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TNO report

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On-road emission measurements with PEMS on a heavy-duty truck with a retrofit dual-fuel system, using diesel and CNG

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Summary

Commissioned by the Ministry of Infrastructure and the Environment of The Netherlands, TNO Sustainable Transport and Logistics regularly performs measurements on heavy-duty vehicles to determine the in-service performance and durability of the tail-pipe emissions under representative driving conditions.

At request of the Ministry an additional dedicated emission test programme was performed to generate insights which are needed to develop a low-cost emission test procedure to screen the tail-pipe emissions of heavy-duty retrofit dual-fuel vehicles. This procedure could be used in a national approval scheme for retrofit dual-fuel vehicles.

The goal of the tests is to determine the real-world emission performance of a truck equipped with a retrofit dual-fuel system, with a focus on the NO_x and the CH_4 emissions and to compare the emissions in diesel mode and dual-fuel mode (diesel-natural gas).

A heavy-duty truck, a DAF XF 105 equipped with a retrofitted dual-fuel system, running on diesel and compressed natural gas, was tested with a Portable Emission Measurement System on the road.
Various trips were driven with different payloads and repeated in diesel mode and dual-fuel mode to enable a comparison of the emission performance of the two fuel modes. The standard gaseous emissions, including methane (CH_4) were measured and analysed according to the formal In-Service Conformity method (Annex II of 582/2011/EC) and according to alternative methods to judge the real-world emission performance. This has led to the following conclusions:

- In dual-fuel mode the NO_x and NO_2 emissions are somewhat lower than in diesel mode.
- In dual-fuel mode the CH_4 emissions are very high. The high CH_4 emissions are the highest during the for the vehicle typical motorway operation. The CH_4 emissions decrease at a lower blend ratio but are still high.
- In dual-fuel mode the CO_2 emissions are lower, as could be expected from the lower energy specific CO_2 emission of natural gas. However, when the high CH_4 emission and its Global Warming Potential of 25 in CO_2 equivalents are considered, the total CO_2 emissions are 14-40% higher in dual-fuel mode than in diesel mode, depending on the trip and blend ratio.
- With a high payload (100%), the CO_2 specific CH_4 emission decreases somewhat compared to lower payloads (55 and 10%).

It is recommended to investigate a vehicle with a semi-OEM solution for the dual-fuel system to see how this technology performs with regard to the methane emissions. The semi-OEM solution has interaction with the vehicles engine control system and has a methane catalyst to reduce the methane emissions.

Aggregate results of the programme and of other tested Euro V and Euro VI heavy-duty vehicles can be found in a separate report which will be published beginning of 2013.

Contents

1 Introduction

1.1 Background

Commissioned by the Ministry of Infrastructure and Environment of The Netherlands, TNO Environmentally Sustainable Transport regularly performs measurements to determine the emissions performance and durability of vehicles in-use in The Netherlands. The aim of this measurement programme is, amongst others, to gain insight into trends in real-world emissions of generations of heavy-duty vehicles, under the usage conditions relevant for the Dutch situation. Another aim of this national measurement programme is to test and evaluate the emission performance of the available technology on the market.

These are long-term goals and provide a stable and continues bases for the generation of emission trends and emission factors as for instance used in the national model for vehicle emissions Versit+. Additionally, dedicated measurements can be performed at request of the Ministry on an ad-hoc bases.

Recently, retrofit dual-fuel systems have appeared on the market in The Netherlands. For vehicles equipped with these systems there are no national provisions which secure a certain good emission performance. Therefore, the Ministry considers the introduction of a simple and cost-effective method for screening of the emission performance to be used in a national approval scheme for the retrofit systems. To support the development of such a test procedure, trial tests are needed, which support the development of the procedure, and additionally typical emission data is needed from vehicles using a dual-fuel system to be able to compare the emission performance with that of the conventional diesel vehicle. Therefore, at request of the Ministry an additional dedicated emission test programme was performed to generate insights which are needed to develop the test procedure to screen the tail-pipe emissions of heavy-duty retrofit dual-fuel vehicles.

