chassis dynamometer

Particulate number is well below emission limit for the WHTC. The first two warm tests show a significantly higher PN result compared to the last two. The subsequent cold star test (WHVC cold 2) also shows raised levels. The reason for this is unclear but may be due to particulate filter regeneration during the test preparation prior to WHVC warm 1. The amounts of small particles during these tests are also higher compared to the other tests which support the theory.

Influence of different aspects of test route composition on the emission levels and the Conformity Factor

The exhaust emissions of the vehicle were in most cases well below the emission limits for all of the regulated emissions. The influence of trip composition on the emission levels and the conformity factor seems to be limited.

However, a factor with a very clear influence on the test results when testing this vehicle was the 20% power threshold boundary. For this vehicle the power during the urban part was close to 20%, and depending on the amount of driving on each side of the boundary, different amount of data was invalidated which consequently influenced the conformity factor. By designing a “softer” urban part, more urban driving emissions would probably be invalidated and since most NOx emissions are emitted during the urban part, this may be a benefit for many vehicles.

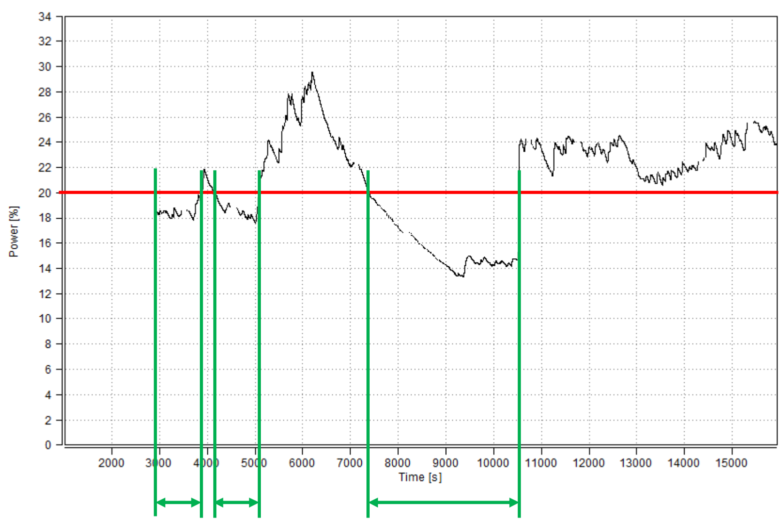

Figure 40 Test with much of the urban part below the 20 % power threshold

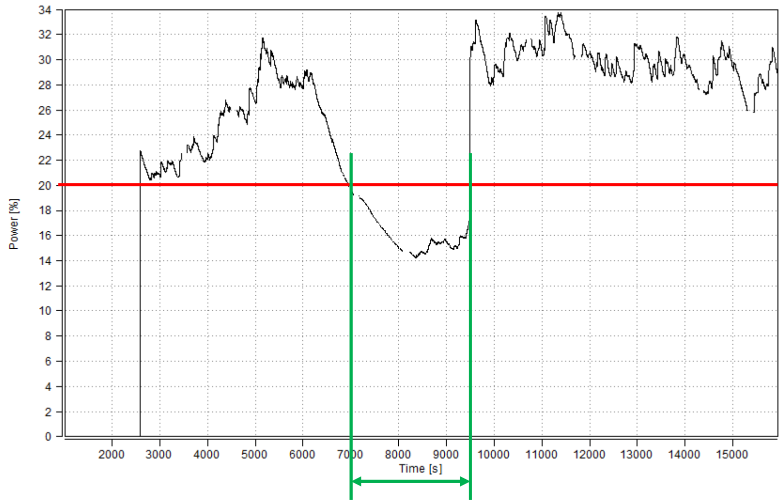

Figure 41 Test where the whole urban part is above the 20 % power threshold

Comparing the EUVI-route driven forwards vs backwards, expected NOx results were achieved. When starting with the motorway part, higher temperatures were reached earlier in the test and therefore were lower levels of NOx obtained. It is however not clear why the levels of PM are higher when driving backwards, but the levels are very low (Figure 44).

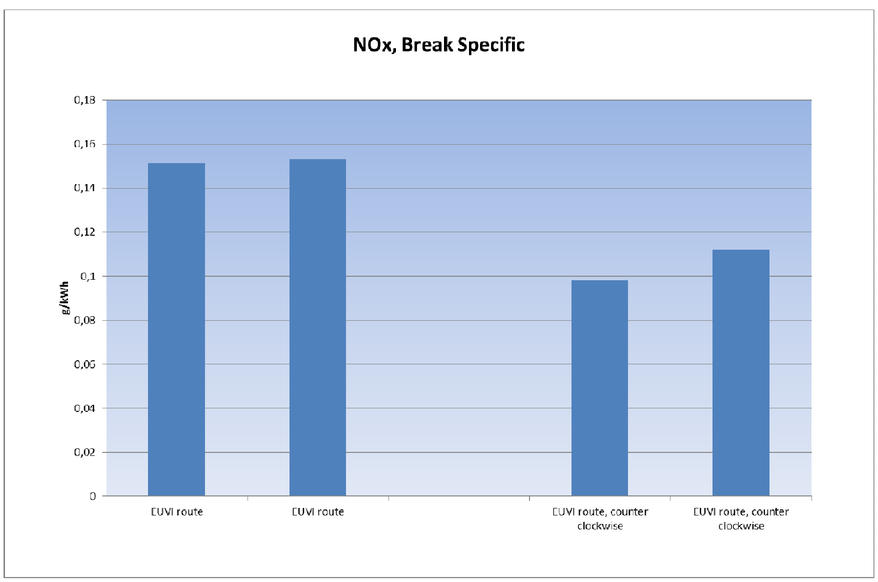

Figure 42 NOx emissions All events during the EUVI route

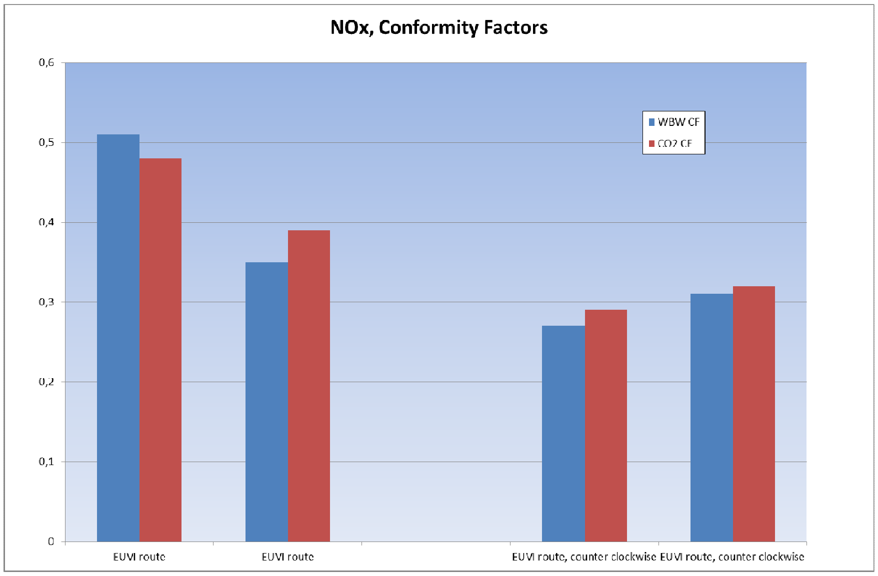

Figure 43 NOx conformity Factors during the EUVI route

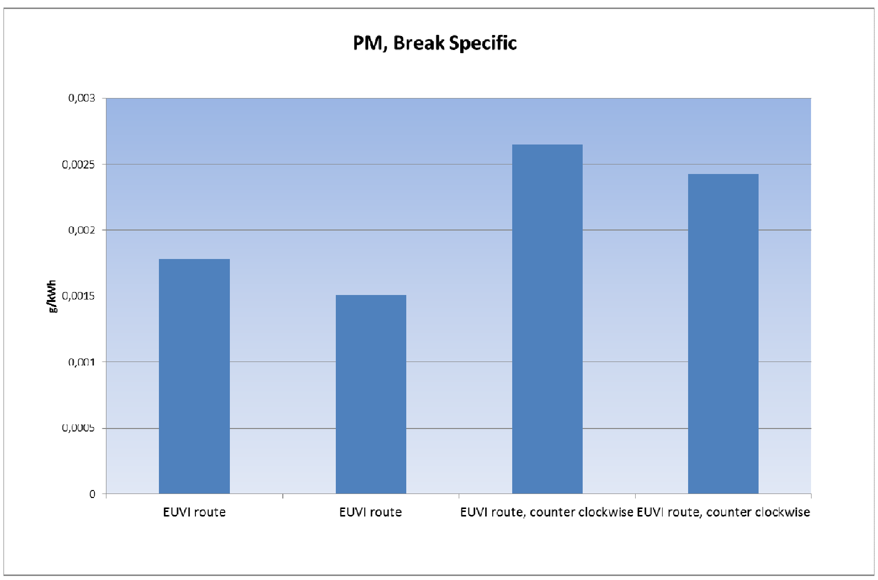

Figure 44 PM emissions All events during the EUVI route

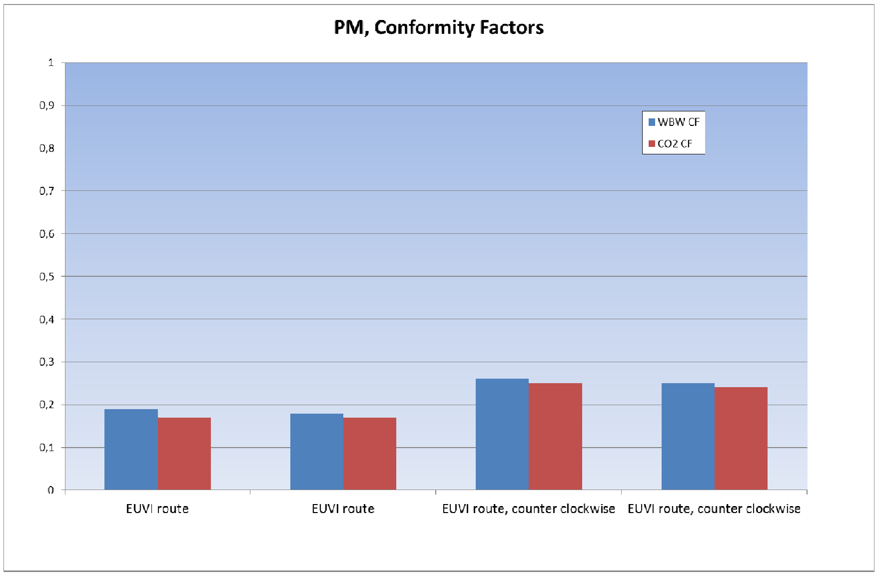

Figure 45 PM Conformity Factors during the EUVI route

The EUV Pilot test route did not show the same clear trend as the Euro VI-route when driving it forward vs backward and very unstable results were obtained. When studying the results more in detail, it was discovered that the starting conditions were slightly different. All EUV Pilot tests starts with the approximately the same coolant temperature, but for test 1 and 4, the exhaust temperature is lower which is immediately reflected in the NOx emissions.

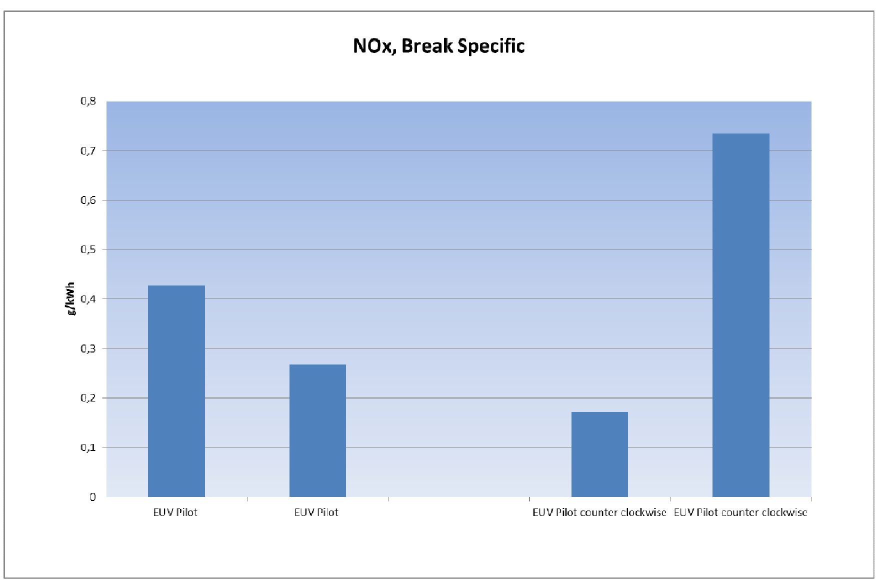

Figure 46 NOx emissions All events during the EUV Pilot route

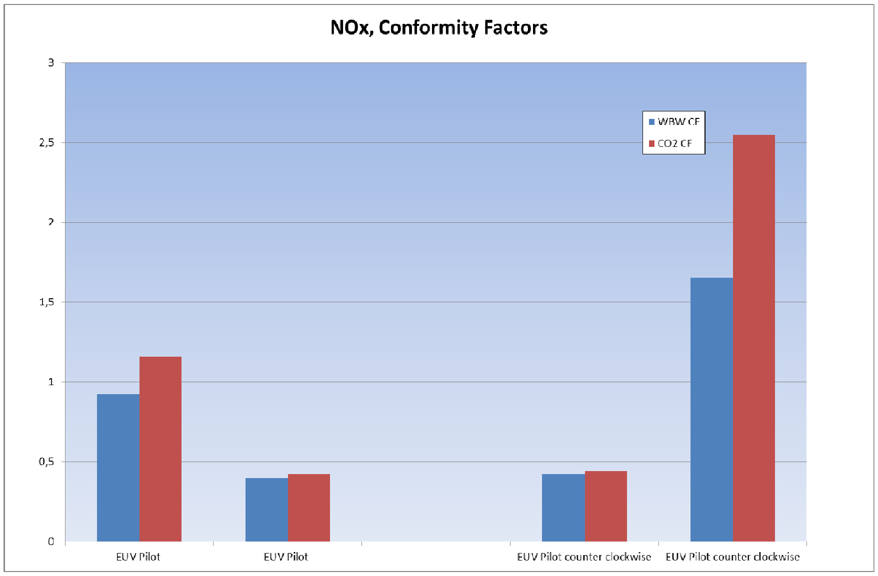

Figure 47 NOx conformity factors during the EUV Pilot route

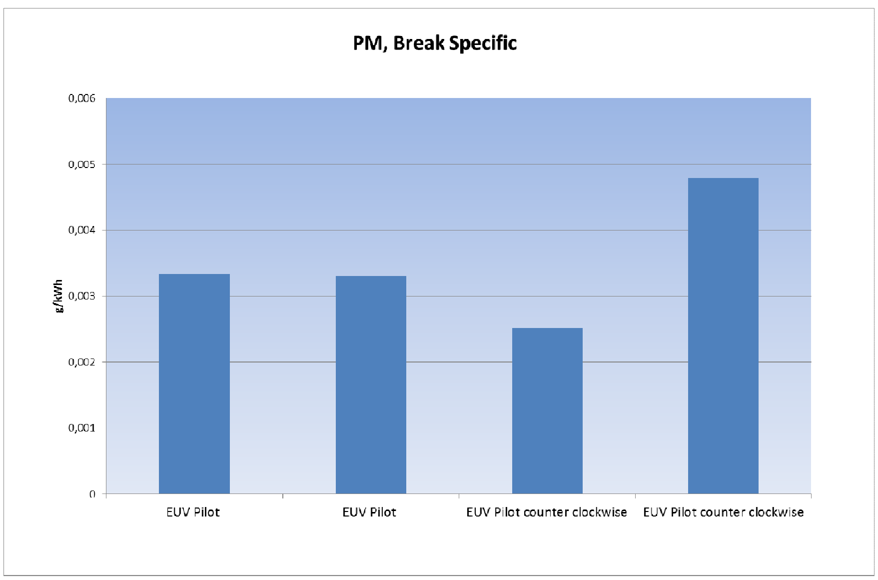

Figure 48 PM emissions All events during the EUV Pilot route

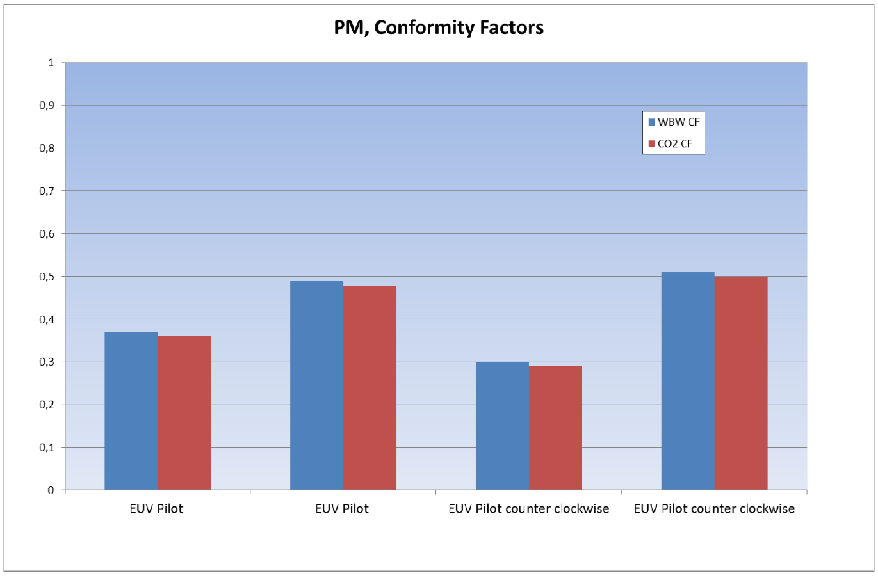

Figure 49 PM conformity factors during the EUV Pilot route

The preconditioning of the vehicle prior to the test plays a far more important role compared to when testing an older, higher emitting vehicle. Although the coolant temperature of all warm start tests is approximately the same, the exhaust gas temperature may vary. All EUV Pilot tests with higher emissions of NOx have a lower exhaust gas temperature when the test starts compared to the other tests. When the exhaust gas temperature in the beginning of the test is not high enough for the SCR to work, this will result in higher NOx emissions which may influence the conformity factor.

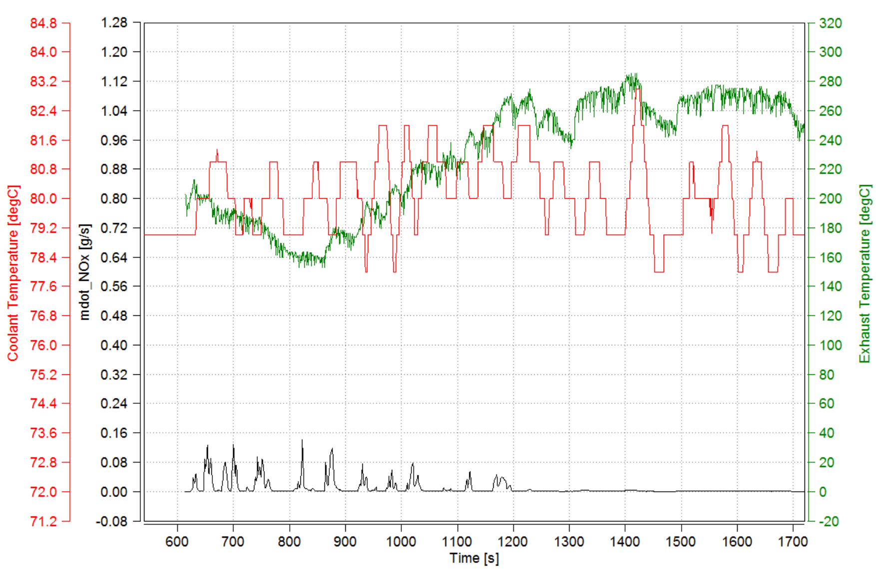

Figure 50 First EU V Pilot counter clockwise with low NOx emissions and high initial exhaust gas temperature

Figure 51 shows a warm start test where the exhaust gas temperature in the beginning of the test is too low for the SCR-system to work properly.

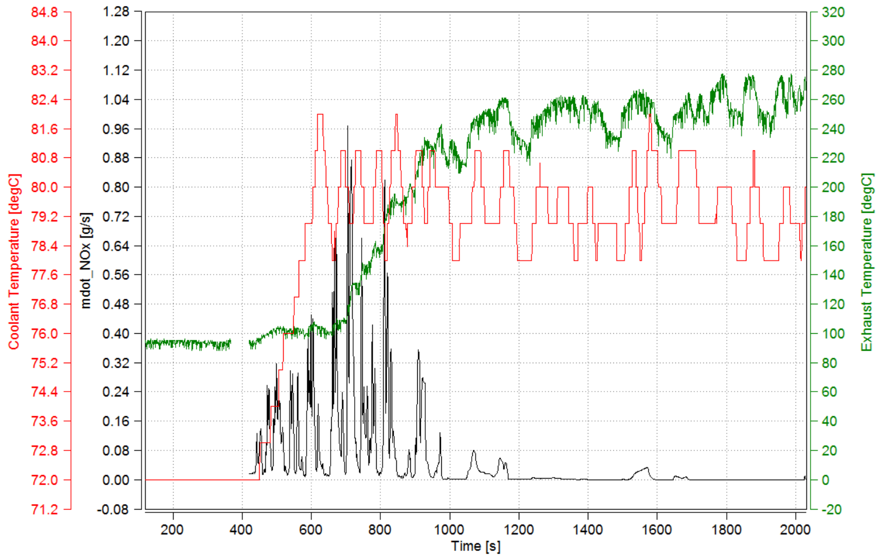

Figure 51 Second EU V Pilot counter clockwise with high NOx emissions and low initial exhaust gas temperature

Figure 52 present break specific NOx emission results for each individual test. Figure 53 show the conformity factors.

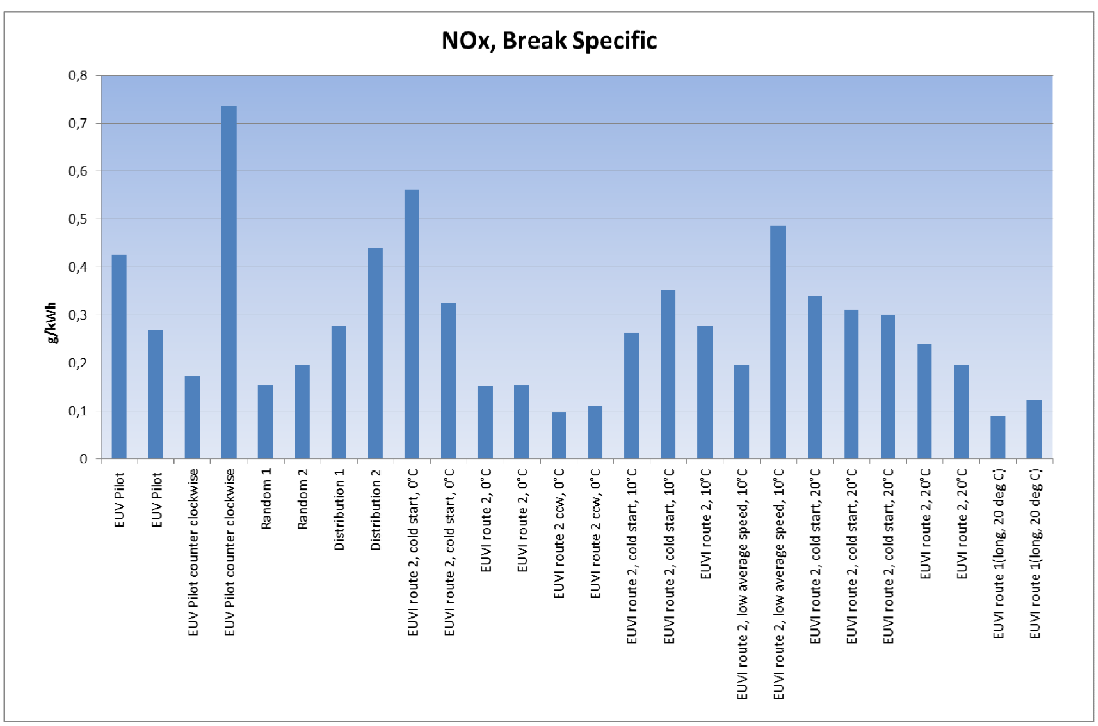

Figure 52 NOx emissions All events

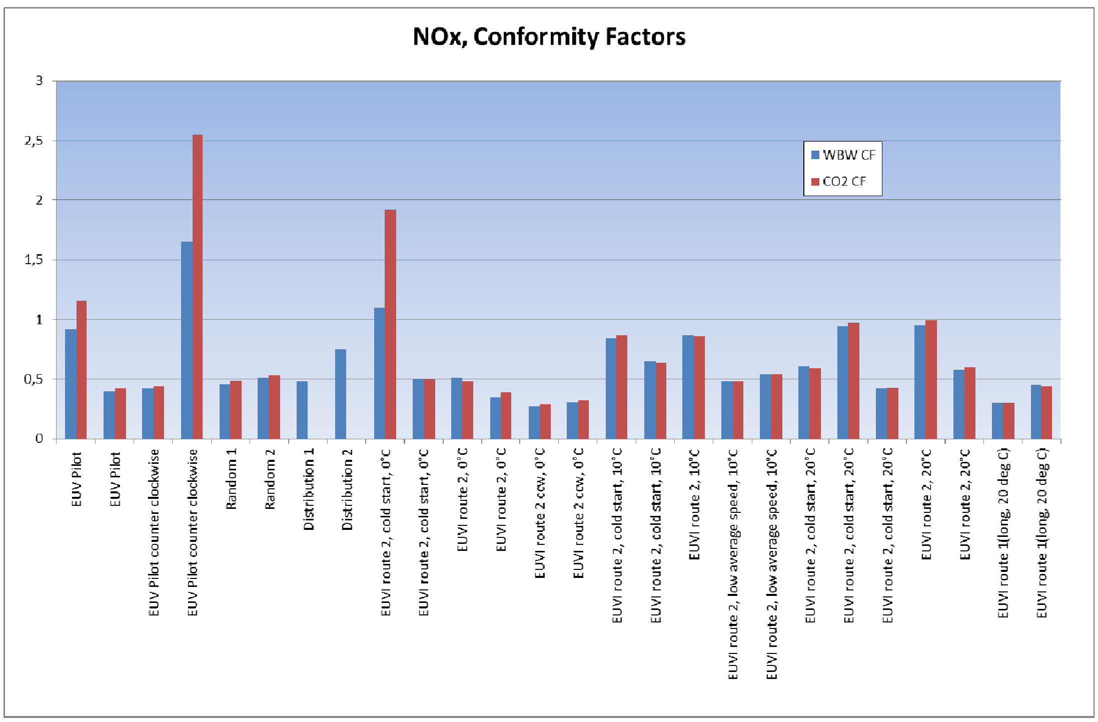

Figure 53 NOx conformity factors

Figure 54 present break specific PM emission results for each individual test. Figure 55 show the conformity factors. The influence of test route composition on the emissions of PM seems to be limited.

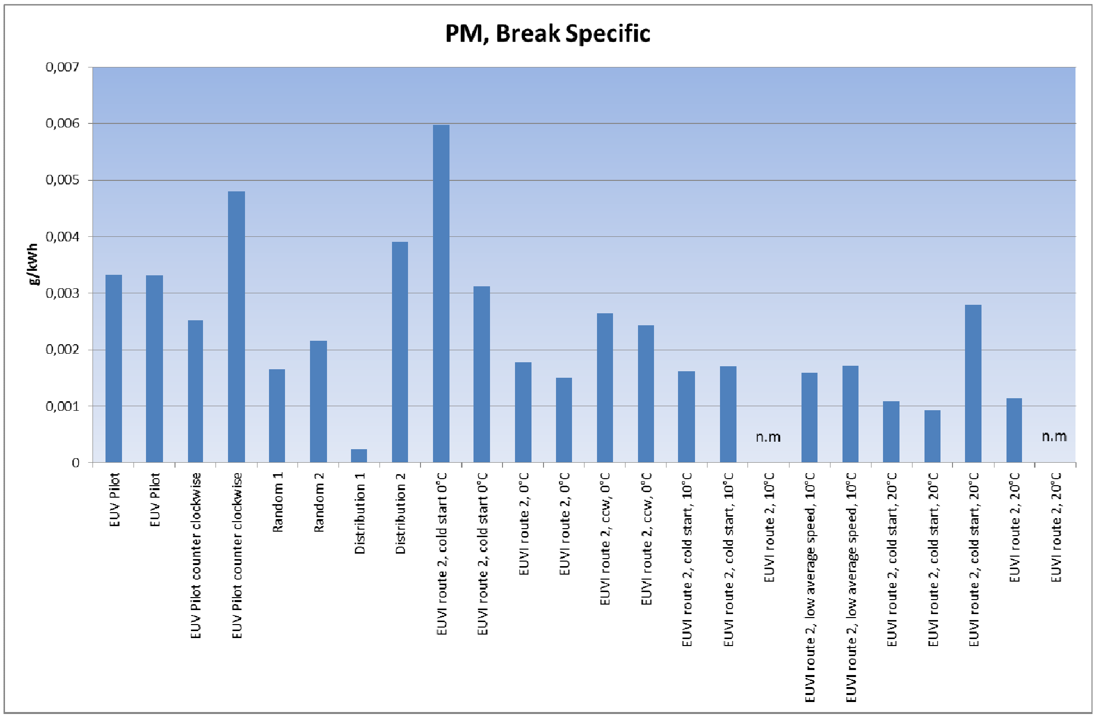

Figure 54 PM emissions All events

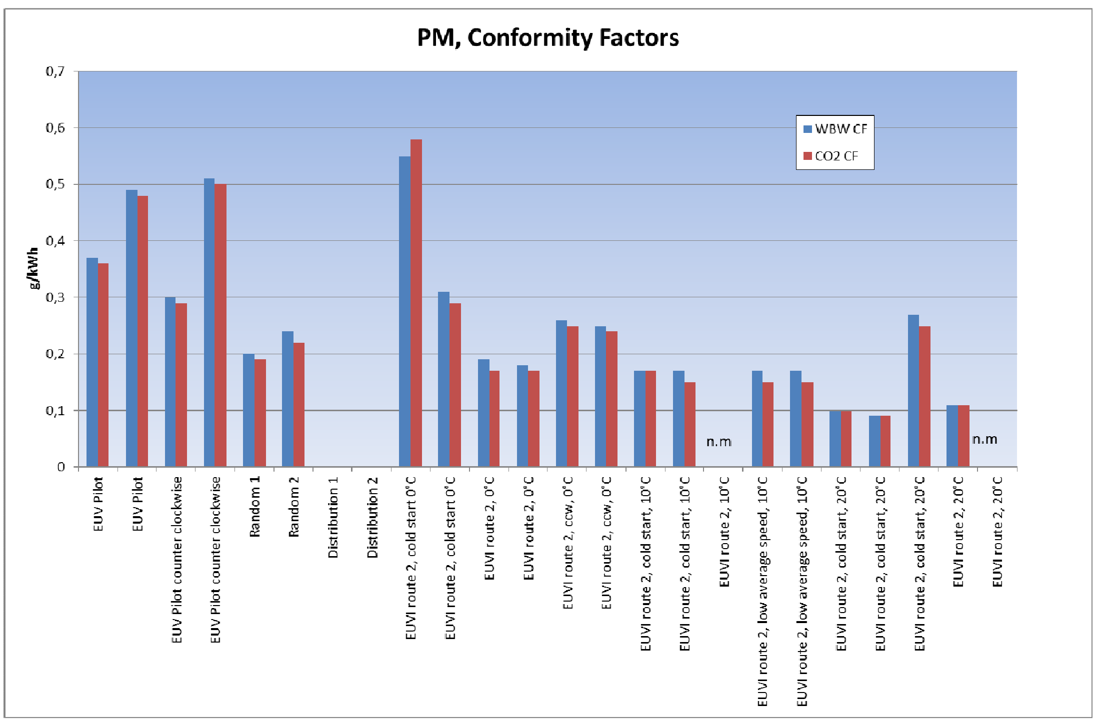

Figure 55 PM conformity factors

Influence of speed variations within the legal boundaries on the emission levels and conformity factor