The measurements and the evaluation presented in this report are performed under the national programme mentioned above and give an overview of the results from on-road emission tests performed with PEMS on a Euro V N3 heavy-duty vehicle, with a retrofit duel-fuel system running on diesel and natural gas. The focus of the tests and the evaluation is on the NO_x and CH_4 (methane) emissions.
The emission of CH_4 may occur when the mixture of air and fuel is not burned completely in the combustion chamber of the engine. Further, downstream in the aftertreatment of the Euro V engine, the unburned CH_4 is hard to oxidize and may finally result in CH_4 emissions from the tail-pipe. CH_4 has a Global Warming Potential of 25 and because of that the emission level of this compound is measured and monitored extensively in the test programme. NO_x emissions are important, because locally the currently air quality targets concerning NO_2 ,one of the two compounds in NO_x ,are still exceeded and heavy-duty traffic has a signifycant contribution.
PEMS (Portable Emission Measurement System) can measure the regulated gaseous emissions (CO, THC, NO_x) and CO_2 and NO and NO_2 separately. Exceptions are the regulated NH_3, PM and PN emissions which cannot be measured on-board of a vehicle with PEMS. For this occasion an additional instrument was added which enables the accurate measurement of CH_4.

PEMS is able to measure under a wide range of real-world operating conditions. PEMS is also used for the current procedure to evaluate the In-Service Conformity of Heavy Duty emissions (Euro V and Euro VI). This procedure uses a special data-evaluation method and tool EMROAD to calculate the Conformity Factor for a regulated emission component of a given engine type in a vehicle by means of a specially developed pass fail method.

1.2 Aim and approach

The aim of the research is to gain insight in the emission performance of a dual-fuel Euro V truck on diesel and CNG trucks in real-world operation with a focus on the NO_x and CH_4 emission.

Measurements on the road were performed with one long haulage truck from category N3, using a Portable Emission Measurement System (PEMS). Measurements were done in diesel mode and dual-fuel mode. For the evaluation of the measurements the results of both situations were compared.

1.3 Structure of the report

The research method is described in Chapter 2. The research results, obtained for each test, are presented in Chapter 3.

2 Emission measurement programme

The exhaust gas emissions of the truck were measured with a Portable Emission Measurement System (PEMS) on the road. This chapter describes the set-up of the programme, consisting of the selection of on-road trips and the methods to process and analyse the data.

2.1 Measuring real world emissions with PEMS and SEMS

European type approval for emissions of Euro V truck engines is obtained from tests performed on prescribed engine cycles on an engine test bed under laboratory conditions. For the determination of real world emissions of in-use vehicles, execution of engine tests on an engine test bed may not be representative. With the introduction of PEMS, or Portable Emission Measurement System, it has become possible to monitor real-world emissions of vehicles in normal traffic situations. In 2011 the EU Directive 582/2011/EC was introduced which describes on-road emission tests using PEMS for checking the conformity of vehicles in service for Euro V and Euro VI (Annex II and Annex XII).

PEMS is a system to measure exhaust gas emissions of a vehicle. The measurements can take place on the road in normal traffic. PEMS yields estimates for real-world emissions performance of the investigated vehicle. The system is introduced in the Euro-V and Euro VI heavy duty engine emission legislation for determination of ‘In-Service-Conformity’ [(EU)582/2011]. For Euro V it is allowed to use PEMS as an alternative test method for ‘In-Service-Conformity’.

For a national approval scheme for retrofit heavy-duty, dual-fuel vehicles PEMS could be used. This method, the EU standard for on-road emission testing, is accurate and widely accepted. However, it is not plug and play (complex) and quite costly. Therefore, for national screening of the tail-pipe emissions of the retrofit systems the Ministry considers a simplified, less costly method based on (much cheaper) sensors, called SEMS (Simple Emission Measurement System).