According to the requirement shall the PEMS trip consist of a certain amount of urban, rural and motorway operation. Each driving operation is characterized by vehicle speeds within a certain span (Table 17). An investigation was made of how the emission levels were influenced by trying to drive the test route as close as possible to the lower speed targets i.e. as close as possible to the lower limit for urban, rural and motorway driving respectively. From the tests performed could no clear conclusion be drawn regarding emission levels, however it was found that it is very difficult to, on the road in real life traffic, drive close to a certain speed limit and still end up with a test with the right trip composition.

Influence of different ambient temperatures on the emission levels and the Conformity Factor/ How a Euro VI vehicle performs at cold start during start at different ambient temperatures

Cold start and warm start tests were performed at 0°C, 10°C and 20°C.

When looking at the test results it is important to keep in mind that the tests at ambient temperature 0°C were performed at a different test occasion than the other tests. At the low emission levels measured, mileage accumulation may cause small variances of for example engine performance or aftertreatment system performance, which could be reflected in the result. In this case, it can be suspected that the emission performance for NOx was a little bit better when the vehicle was tested the first time.

One test, "cold start 0°C, test 1", which was the first test performed in the series, clearly stands out from the other tests regarding emissions of NOx and has therefore been removed from average calculations in this investigation. However, since it's a non-fail result regarding Conformity Factor and there is no indication of vehicle failure, the individual test result is presented in order to demonstrate variance of emission performance of an otherwise well performing vehicle.

The test results show that cold starts have a large influence of the NOx emissions when looking at "all events" and the influence of the cold start becomes more clear the lower the ambient temperature is (**Figure 56** and **Figure 57**).

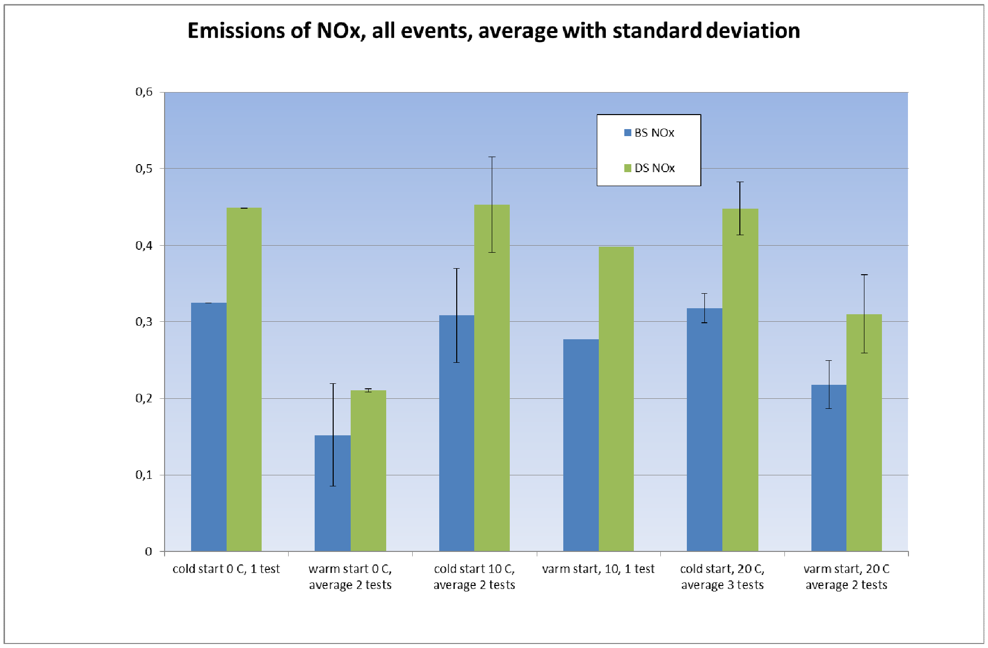

Figure 56 All event NOx emission results, average test results

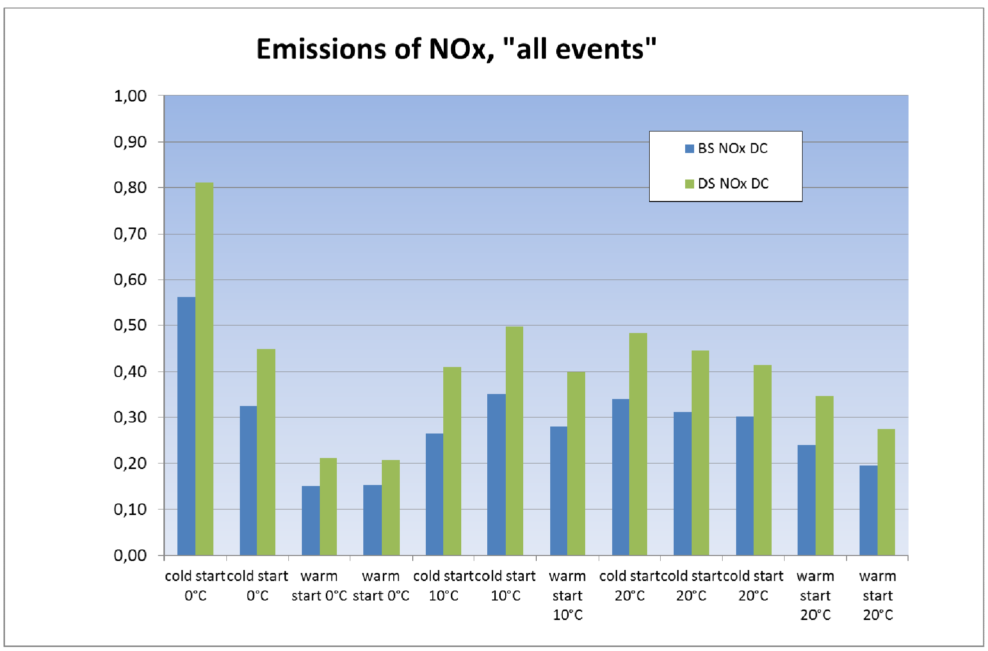

Figure 57 All event NOx emission results, individual test results

However, the cold start does not automatically generate a higher conformity factor in comparison to the warm start test (Figure 58 and Figure 59) since the variation of the influence from the data exclusion (Described in chapter “Test information”) is large. The factor with the clearest influence on the test results when testing this vehicle was not, as perhaps expected, the low coolant temperature exclusion, but the power threshold boundary. Even though the same test route and the same driver was used for each test, the power during the urban part moved around 20%, and depending on the amount of driving on each side of the boundary, the influence of this data invalidation strategy varied.

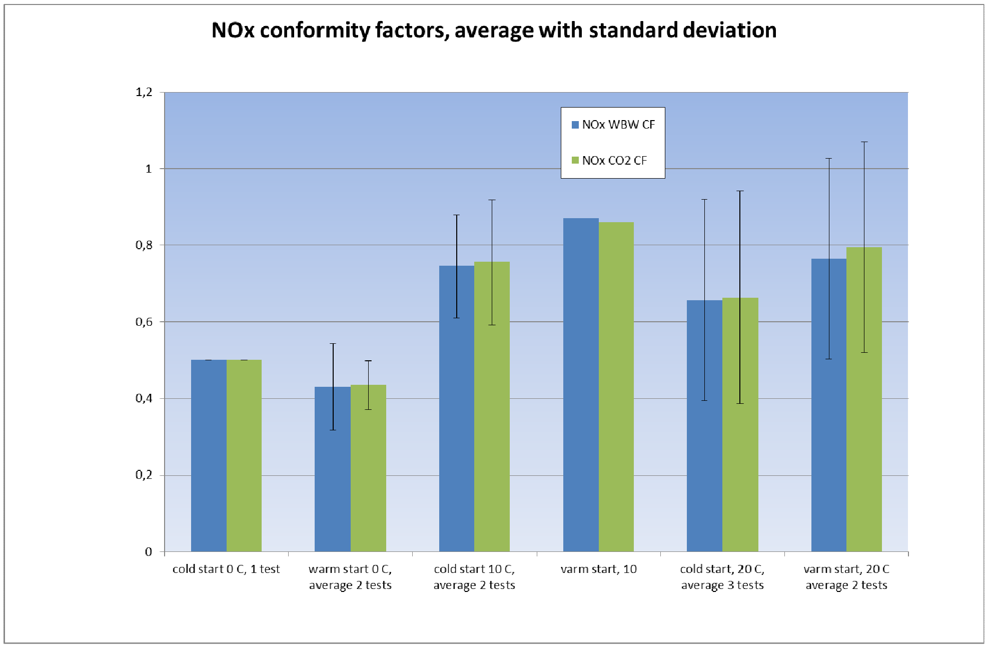

Figure 58 Conformity Factor NOx, average test results

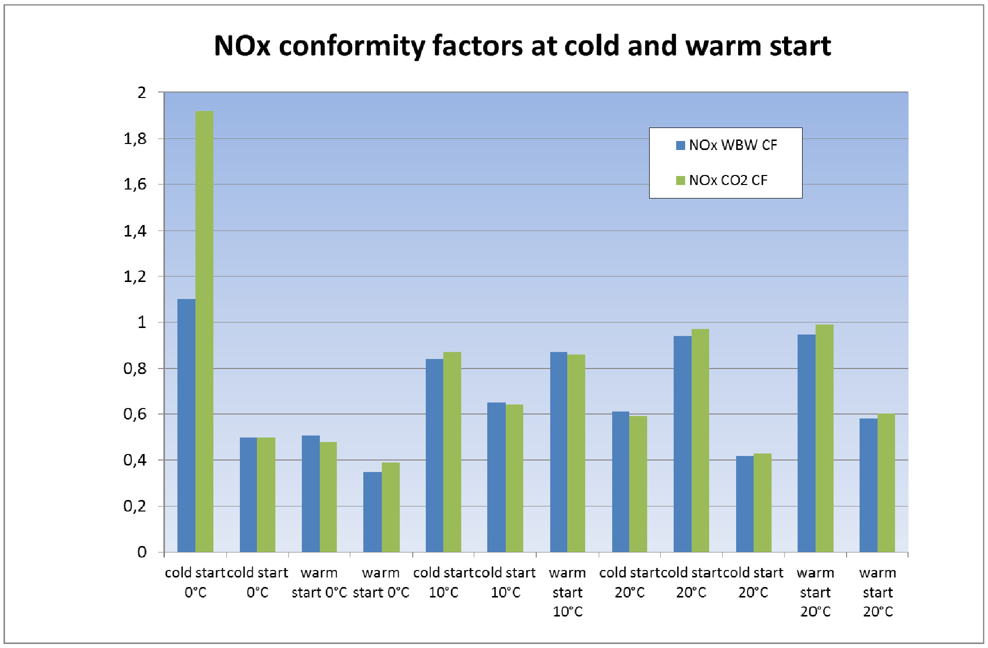

Figure 59 Conformity Factor NOx, individual test results

The majority of the NOx emissions are emitted during the first 15-20 minutes of the test which is approximately half of the urban driving. Cold start clearly results in higher NOx emissions compared to a warm start. A cold start at 0°C results in higher NOx emissions than a cold start at 10°C and cold start at 10°C results in higher NOx emissions than cold start at 20°C. A warm start at 10°C results in higher NOx emissions than a warm start at 20°C. If all tests had been performed at the same test occasion, warm start at 0°C would most likely have generated more NOx emissions than warm start at 10°C.

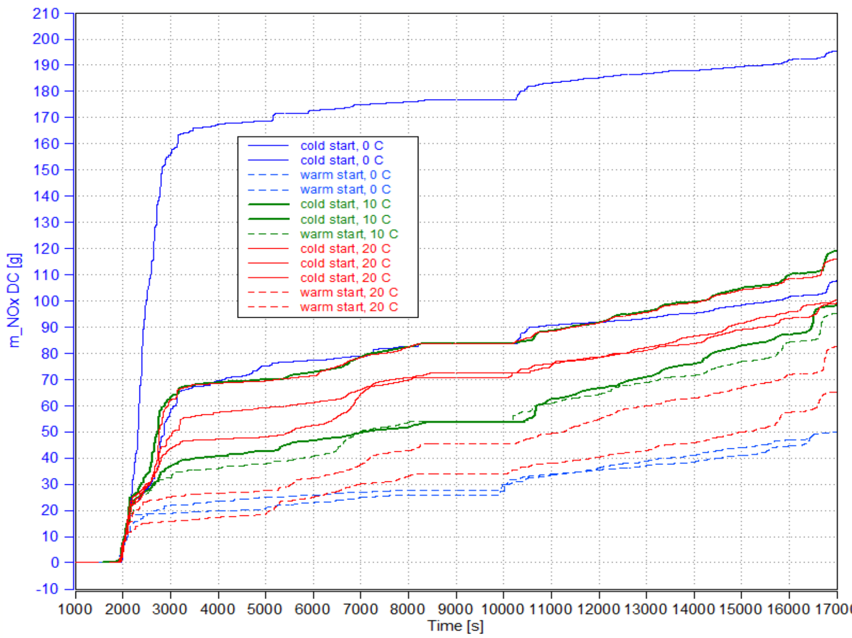

Figure 60 Accumulated emissions of NOx during all tests

The test results show that there is no effect of different ambient temperatures on a warmed up vehicle operating in rural or motorway speeds. Also in urban driving the ambient temperature does not seem to matter once the vehicle has reached optimal operating temperatures.

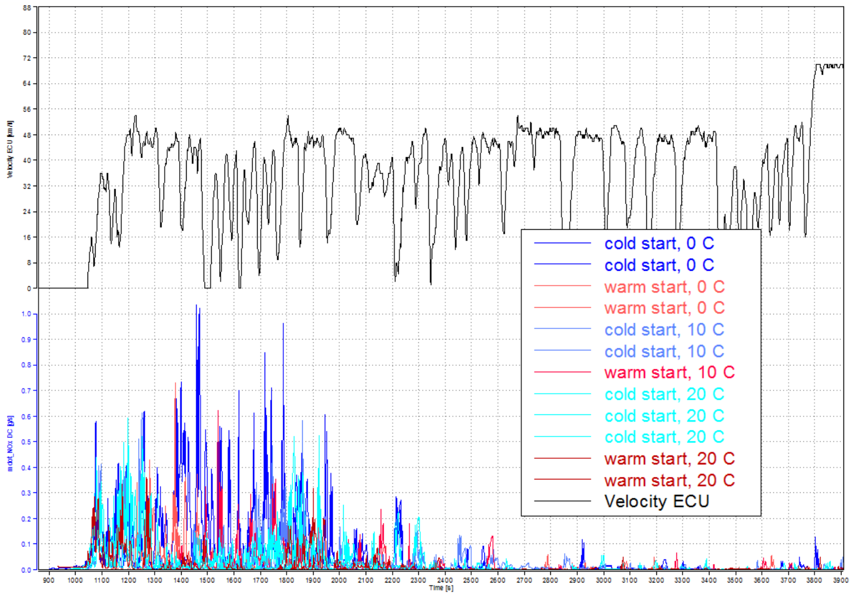

Figure 61 Emissions of NOx during urban driving

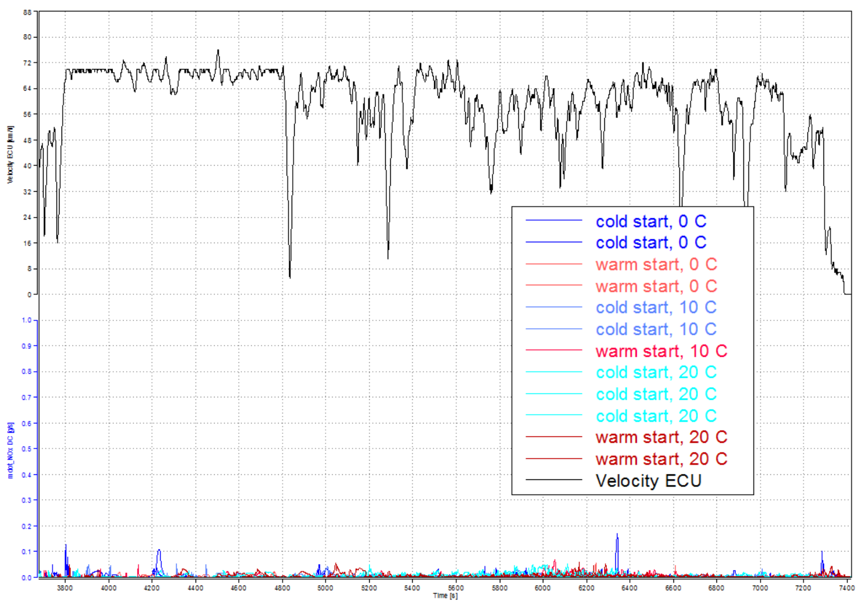

Figure 62 Emissions of NOx during rural driving

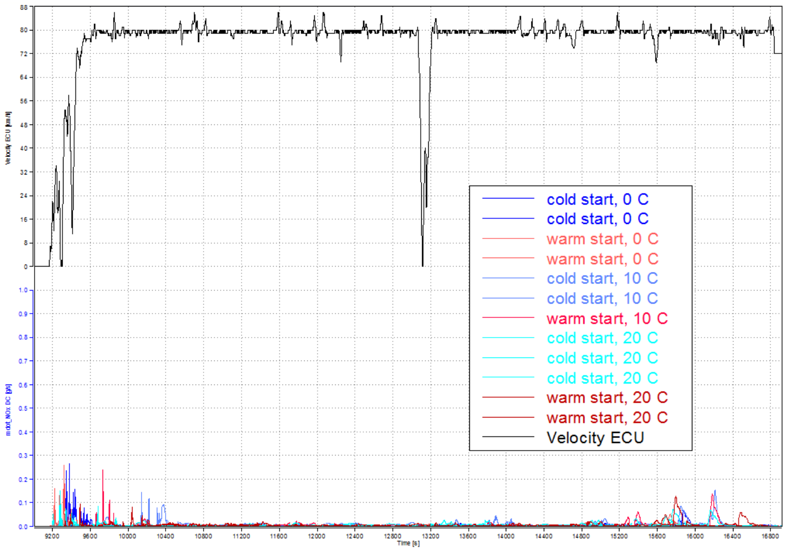

Figure 63 Emissions of NOx during motorway driving

In the first "0°C" cold start test, with higher NOx peaks in the beginning of the test (Figure 64), the driving power during the first part of the test is higher compared to the second "0°C" cold start test (Figure 65), thus, the 20% power threshold invalidates less data which results in a higher conformity factor.

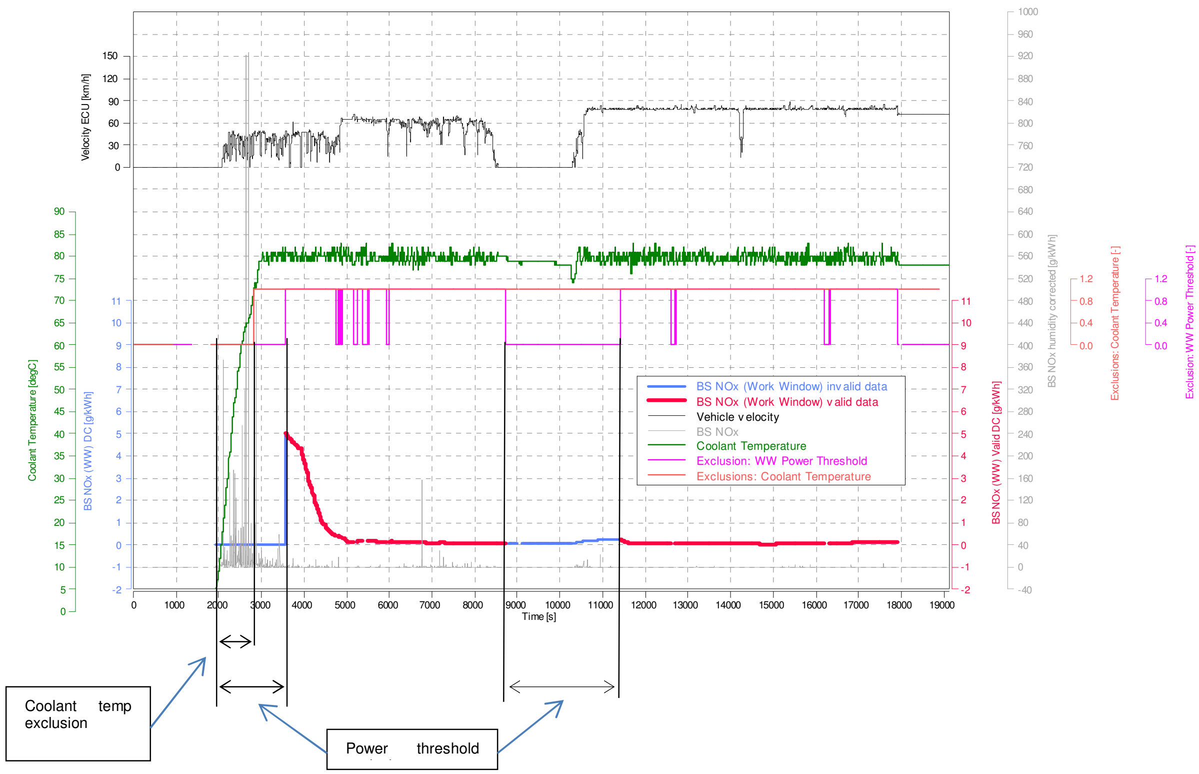

Figure 64 Effect of data exclusion, cold start test 1, +3°C

In the second 0°C cold start test, (Figure 65), the driving power during the first part of the test is lower and the 20% power threshold invalidates more data which results in a lower conformity factor. Emissions emitted during most of the urban part are in this case excluded from the test.

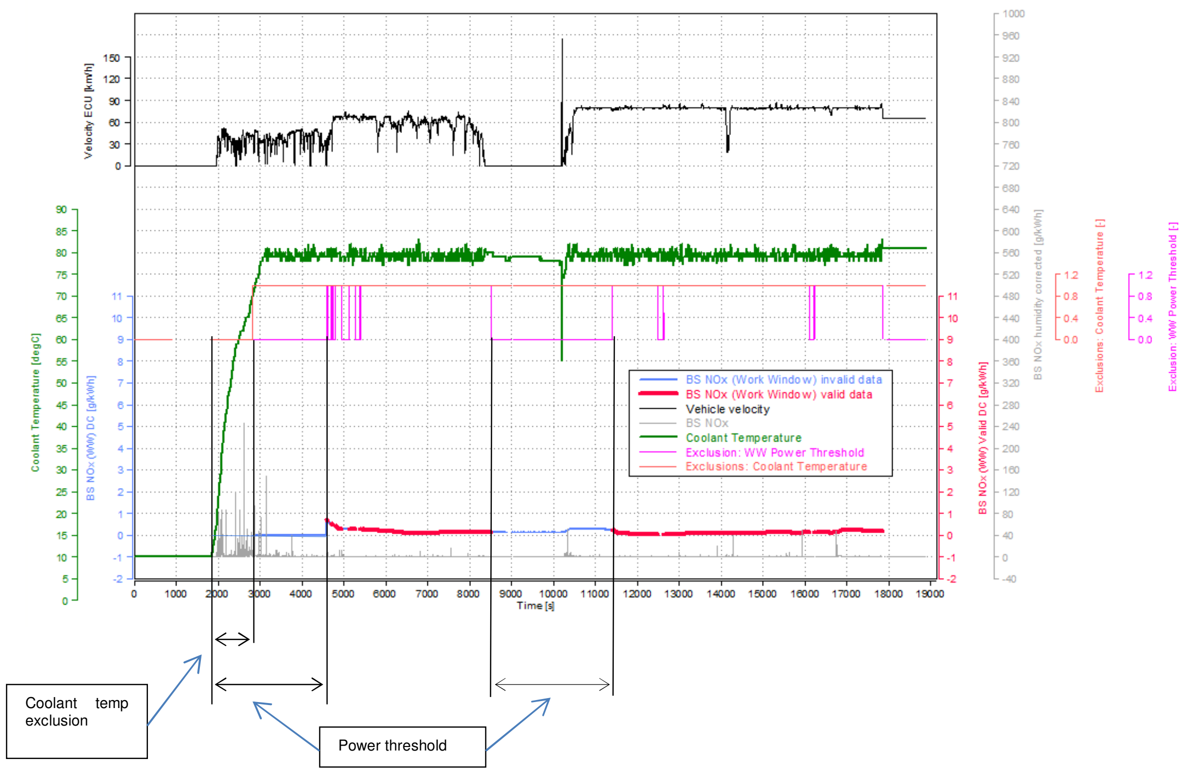

Figure 65 Effect of data exclusion, cold start test 2, -2°C

Despite that the exhaust gas temperature reaches optimum levels (above 220°C) about the same in the first 0°C cold start test as in the second, the emissions of NOx does remain on a high level for a longer time in the first cold start test. The reason for this is not clarified but the aftertreatment systems of Euro VI vehicles are complicated and there are several possibilities. The previous usage of the vehicle may under certain conditions give a different initial start-up response in NOx. A SCR system without urea stored on the catalytic surface could possibly give raise to such high initial NOx levels. Another possible cause may be particulate filter regeneration prior to the test.

With the current data exclusion methods, cold start emissions are in most cases almost completely eliminated from the test. If cold start should be implemented in the legislation there is a need to change how the calculation is performed. JRC (Joint Research Center) is looking at several alternatives.

In the first 0°C cold start test, the CO_2 based window conformity factor for NOx is approximately 40% higher than the corresponding Work Based Window conformity factor. This was only seen for the NOx Conformity factors and only during this test. The reason for this is unclear.

Cold start at 0°C resulted in significantly more PM emissions compared to the corresponding warm start tests. For cold starts at higher temperatures, no significant difference could be seen compared to the corresponding warm start tests. Unfortunately, the PM measurement in the warm start test at 10°C failed.

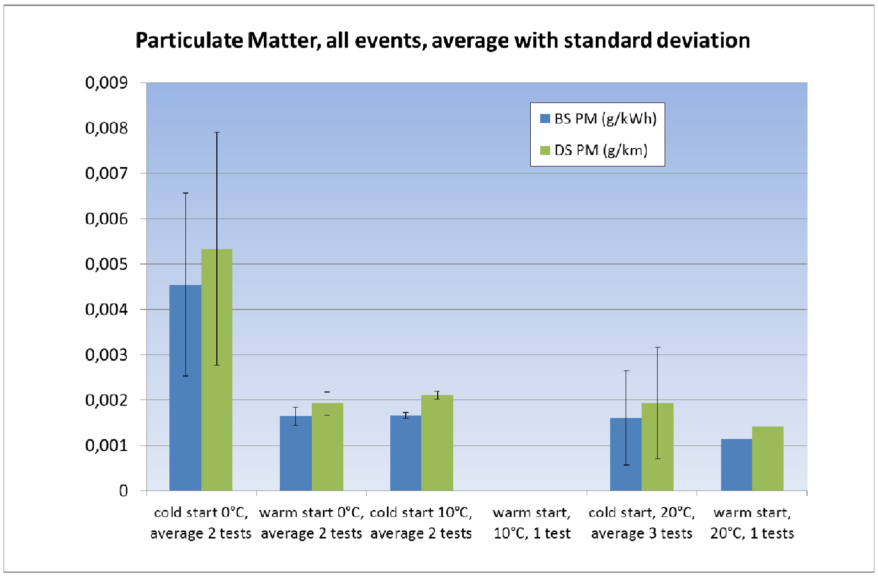

Figure 66 All event PM emission results, average test results

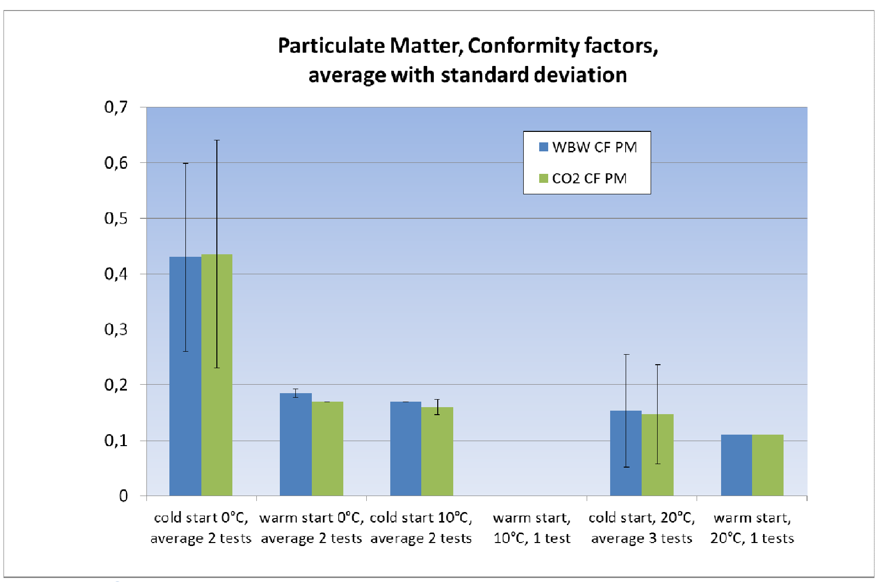

Figure 67 Conformity Factor PM, average test results

Influence of different payloads on the emission levels and the Conformity Factor (and fuel consumption)

The influence on the real world driving emissions when driving with different payloads (10%, 50% and 90% of European maximum allowed payload (40 ton). 50% and 90% maximum allowed EU payload corresponds to 10% and 50% maximum allowed Swedish payload (60 ton)), was investigated (detailed information **Table 18**) . The gaseous emissions NOx, THC and CO was measured as well as Fuel consumption. THC was very low.