For this investigation, TNO used a PEMS for determination of the real-world truck emissions together with the sensor based measurement method (SEMS). The data from the latter was used for the development of the procedure, which is not presented in this report. The data from the PEMS was used for the results presented in this report with the main goal to compare the emission of the vehicle in dual-fuel mode and in diesel mode. The measured exhaust gas components with PEMS are NO_x, NO_2, CO_2, CO, HC and CH_4.

2.2 Test procedure representing typical Dutch driving conditions

Using the PEMS, one N3 long-haulage truck equipped with a retrofit dual-fuel system was tested by driving a set of specified trips.

Aim of the specified trips was to:

- represent typical Dutch urban, rural and motorway conditions.
- represent conditions typical for the given vehicle.

- yield results that are comparable with the results that were obtained during the previous PEMS measurement programme [Verbeek et al, 2010].
- be conform the requirements for performing an In-Service Conformity test according to [(EU)582/2011].
- enable a comparison between the diesel mode and the dual-fuel mode for two different blend ratios.
- investigate the influence of payload and trip composition.

This resulted in the choice for two trip types:

1. The TNO reference trip for heavy-duty vehicles, hereafter referred to as REF. This trip makes it possible to compare results with other vehicles.
2. The Euro VI N3 trip as required according to EU legislative specifications for testing the In-Service Conformity. This trip contains sub trips of urban, rural and motorway driving in shares which are found to be representative for EU driving of N3 category trucks (GVM>12t). Hereafter referred to as EUVI N3.

The reference trips (REF) were used to perform test with the different blend ratios and payloads. The fuels were market diesel (EN590) and natural gas (Groningen quality gas) fuelled at ACHT bv. Eindhoven.

Table 1: Overview of the test trips performed, together with fuel mode, blend ratio variant (two fuel dosing maps were used) and the calculated blend ratio over the trip.

Test #	Trip	Mode*	Blend ratio variant**	Blend ratio, energy based [-]	Payload [%]
1	REF	D	-	0,00	55
2	REF	DF	1	0,37	55
3	REF TJ***	DF	2	0,27	55
7	EUVI N3	D	-	0,00	55
4	EUVI N3	DF	1	0,43	55
5	EUVI N3	D	-	0,00	55
6	EUVI N3	DF	1	0,42	55
8	REF	D	-	0,00	100
9	REF	DF	1	0,35	100
10	REF	D	-	0,00	10
12	REF	DF	1	0,38	10
13	REF	DF	2	0,33	10

* D=Diesel only mode, DF is dual-fuel mode.

** Blendratio variant: two fuel dosing maps were used. Map 2 was an engine speed engine torque map with 50% of the duel dosing quantities of map 1. Map 1 was the original map provided in the dual-fuel system.

*** TJ: a Traffic Jam occurred during this trip and has influenced the results such that they are not fully comparable with other REF trips. The results are indicative.

Table 2: Overview of the payloads.

Payload [%]/[kg]	**Vehicle (combination) mass [kg]**
10%	18374
55%	34200
100%	50000

Table 3: Overview of trip requirements for various EU vehicle categories. [(EU)582/2011]. For the tested vehicle the N3 trip was used.

Vehicle category	**Trip duration percentage (± 5%)**		
	Urban	**Rural**	**Motorway**
M1 and N1	45	25	30
N2	**45**	**25**	**30**
N3	**20**	**25**	**55**
M2 / M3	45	25	30
M2 / M3 M3 of Class I, II or Class A	70	30	0