For this vehicle, emissions of NOx and NOx CF are lowest when the vehicle load is 10 tons which corresponds to approximately 50% of maximum 40 ton.

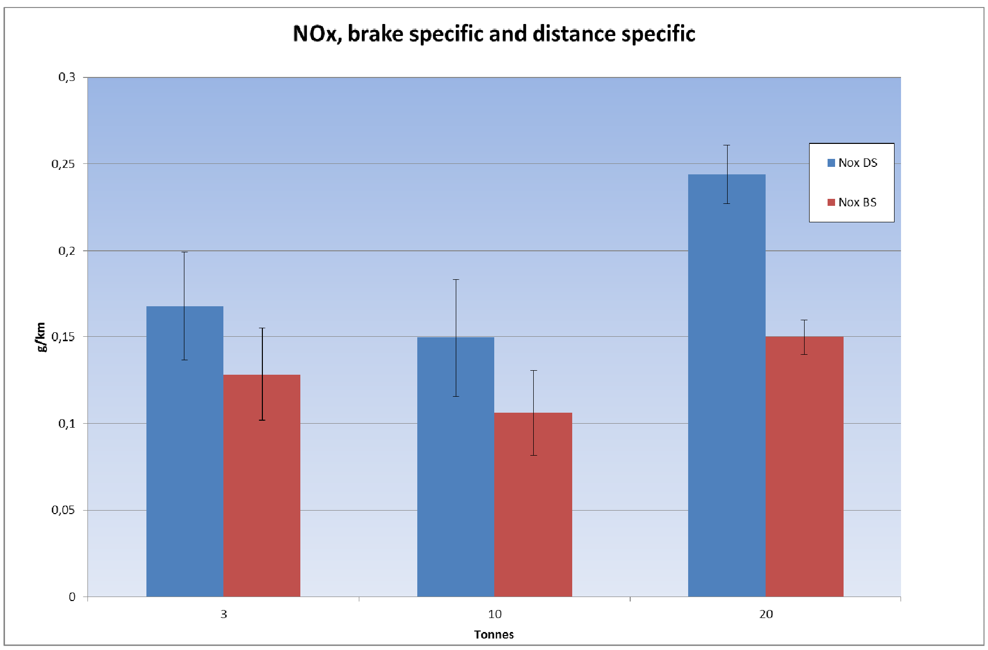

Figure 68 NOx at different loads

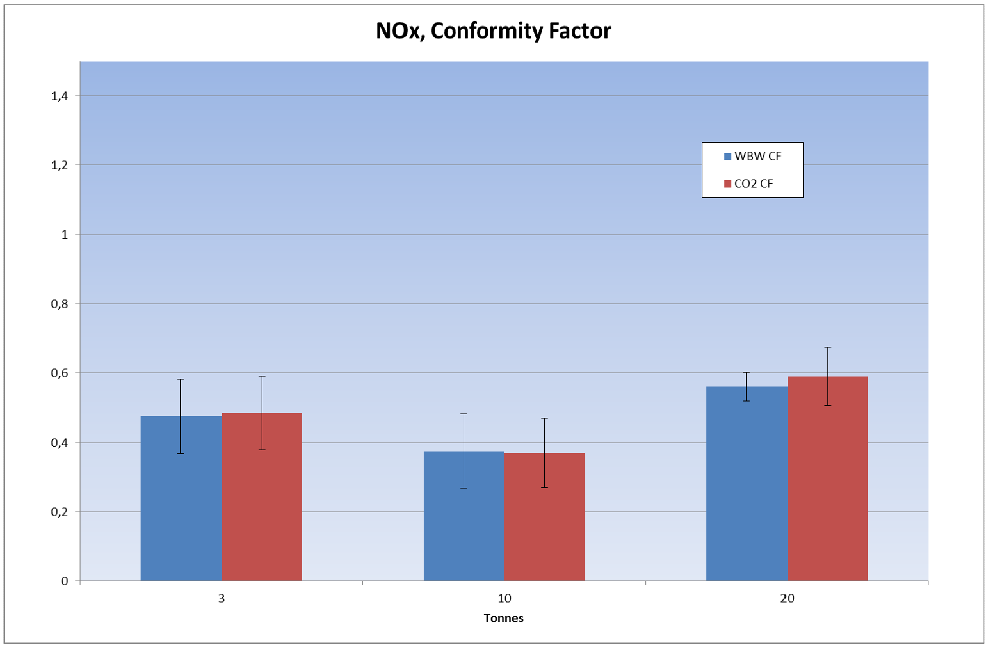

Figure 69 NOx CF at different loads

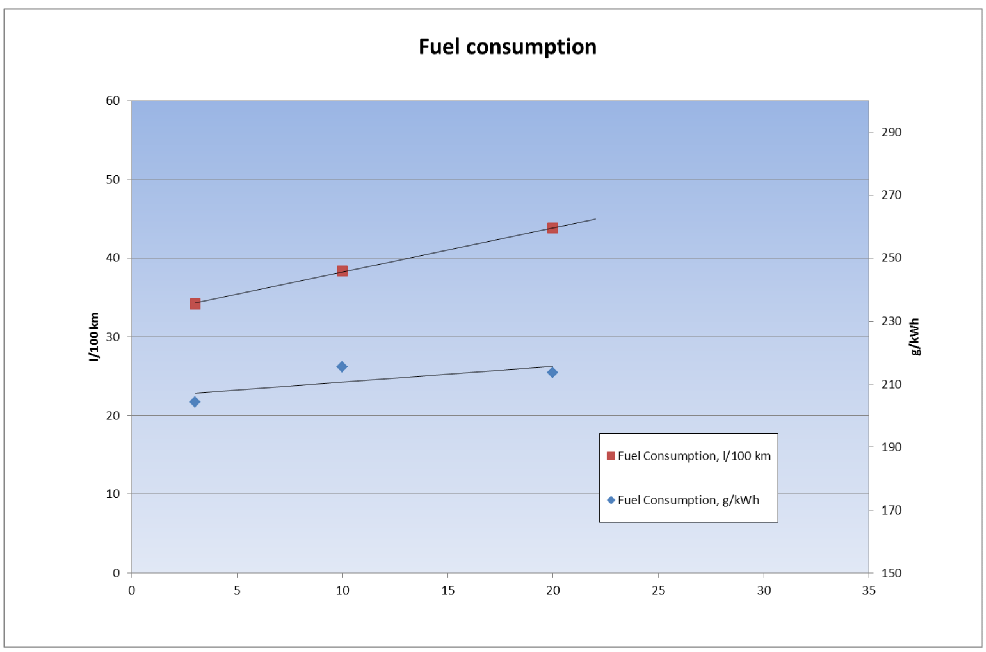

Figure 70 Fuel consumption at different loads

As expected, the distance specific fuel consumption increased at higher loads while the brake specific fuel consumption remained relatively constant (Figure 70). The distance specific fuel consumption per transported ton decreased with higher load (Figure 71).

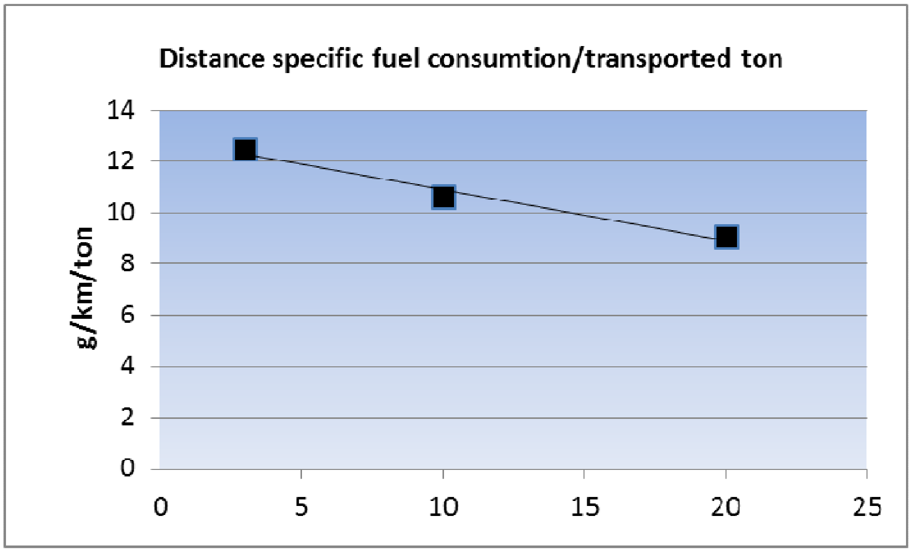

Figure 71 Distance specific fuel consumption per transported ton

Conclusions

The influence of trip composition on the emission levels and the conformity factor seems to be limited. However, a trip designed to a faster warm up of the SCR system may result in lower NOx emissions. The 20% power threshold may influence the conformity factor by excluding emission data from the urban part of the trip.

Preconditioning before the test seems to have a large influence on the test result. According to the legislation the test shall start after the coolant temperature has reached 70 C or is stable more than 5 minutes, but it does not involve exhaust gas temperature. Even if the coolant temperature prior to the test is the same for all tests, are differences in exhaust gas temperature possible and may influence the test result.

Study of the data from this vehicle indicates that a cold start will influence the emission result, but not necessarily the conformity factor.

Analysis of the data from this vehicle shows that different payloads do affect the results but not significantly. The lowest conformity factor was achieved with a 50% (of 40 tons) payload. However, data from other vehicles of the same category, analyzed by JRC, show their lowest conformity factors on other loads[1].

[1] JRC Presentation, 5TH Meeting PEMS Experts Working Group

Appendix 1: Test results

Drive cycle	CO		THC		NOx		NO_2		CO_2		PM		PN		FC	
	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(#/kWh)	(#/km)	(g/kWh)	(l/100km)
WHVC cold 1	0.075	0.090	0.024	0.028	0.501	0.600	0.041	0.049	922	1105	0.0015	0.0018	3.1.E+09	3.8.E+09	288	42.2
WHVC cold 2	0.053	0.066	0.015	0.019	0.450	0.556	0.039	0.048	898	1109	0.0008	0.0010	9.5.E+09	1.2.E+10	279	42.1
WHVC cold 3	0.077	0.097	0.025	0.031	0.486	0.606	0.019	0.024	881	1098	0.0007	0.0008	5.2.E+09	6.3.E+09	273	41.7
WHVC warm 1	0.022	0.026	0.022	0.026	0.079	0.096	0.000	0.000	835	1015	0.0012	0.0015	3.1.E+10	3.8.E+10	263	39.0
WHVC warm 2	0.035	0.042	0.012	0.015	0.110	0.132	0.000	0.000	820	984	0.0014	0.0017	5.5.E+10	6.8.E+10	259	38.1
WHVC warm 3	0.026	0.032	0.019	0.023	0.074	0.092	0.000	0.000	814	1010	0.0007	0.0008	3.6.E+09	4.5.E+09	255	38.8
WHVC warm 4	0.034	0.042	0.015	0.018	0.212	0.265	0.015	0.019	831	1039	0.0009	0.0011	3.1.E+09	3.5.E+09	258	39.4
FIGE	0.023	0.026	0.009	0.011	0.148	0.168	0.013	0.015	720	817	0.0008	0.0009	n.m	n.m	226	31.3

Drive cycle		CO		THC		NOx		NO2		CO2		PM		FC	
		(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(g/km)	(g/kWh)	(l/100km)
PEMS Pilot route		n.d	n.d	0.02	0.03	0.43	0.73	0.05	0.09	634	1088	0.003	0.005	188	40
		n.d	n.d	0.01	0.01	0.27	0.45	0.05	0.08	637	1061	0.003	0.005	188	39
	counter clockwise	n.d	n.d	0.00	0.01	0.17	0.30	0.05	0.09	633	1102	0.003	0.004	188	40
	counter clockwise	n.d	n.d	0.01	0.02	0.74	1.20	0.27	0.44	632	1033	0.005	0.007	188	38
Distribution route		n.d	n.d	0.01	0.02	0.28	0.56	0.04	0.07	628	1276	0.000	0.000	190	47
		n.d	n.d	0.02	0.05	0.44	0.93	0.09	0.19	633	1345	0.004	0.007	191	50
Random		n.d	n.d	0.00	0.01	0.15	0.24	0.06	0.09	644	990	0.002	0.002	191	36
		n.d	n.d	0.00	0.01	0.19	0.30	0.07	0.11	645	997	0.002	0.003	190	36
EUVI route 2	cold start approx 0°C	n.d	n.d	0.01	0.01	0.56	0.81	0.31	0.45	635	917	0.006	0.007	186	33
	cold start approx 0°C	0.01	0.01	0.01	0.01	0.32	0.45	0.15	0.21	641	886	0.003	0.004	186	32
	warm start 0°C	n.d	n.d	0.00	0.01	0.15	0.21	0.05	0.07	637	892	0.002	0.002	187	32
	warm start 0°C	n.d	n.d	0.01	0.01	0.15	0.21	0.03	0.03	638	869	0.002	0.002	186	31
	warm start 0°C ccw	n.d	n.d	0.00	0.01	0.10	0.14	0.02	0.04	636	915	0.003	0.003	188	33
	warm start 0°C ccw	n.d	n.d	0.00	0.01	0.11	0.16	0.02	0.03	637	882	0.002	0.003	189	32
	cold start, 10°C	n.d	n.d	0.01	0.01	0.26	0.41	0.08	0.12	635	983	0.002	0.002	207	35
	cold start, 10°C	n.d	n.d	0.00	0.01	0.35	0.50	0.16	0.22	653	923	0.002	0.002	174	32
	warm start, 10°C	n.d	n.d	0.00	0.01	0.28	0.40	0.08	0.12	640	919	n.m.	n.m.	188	33
	warm start 10°C, low average speed	n.d	n.d	0.00	0.01	0.20	0.27	0.08	0.11	651	894	0.002	0.002	196	32
	warm start 10°C, low average speed	n.d	n.d	0.01	0.02	0.49	0.65	0.18	0.24	630	845	0.002	0.002	198	31
	cold start, 20°C	n.d	n.d	0.00	0.01	0.34	0.48	0.14	0.20	636	906	0.001	0.001	170	33
	cold start, 20°C	n.d	n.d	0.01	0.01	0.31	0.45	0.11	0.15	643	920	0.001	0.001	187	33
	cold start, 20°C	n.d	n.d	0.00	0.01	0.30	0.41	0.12	0.16	639	878	0.003	0.003	187	32
	warm start, 20°C	n.d	n.d	0.01	0.01	0.24	0.35	0.05	0.07	616	890	0.001	0.001	187	33
	warm start, 20°C	n.d	n.d	0.00	0.01	0.20	0.27	0.06	0.08	635	888	n.m.	n.m.	187	32
EUVI route 1	10% load	n.m.	n.m.	0.00	0.01	0.11	0.15	0.06	0.08	655	871	n.m.	n.m.	185	30
	10% load	n.m.	n.m.	0.01	0.01	0.15	0.19	0.10	0.13	667	861	n.m.	n.m.	186	29
	50% load	n.m.	n.m.	0.01	0.01	0.09	0.13	0.04	0.06	690	975	n.m.	n.m.	186	32
	50% load	n.m.	n.m.	0.01	0.01	0.12	0.17	0.06	0.09	683	959	n.m.	n.m.	185	32
	90% load	n.m.	n.m.	0.01	0.01	0.16	0.26	0.10	0.16	684	1115	n.m.	n.m.	187	38
	90% load	n.m.	n.m.	0.01	0.01	0.14	0.23	0.09	0.15	686	1112	n.m.	n.m.	187	37

Drive cycle	CO		THC		NOx		PM	
	WBW CF	CO2 CF	WBW CF	CO2 CF	WBW CF	CO2 CF	WBW CF	CO2 CF
EUV Pilot	n.d	n.d	0.08	0.14	0.92	1.16	0.32	0.35
EUV Pilot	n.d	n.d	0.04	0.06	0.4	0.42	0.41	0.44
EUV Pilot counter clockwise	n.d	n.d	0.04	0.04	0.42	0.44	0.27	0.29
EUV Pilot counter clockwise	n.d	n.d	0.04	0.05	1.65	2.55	0.46	0.51
Cold start approx +3°C	n.d	n.d	0.06	0.06	1.1	1.92	0.7	0.73
Cold start approx -2°C	0.00	0.00	0.04	0.04	0.5	0.5	0.26	0.28
warm start 0°C	n.d	n.d	0.05	0.04	0.51	0.48	0.15	0.16
warm start 0°C	n.d	n.d	0.04	0.04	0.35	0.39	0.15	0.16
warm start 0°C ccw	n.d	n.d	0.04	0.04	0.27	0.29	0.24	0.24
warm start 0°C ccw	n.d	n.d	0.04	0.04	0.31	0.32	0.23	0.23
warm start 10 deg, low average speed	n.d	n.d	0.04	0.04	0.48	0.48	0.13	0.14
warm start 10 deg, low average speed	n.d	n.d	0.04	0.04	0.54	0.54	0.14	0.14
Distribution route	n.d	n.d	0.06	(*)	0.48	(*)	0.02	(*)
Distribution route	n.d	n.d	0.07	(*)	0.75	(*)	0.26	(*)
Random	n.d	n.d	0.03	0.03	0.46	0.49	0.17	0.18
Random	n.d	n.d	0.03	0.03	0.51	0.53	0.2	0.21
Long EUVI route, 10% load	n.m.	n.m.	0.03	0.03	0.4	0.41	n.m.	n.m.
Long EUVI route, 10% load	n.m.	n.m.	0.04	0.04	0.55	0.56	n.m.	n.m.
Long EUVI route, 50% load	n.m.	n.m.	0.05	0.05	0.3	0.3	n.m.	n.m.
Long EUVI route, 50% load	n.m.	n.m.	0.05	0.05	0.45	0.44	n.m.	n.m.
Long EUVI route, 90% load	n.m.	n.m.	0.07	0.04	0.59	0.65	n.m.	n.m.
Long EUVI route, 90% load	n.m.	n.m.	0.06	0.06	0.53	0.53	n.m.	n.m.

(*) Less than 50% valid windows

Appendix 2: Test equipment

PEMS – Portable Emission Measurement System

For on-road measurement, two different units of PEMS have been used. One unit is Semtech-DS, developed by Sensors Inc. USA and one unit is M.O.V.E (Mobile on-board Vehicle Equipment), developed by AVL List GmbH, Austria.

Both devices are developed for testing all classes of light as well as heavy duty vehicles under real-world operating conditions. The instruments consists of on-board emissions analyzers which enables tailpipe emissions to be measured and recorded simultaneously while the vehicle is in operation. Sampling of data and measurements is carried out on a second-by-second basis.

The following measurement subsystems are included in the emission analyzers of both instruments:

- Heated Flame Ionization Detector (HFID) for total hydrocarbon (THC) measurement.
- Non-Dispersive Ultraviolet (NDUV) analyzer for nitric oxide (NO) and nitrogen dioxide (NO_2) measurement.
- Non-Dispersive Infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO_2) measurement.
- Electrochemical sensor for oxygen (O_2) measurement.

The Semtech-DS instrument uses the flow data together with exhaust component concentrations to calculate instantaneous and total mass emissions. The two instruments are operated in combination with identical electronic vehicle exhaust flow meter, Semtech EFM. The flow meter is available in different sizes depending on engine size. All tests in the project were carried out with a flow meter which was suitable for the engine size of the tested vehicle.

In addition to the gas analyzing instrument (Semtech-DS) an AVL 483 Micro Soot Sensor was used to measure the soot emissions. The AVL 483 Micro Soot Sensor works on a photo-acoustic principle (PASS) and the cell design chosen (called the "resonant measuring cell") allows a detection limit of ≤10 µg/m³, (typically ~ 5 µg/m³).

The AVL MOVE PM PEMS combines the AVL photo-acoustic soot measurement principle with a gravimetric PM measurement which operates with a gravimetric filter. The time-resolved particulate emissions are calculated by weighing the loaded gravimetric filter after the end of the tests and additionally using the time resolved soot signal and the exhaust mass flow as inputs. The complete system consists of two 19” enclosures for the Micro Soot Sensor Measuring Unit (MSS), the Gravimetric Filter Module (GFM) and an external heated dilution cell and transfer line.

The on-road testing and calculation has for all vehicles been performed in accordance with the Euro VI emission requirements (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:167:0001:0168:EN:PDF)

For the purpose of calculation of emissions from the PEMS instruments has either EMROAD (“reference calculation tool” developed by JRC) or AVL Concerto PEMS (Data evaluation software which has been verified by TÜV, is according to EMROAD and meets the requirements of the regulation (EU) NO. 582/2011 Annex II and (EU) No. 64/2012) been used.

Chassis dynamometer test cell

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

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

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

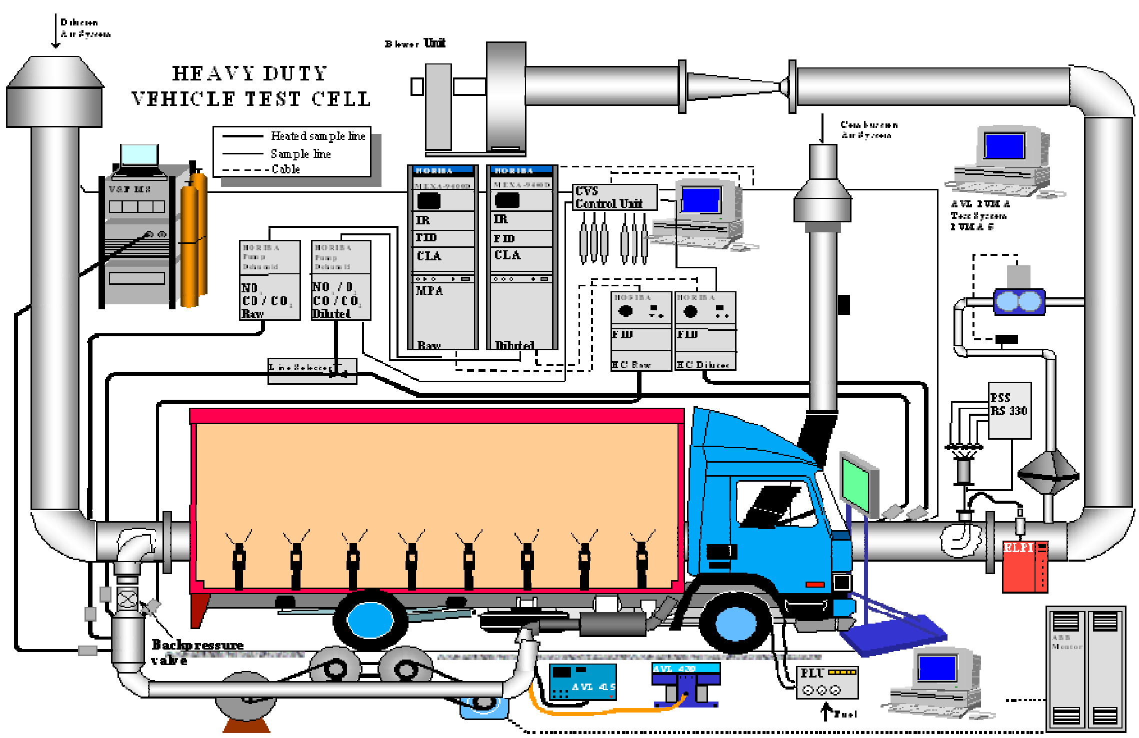

Figure 72 A schematic description of the test cell.

Engine power

The engine power was estimated by adding the integrated signals from measured acceleration force of the inertia used and the road load. No fan correction has been applied to the calculations. The integrated power is then used to calculate the total estimated work (kWh) during the test cycle which is used to calculate emissions in g/kWh.

Regulated gaseous emissions and CO_2

The sampling- and analysing equipment are based on full flow dilution systems, i.e. the total exhaust is diluted using the CVS (Constant Volume Sampling) concept. The total volume of the mixture of exhaust and dilution air is measured by a CFV (Critical Flow Venturi) system. For the subsequent collection of particulates, a sample of the diluted exhaust is passed to the particulate sampling system. The sample is here diluted once more in the secondary dilution tunnel, a system referred to as full flow double dilution.

According to the regulations for transient tests the diluted exhaust gases are both bagsampled and sent for further analysis *and* on-line sampled. Through the CVS system a proportional sampling is guaranteed.

The equipment used for analysing the gaseous regulated emissions consist of double Horiba 9400D systems. Hereby exists the possibility to measure both diluted and raw exhaust emissions on-line simultaneously. The sampling system fulfils the requirements of Regulation (EU) 582/2011 in terms of sampling probes and heated lines etc.

The measured components and measurement principles are specified in **Table 21**.

Table 21 Measured components and measurement principles.

Component	Measurement principle
Total hydrocarbons (THC)	HFID (heated flame ionization detector) (190°C)
Carbon monoxide (CO)	NDIR (non-dispersive infrared analyzer)
Carbon dioxide (CO_2)	NDIR
Nitrogen oxides (NO_X)	CL (chemiluminescence)
Ammonia (NH_3)	FTIR (Fourier Transform InfraRed)
Fuel consumption (FC)	Carbon balance of HC, CO and CO_2

Fuel consumption

The total fuel consumption (Fc) was calculated using the carbon balance method. The diesel consumption was also measured with a PLU (fuel mass flow meter measuring device).

Particulate emissions

The particulate emissions were analyzed gravimetrically, by number and by size distribution.

Particulate mass

The particulate mass was measured gravimetrically by the use of glass fibre filters. For the collection of particle matter (PM), a sample of the diluted exhaust is passed to the particulate sampling system. The sample is then diluted once more in the secondary dilution tunnel, a system referred to as full flow double dilution. The particles are collected on Teflon-coated Pallflex™ filter and measured gravimetrically. The sampling of particle matter is in accordance with Directive 2005/55/EEC.

Particle number

The particle number is measured in a Condensation Particle Counter (CPC) with a size range of 23nm to 2.5µm. The particle number is limited for heavy duty diesel engines from emission standard Euro VI (limits for positive ignited engines are not yet decided).

In the counter, the particles are enlarged by condensation of butanol and are thereafter detected and counted using a light-scattering method. A schematic description of the detector is presented in Figure 73.

In order to count non-volatile particles, a special sampling method has been developed. A pump draws the exhaust gas into a sampling probe which eliminates all particles >2.5 µm due to its special shape. The sampled exhaust gas is then diluted with cleaned hot air at a temperature of 150°C. This stabilizes the particle number concentration and reduces the concentration so that agglomerations and particle deposits are largely prevented.

After the hot primary dilution, the diluted exhaust gas is further heated up to a temperature of 300°C to 400°C in an evaporation tube in order to convert all volatile particles into gaseous phase. A secondary dilution is then performed to prevent further condensation or adsorption of volatile substances and to ensure that the maximum inlet temperature of 35°C is not exceeded. The particle number concentration is measured in the Condensation Particle Counter (with a size range of 23nm to 2.5µm according to UNECE-R83 specifications). The particles are enlarged due to the condensation of butanol and are detected and counted using the lightscattering.method.

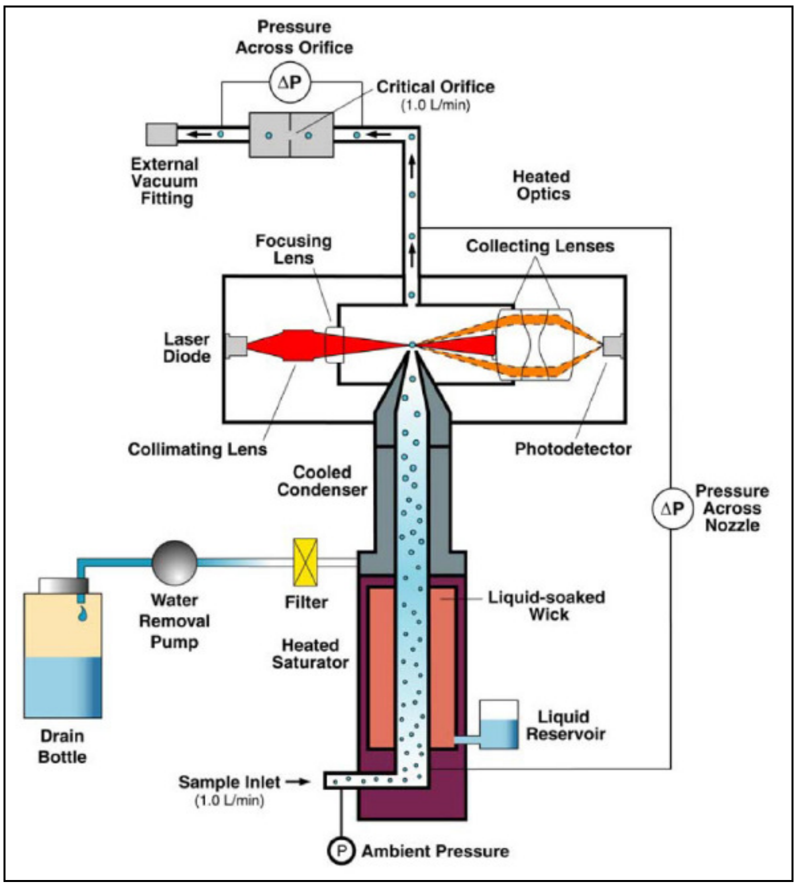

Figure 73 Schematic description of the detector in the Condensation Particle Counter.