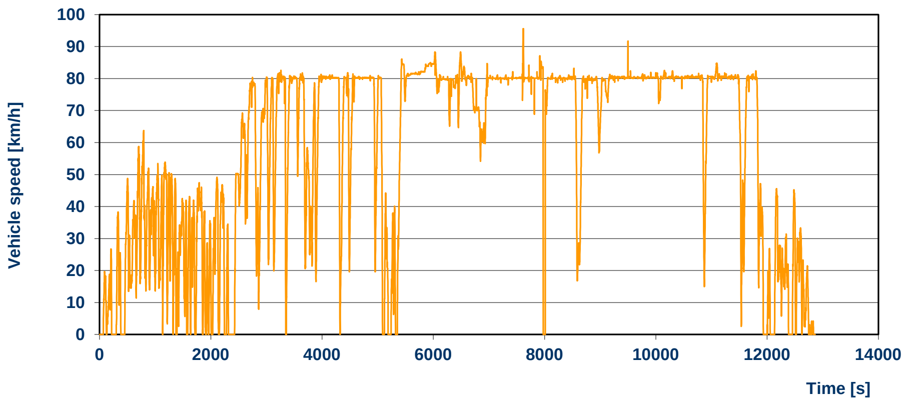

Figure 1: Example of a speed trace of the N3 trip according to Euro VI specifications.

2.3 Test vehicle; category N3 tractor semi-trailer equipped with a retrofit dual-fuel system for running on diesel and compressed natural gas.

Table 4: Test vehicle specifications.

Vehicle brand, type	DAF FT XF105
Legislative category	Euro V
2007/46/EC Vehicle category	N3
Vehicle type, axle config.	4x2, tractor semi-trailer
VIN/Engine code	XLRTE47MS0E908524
TNO test code	DA119
Engine # cyl / displacement [liter]	Line 6, 12,902
Engine power [kW]	300
Engine hardware	Turbo, intercooler, retrofit dual-fuel system Diesel-CNG, multi-point injection
After treatment	SCR + AMOC
Odometer [km]	177578

2.4 Data processing for measurements on a dual-fuel vehicle

When measurements of a dual fuel vehicle are processed and evaluated some precautions have to be made. Also adaptations are required for the calculations.

Emission mass calculation
The blending of two fuels (in this case diesel and natural gas) changes the properties of the exhaust gas. The properties of the exhaust gas are used in the calculation of the emissions in terms of mass per second from the measured concentrations and the flow measured with an exhaust flow meter according to

ISO 16183. An evaluation of the properties showed that a maximum error of 2,2% is made between full diesel and full natural gas operation, when this factor is not taken into account. For real blend ratios the error is obviously lower and typically around maximum 1% for the maximum momentary blend ratios of 50-60% occurring for the given dual-fuel system and even lower over complete tests, where trip average blend ratios were estimated to be around 25-40%.

Blend ratio determination
The blend ratio cannot be measured directly, but can be estimated in different ways;

- using the fuel dosing map and the engine CAN signals (engines speed and engine torque -% in the case of the given retrofit system).
- using the instantaneous diesel consumption from the CAN, converted to CO_2 and the measured CO_2. The difference between the two signals is the CO_2 from the natural gas.
- from the refuelling after a test. The refuelling of CNG proved to be not reproducible, due to temperature effects and filling station capacity effects. As an alternative the diesel consumption between a diesel only test and a dual–fuel test can be compared. This method clearly indicated that a significant part of CNG must have been dosed, however, this method is not able to determine the blend ratio very exact as the fuel consumption may differ from trip to trip by about 5%.

CO_2 benefit of natural gas
By its chemical composition, the combustion of natural gas leads to less CO_2 emissions per unit of energy than diesel. This benefit (less CO_2 emission) depends on the exact composition of natural gas. For Groningen gas this benefit is about 24% in case of a 100% replacement rate, assuming equal efficiency of a CI engine. The blending of a certain share of natural gas, therefore, leads to lower CO_2 emissions than in diesel only mode.

Usually, when PEMS results are analysed, the emissions are normalised by relating the emissions to the CO_2 emission (e.g. NO_x/CO_2 in g/kg, see paragraph 0). For pure diesel vehicles this proves a good way to compare vehicles of different sizes over different trips, with different payloads. For dual-fuel vehicles, however, the CO_2 benefit causes the CO_2 specific quantification of the emissions to be less beneficial, as the lower CO_2 in the denominator of the fraction increases the overall fraction.

2.5 Data processing with EMROAD and the binning method

This paragraph deals with the processing methods of the PEMS data; the binning method and the In-Service Conformity checking methodology [(EU)582/2011], using the EMROAD tool.