Particulate size distribution

An Electrical Low Pressure Impactor (ELPI) was used for particle size distribution. In an impactor, the particles are classified according to their aerodynamic diameter. The ELPI impactor has 12 stages ranging from 7 nm to 10µm. The instrument was manufactured by Dekati Ltd. in Finland. The principle of the ELPI instrument is described below and a schematic description is presented in Figure 6.

Before entering the ELPI instrument, the exhaust gases are diluted in order to reduce their concentration. In this case, sampling was carried out from the full flow primary dilution tunnel.

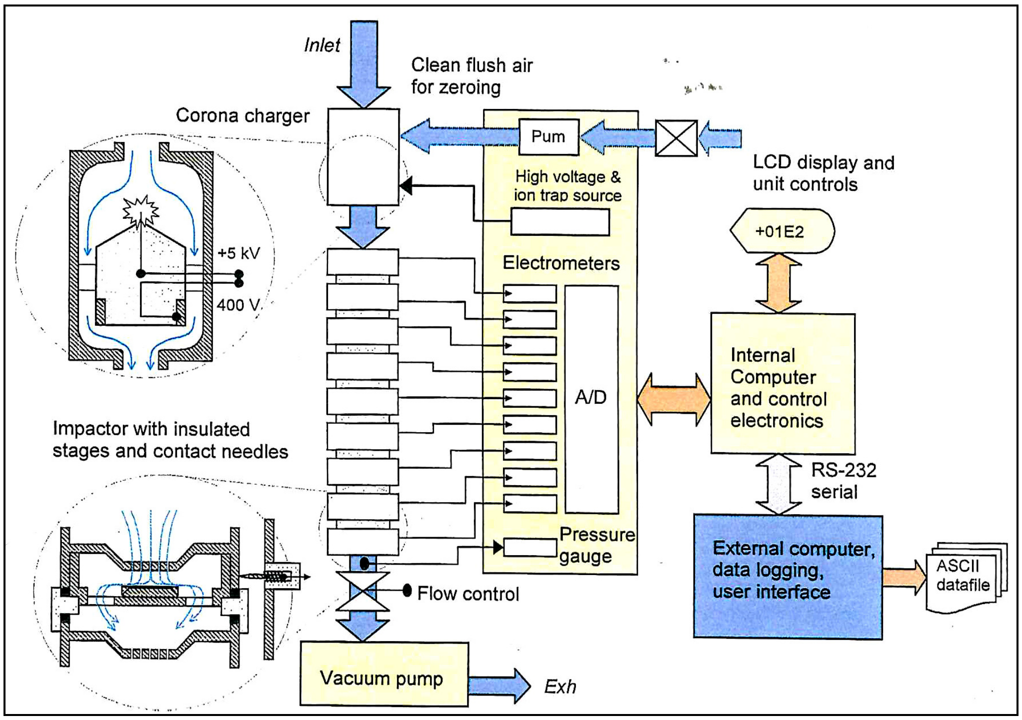

Figure 74 Schematic description of the operating principles in an ELPI instrument.

The ELPI™ operating principle can be divided into three major parts; particle charging in a unipolar corona charger, size classification in a cascade impactor and electrical detection with sensitive electrometers. The particles are first charged into a known charge level in the charger. After charging the particles enter a cascade low pressure impactor with electrically insulated collection stages. The particles are collected in the different impactor stages according to their aerodynamic diameter, and the electric charge carried by particles into each impactor stage is measured in real time by sensitive multichannel electrometers. This measured current signal is directly proportional to particle number concentration and size. The operating principle for the impactor is schematically described in Figure 75.

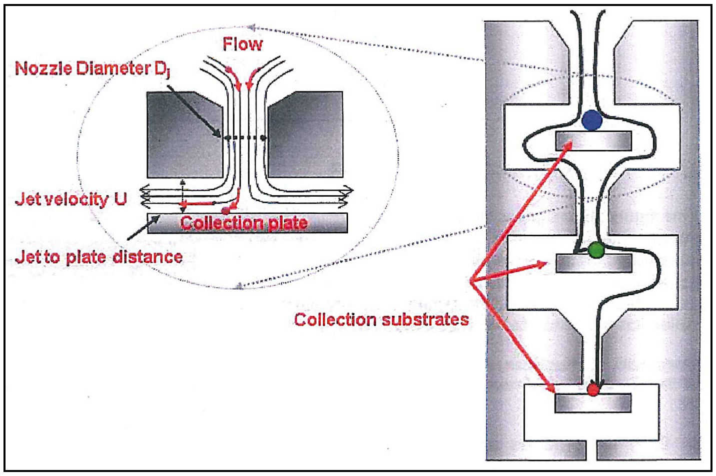

Figure 75 Operating principle for the impactor in ELPI.

The particle collection into each impactor stage is dependent on the aerodynamic size of the particles. Measured current signals are converted to (aerodynamic) size distribution using particle size dependent relations describing the properties of the charger and the impactor stages. The result is particle number concentration and size distribution in real-time.

Appendix 3: Test cycles

Chassis dynamometer drive cycles

WHVC driving cycle on chassis dynamometer

The WHTC (World Harmonized Transient Cycle) test cycle will become the future test cycle (probably to be introduced for later version of Euro VI emission requirements) for certification of engines intended for use in heavy duty vehicles. The formal EU approval procedure consists of testing of a stand-alone engine on an engine test bed in accordance with the test cycle specified as WHTC. The engine, including necessary exhaust aftertreatment device, is tested on its own merits i.e. without gearbox, drive train and any auxiliaries for proper operation in a vehicle. The test cycle is well specified and should reflect normal operation of heavy duty vehicle as well as the procedure to condition the engine before the actual test starts. However, not all modes of operation, especially low loads, are reflected by the test cycle.

To verify emission performance of engines used in heavy duty vehicles is a time consuming and expensive task. The engine has to be removed from the vehicle and tested in an engine test cell and after tests are completed, the engine has to be reinstalled in the vehicle again. Therefore, huge efforts have been made to transform test cycles and procedures used in engine test cells to instead be used on chassis dynamometers for testing the whole vehicle.

In the case of WHVC (World Harmonized Vehicle Cycle), the test cycle was developed by sampling of information about actual driving pattern form heavy duty vehicles in normal operation. This test cycle was then further developed to be used for engine testing (WHTC).

The WHVC is fully not identical to the WHTC since it was only an intermediate step from data collection to engine test bench cycle. Especially, grade of accelerations have to be considered as well as the use of gearbox. The bottom line is however, that the WHVC driving cycle is accepted by the industry to give a rough estimate about the emission performance of an engine installed in a heavy duty vehicle. The emission results can be presented either in g/km but also possible to convert to g/kWh using estimations of executed work during the transient test cycle.

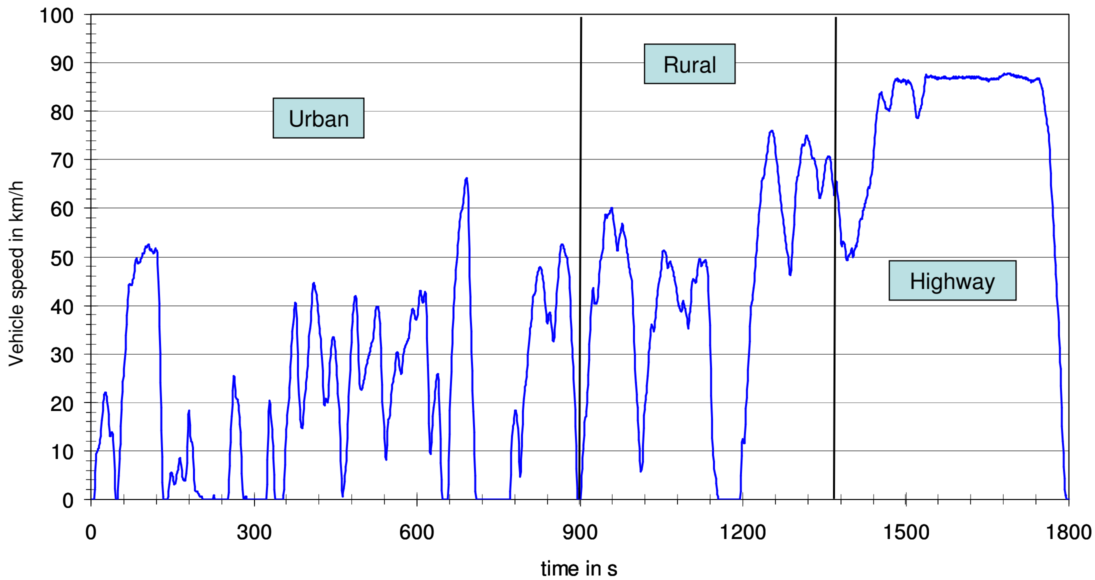

Figure 76 Characteristics of the WHVC driving cycle

During the test program the transient driving cycle WHVC was used.

Different driving conditions are represented by the three parts, urban, rural and highway driving. Before the actual test was started, the vehicle was pre-conditioned on the chassis dynamometer by driving the vehicle on the dynamometer with a steady speed for a specific time either to reach stabilization of the coolant temperature (70-80°C) or stabilization of exhausts temperature.

The duration of the entire WHVC cycle is 1800 sec. The main properties of the test cycle are:

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

FIGE driving cycle on chassis dynamometer

A test cycle for verification of emission performance from heavy duty vehicles has been developed by the FIGE Institute of Germany. The test cycle is called the FIGE test cycle and is based on measurement from real road driving of heavy duty vehicles. FIGE Institute developed the cycle in two variants, one for chassis dynamometer testing and one for engine dynamometer test. The engine dynamometer version is a shortened and slightly modified version of the test and is used for certification purposes of engines intended for heavy duty vehicles and called ETC cycle (European Transient Cycle).

The duration of the entire cycle is 1800 sec. The duration of each part is 600 sec.

- Part one represents urban driving, maximum speed of 50 km/h, frequent starts, stops, and idling.
- Part two is rural driving starting with a steep acceleration segment. The average speed is about 72 km/h
- Part three is motorway driving, average speed of about 88 km/h.

During the test program carried out in Sweden the transient driving cycle FIGE was used.

Different driving conditions are represented by the three parts urban, rural and highway driving. Before the actual test was started, the vehicle was pre-conditioned on the chassis dynamometer by driving the vehicle on the dynamometer with a steady speed for a specific time either to reach stabilization of the coolant temperature (70-80°C) or stabilization of exhausts temperature.

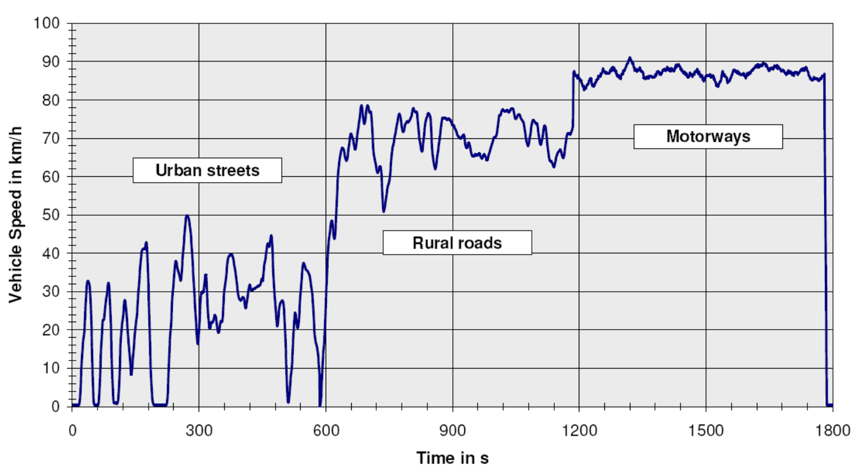

Figure 77 Characteristics of the FIGE driving cycle

PEMS drive cycles

Euro VI route 1

Euro VI route 1 is designed to meet the requirements specified by the regulation for all N_3 vehicles. The route has the following main data:

- Approximate trip duration: 23300 seconds
- Average trip distance: 343 km
- Average speed: 53 km/h (of course dependent on traffic situation)
- Trip composition:
  - Urban driving: 24%
  - Rural driving: 23%
  - Highway driving: 53%
  - Idle: 14%

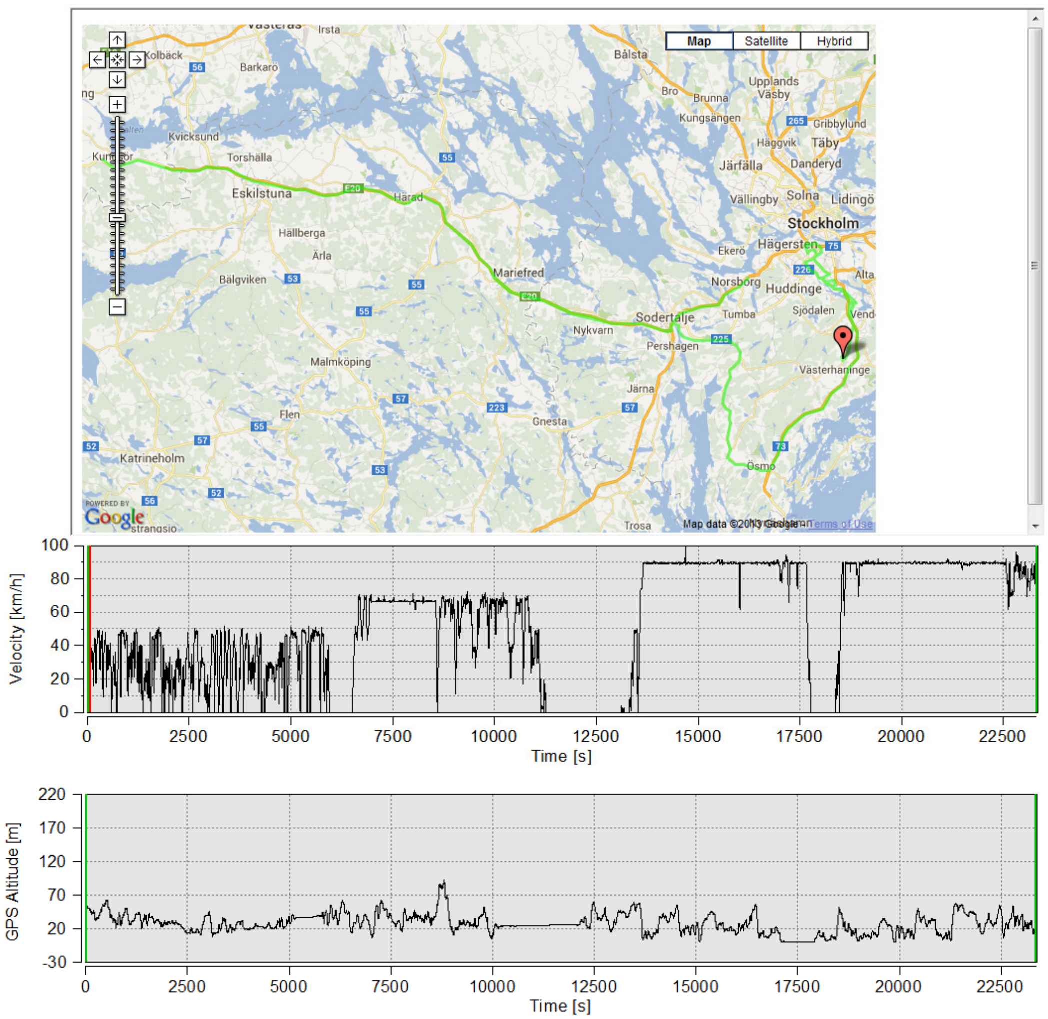

Figure 78 Characteristics of the Euro VI route 1

Euro VI route 2

Euro VI route 2 is also designed to meet the Euro VI requirements but shorter than Euro VI route 1.