2.5.1 Binning method

The primary purpose of the binning method is to facilitate the use of large amounts of PEMS data as input to calculate emission factors for urban, rural and motorway conditions and to gain insight into the emission behavior over the speed range of a vehicle. The method collects all emission data belonging to a defined speed interval and determines the average emissions for every interval over the complete speed range of a truck.

As preparation for the binning method PEMS data of the trips were pre-processed with EMROAD. EMROAD performs a data quality check and aligns the test signals. For the tests that were started with a warm engine no data was excluded, otherwise data was excluded if the coolant temperature was below 70 ^{o}C. There were no big altitude differences during and between the trips.
Vehicle speed bins with a width of 5 km per hour were selected to distinguish emission data for low, intermediate and high vehicle speeds easily. In each bin of vehicle speed, the emissions [g/s] and CO_2 [kg/s] or engine power [kW] from the data points belonging to that speed bin are collected. In the end the average speed within a bin, the average emissions in [g/kg CO_2] or [g/kWh] and the amount of data points within a bin are calculated.

The binning method can also be used to calculate brake specific emissions in gram per kilowatt-hour.

In the box below a calculation example is given to explain the binning method:

Example binning method calculation:

$$gNOx\ per\ kgCO2 = \frac{\sum_{v=vi}^{v=vi+5} NOx[g/s]}{\sum_{v=vi}^{v=vi+5} CO2[kg/s]}$$

Data points in a bin: 1 g/s NO_x, 10 kg/s CO_2
1 g/s NO_x, 0.1 kg/s CO_2
(In reality many more data points are needed)

Weighing of the contribution to the total emission in a bin:
Sum of the emissions / sum of the CO_2
=> (1+1) / (10+0. 1) = 0.2 [gNO_x/kg CO_2]

And not: Arithmetic average of the specific emissions
(1/10+1/0.1) / 2 = (0.1+10)/2 = 5.1 [g/kg CO_2]

The CO_2 specific emission results can be related to brake specific emission results assuming a constant average engine efficiency and fuel consumption. With an average engine efficiency of 40% (BSFC = 200 g/kWh), the g/kg CO_2 results can be divided by 1.6 to get a corresponding g/kWh result. Lower average engine efficiencies lowers this factor and would thus increase the brake specific results accordingly. For comparison, the Euro V NO_x emission limit of 2,0 g/kWh would amount 3,2 g/kg CO_2. When the ISC Conformity factor of 1,5 is taken into account, this would amount to 4,8 g/kg CO_2.

2.5.2 Method used for In-Service Conformity

The pass-fail evaluation method has been applied, using the EMROAD tool (version 5.1 build 8). This tool can upload emission data from PEMS and CAN data from the vehicle in an Excel workbook, to calculate the Conformity Factors (CF) according to the In-Service Conformity rules. A Conformity Factor (CF) is the fraction of the calculated emission value according to the given data-evaluation method, of the ETC limit value. A CF of 1.5 for NO_x means, that an equivalent of 1.5 times 2.0 g/kWh = 3.0 mg/kWh is calculated by the tool for a given regulated emission component. Vehicles are not allowed to emit more than 1.5 times the emission limit value under the for the ISC procedure prescribed conditions and data-evaluation rules. Generally for ISC checking, more than one vehicle should be analysed to determine whether the vehicle type is compliant with the In-Service Conformity requirements. In this programme only one vehicle was tested and, therefore, the results are indicative only.

The next table shows the settings as used for the pass-fail data evaluation with EMROAD. The CO_2 averaging window method was used for the data-evaluation. This method calculates the average emissions over windows as large as the CO_2 mass that would have been emitted during an ETC test. Criteria are defined to exclude windows from the dataset, see the table below. Cold engine operation and high altitudes are excluded from the pass-fail analysis. Furthermore, windows with a very long duration are excluded. This is an alternative for the power threshold as used for the work window method; a power threshold excludes windows where the average power in a window is below a certain percentage of the rated power (at the moment 20% is proposed). A maximum for the window duration also excludes windows with a very low average power, because at a low average power it takes a long time before the CO_2 reference mass is reached.
What remains after exclusion of data is a set of ‘valid windows’ of which the single window, with the largest value of 90 percentile of the data is taken, to calculate the CF for each emission component.

Table 5: EMROAD data evaluation settings for the calculation of the Conformity Factor according to the applicable pass fail method.

EMROAD version	
Reference quantity	CO_2
Reference torque	n.a.
Torque calculation method	n.a.
Reference cycle	ETC
CO_2 estimation	Bsfc = 200 g/kWh
Data exclusion	Engine coolant temperature < 70 ºC, Altitudes > 1500 m, 10^{th} percentile of the maximum values of the valid windows
Time-alignment	On
Fuel density	0.84 kg/litre, (EN590 market fuel) diesel only
Vehicle speed	GPS vehicle speed
Conformity Factor	1.5

3 Results

3.1 Results: test conditions

In this chapter the results of the test programme are presented. The results are presented in tables as emissions per component per (sub-) trip in g/km, binned in speed intervals for CO_2 specific NO_x emission and calculated as Conformity Factor by EMROAD, according to the In-Service Conformity pass fail method.

The results can only be evaluated while taking account of the test conditions. The test conditions are given hereafter.

Table 6: Overview of the test conditions.

Test dates	16-11-2012 to 28-11-2012
Ambient conditions	5-12 ºC, mostly dry or light rain, wind ~2bft
Traffic	Free flowing with medium interactions, with exception of test 3. There a traffic jam occurred due to a police road block.
Driver	Regular driving style
Special conditions	No

3.2 Results: distance specific emissions

The work specific emissions were not calculated because the power from the engine could not be calculated accurately.

The NO_x and NO_2 emissions are lower in the dual-fuel modes compared to the diesel modes.
In the dual fuel modes a significant amount of CH_4 is emitted, which increases at higher blend rates. The CO_2 emission is lower in the dual-fuel modes as could be expected from the relative CO_2 benefit in terms of CO_2 emission per MJ of energy of natural gas. The total CO_2 emission, taking account of the Global Warming Potential of CH_4 of 25, is in dual-fuel mode significantly higher than in diesel mode.

Table 7: Distance specific emission results over all test trips.

Test #		**1**	**2**	**3**	**7**	**4**	**5**	**6**	**8**	**9**	**10**	**12**	**13**
Fuel mode		D	DF	DF	D	DF	D	DF	D	DF	D	DF	DF
Dual-fuel variant		-	1	2	-	1	-	1	-	1	-	1	2
Payload	%	55	55	55	55	55	55	55	100	100	10	10	10
CH_4	g/km	0,00	14,31	7,01	0,00	17,05	0,01	18,10	0,01	11,42	0,01	11,99	8,27
CO	g/km	4,80	8,32	5,29	1,97	4,65	1,93	3,94	4,74	5,60	3,76	11,56	8,99
CO_2	g/km	1332	1264	1378	1041	1005	1077	1029	1645	1632	946	917	941
Total CO_2 equivalent*	g/km	1332	1621	1553	1041	1431	1077	1481	1645	1918	946	1216	1148
NO_x	g/km	7,68	6,02	6,70	5,05	4,49	4,73	4,05	4,99	4,05	7,85	7,10	7,40
NO_2	g/km	0,77	0,40	0,48	0,74	0,19	0,59	0,27	0,39	0,25	0,60	0,35	0,20

*taking account of the Global Warming Potential of 25 of the emitted CH_4

3.3 Results: binned CO_2 specific emissions

The CO_2 specific NO_x emission is generally lower over the complete speed interval in the dual-fuel mode. This is confirmed by the distance specific emission of NO_x which in all dual-fuel cases lower than in the diesel mode.