The route has the following main data:

- Approximate trip duration: 15500 seconds
- Average trip distance: 242 km
- Average speed: 56 km/h (of course dependent on traffic situation)
- Trip composition:
    - Urban driving: 23%
    - Rural driving: 27%
    - Highway driving: 50%
    - Idle: 12%

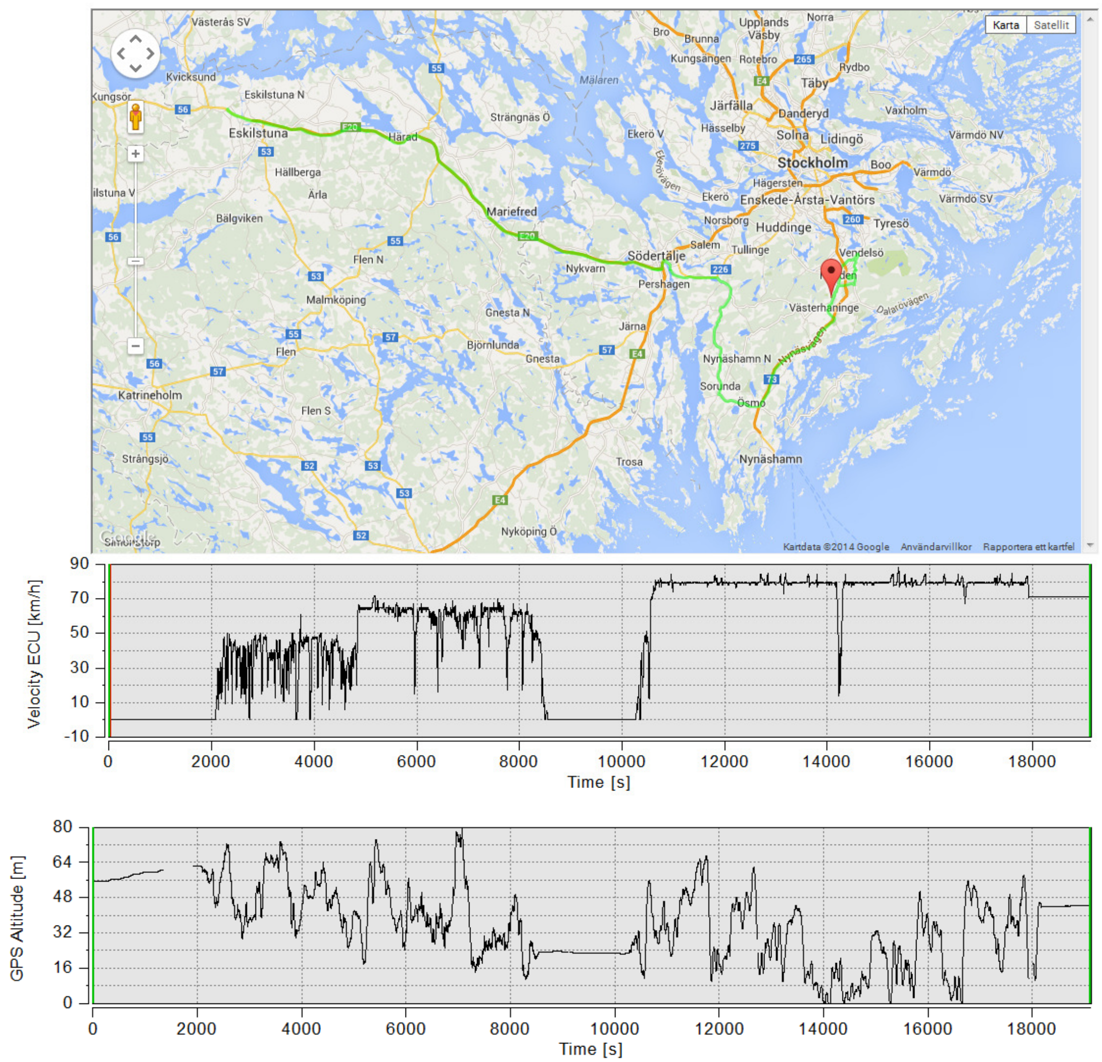

Figure 79 Characteristics of the Euro VI route 2

PEMS Pilot route (Euro V)

The route has the following main data:

- Approximate trip duration: 5 000 seconds
- Average trip distance: 77 km
- Average speed: 55 km/h (of course dependent on traffic situation)
- Trip composition:
    - Urban driving: 43%
    - Rural driving: 17%
    - Highway driving: 40%
    - Idle: 7%

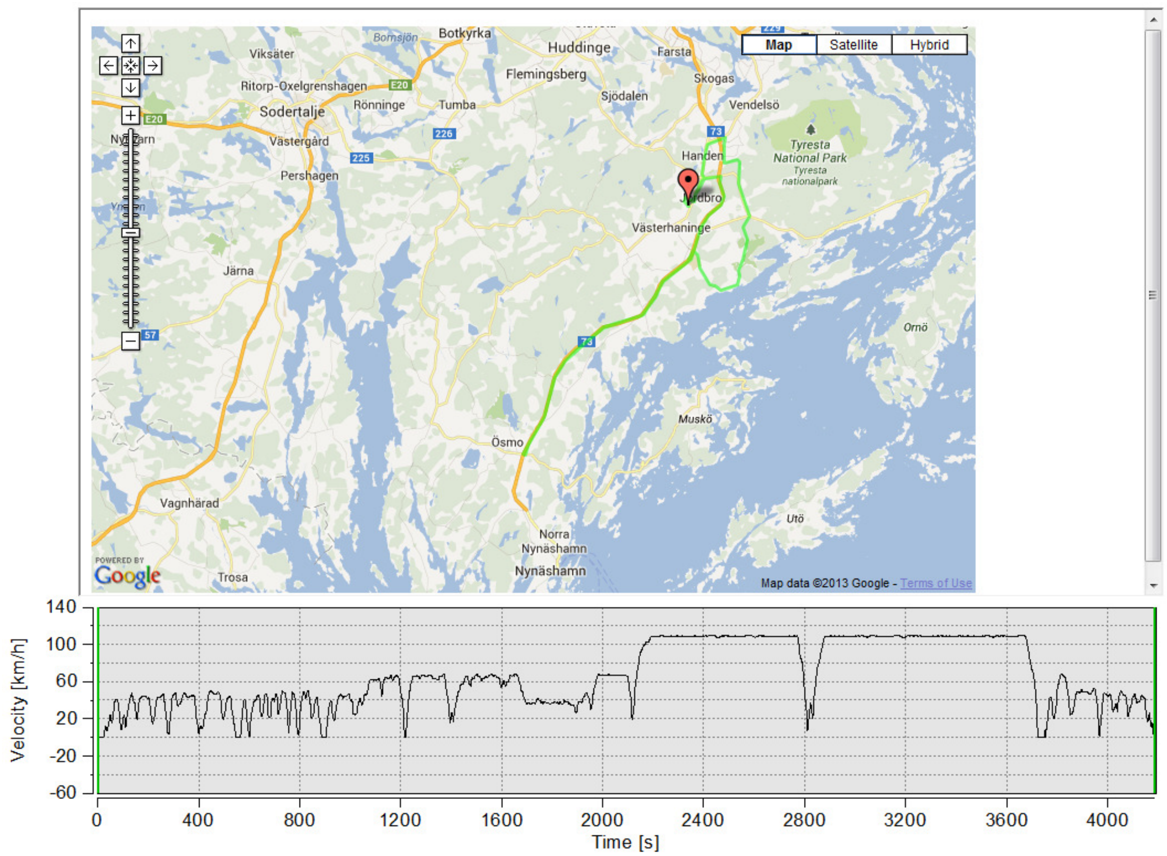

Figure 80 Characteristics of the PEMS Pilot route

<u>Distribution route</u>

The Distribution route is a typical distribution test route performed in the Stockholm southern suburbs.

- Approximate trip duration: 13100 seconds
- Average trip distance: 78 km
- Average speed: 21 km/h (of course dependent on traffic situation)
- Trip composition:
    - Urban driving: 82%
    - Rural driving: 16%
    - Highway driving: 2%
    - Idle: 44%

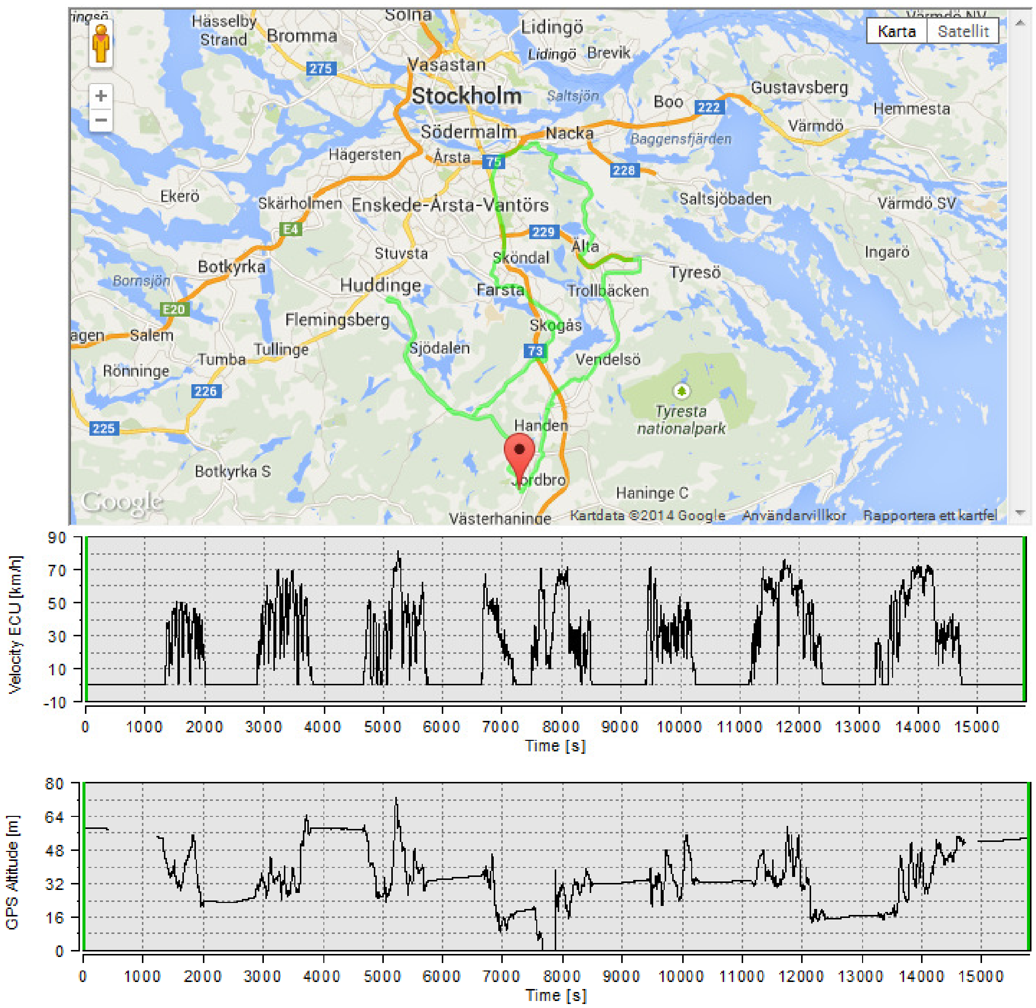

Figure 81 Characteristics of the distribution route

Random Route

The Random Route is a short test route containing urban, rural and highway driving which can be repeated several times in order to reach the desired work of 5 times the reference work:

- Approximate trip duration: X*1700 seconds
- Average trip distance: X*23 km
- Average speed: 49 km/h (of course dependent on traffic situation)
- Trip composition:
    - Urban driving: 43%
    - Rural driving: 32%
    - Highway driving: 25%
    - Idle: 2%

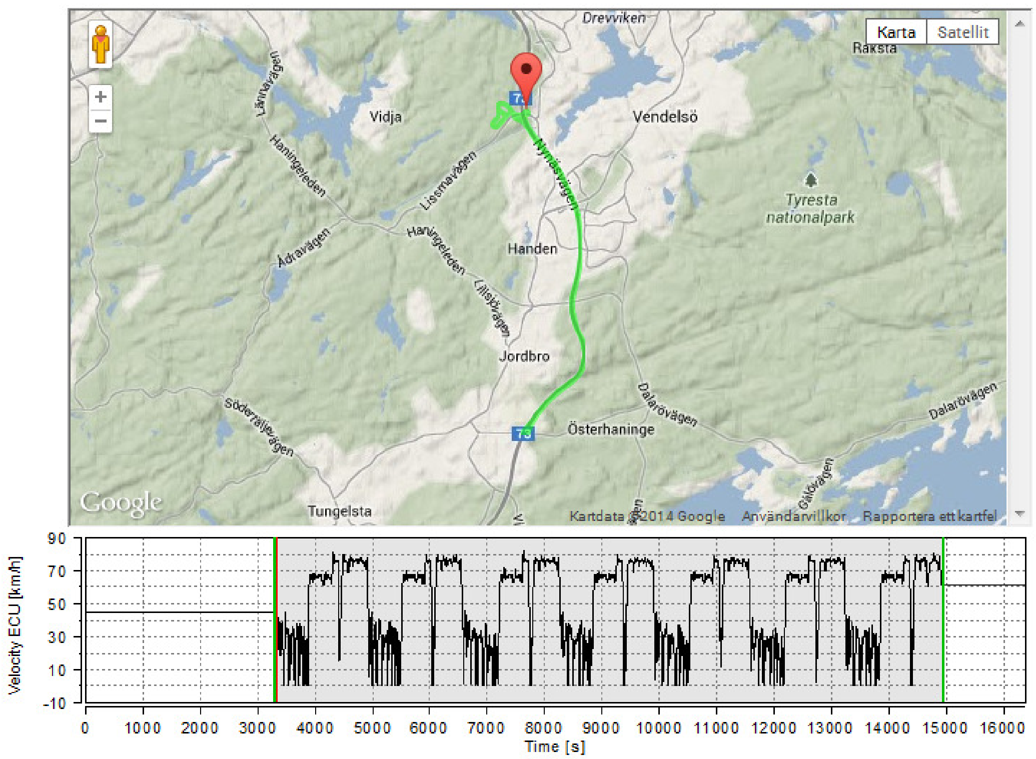

Figure 82 Characteristics of the Random route