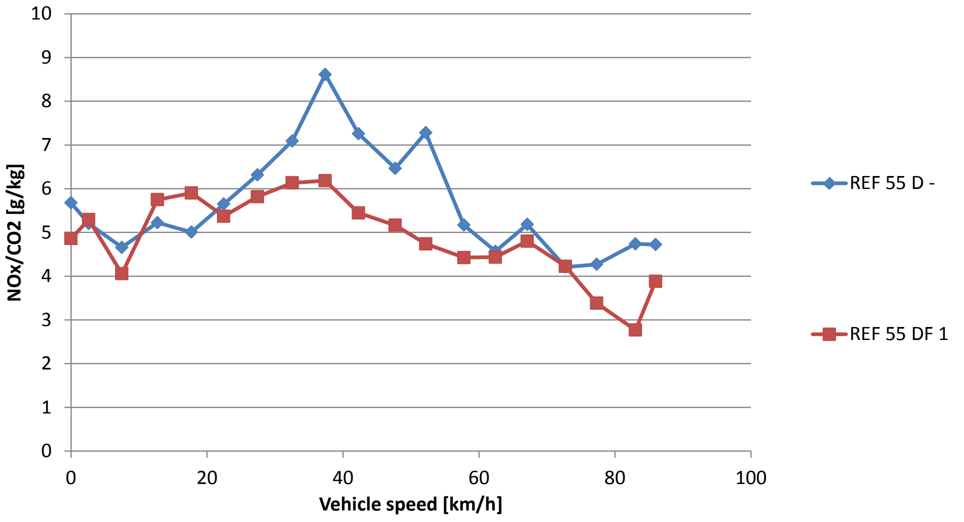

Figure 2: CO_2 specific NO_x emissions averaged per speed interval of 5 km/h over the speed range for reference trips in diesel mode and dual-fuel mode (blend rate variant 1, blend rate variant 2 is not shown because the NO_x results of this trip were affected by a traffic jam.)

The CO_2 specific CH_4 emission is obviously higher in the dual-fuel modes. The level increases at higher speeds and higher blend ratio (blend ratio variant 1 versus variant 2, the latter has 50% lower gas dosing rates in the dosing map).

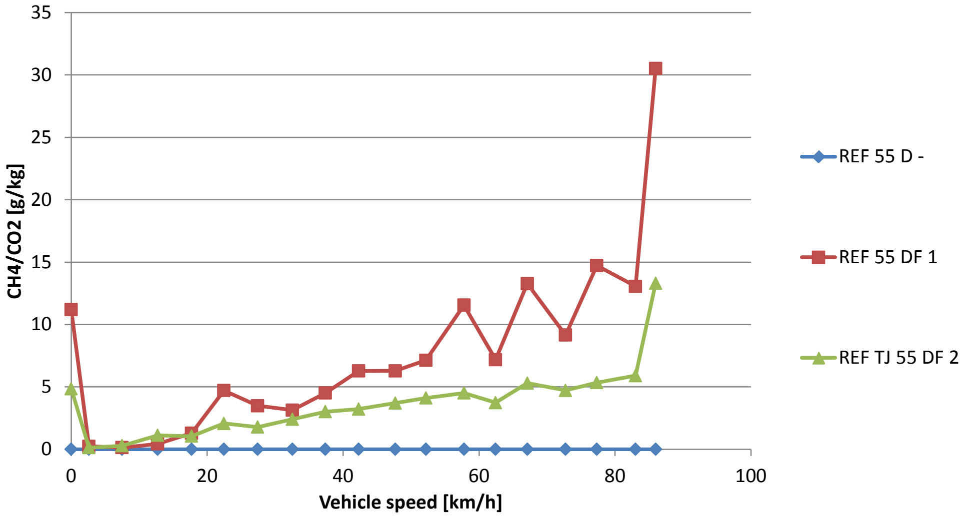

Figure 3 : CO_2 specific CH_4 emissions averaged per speed interval of 5 km/h over the speed range for reference trips (55% payload) in diesel mode and dual-fuel mode (blend rate variant 1 and blend rate variant 2).

The CO_2 specific CH_4 emission is obviously higher in the dual-fuel modes. The level increases at higher speeds and somewhat at a higher blend ratio (blend ratio variant 1 versus variant 2, the latter has 50% lower gas dosing rates in the dosing map).

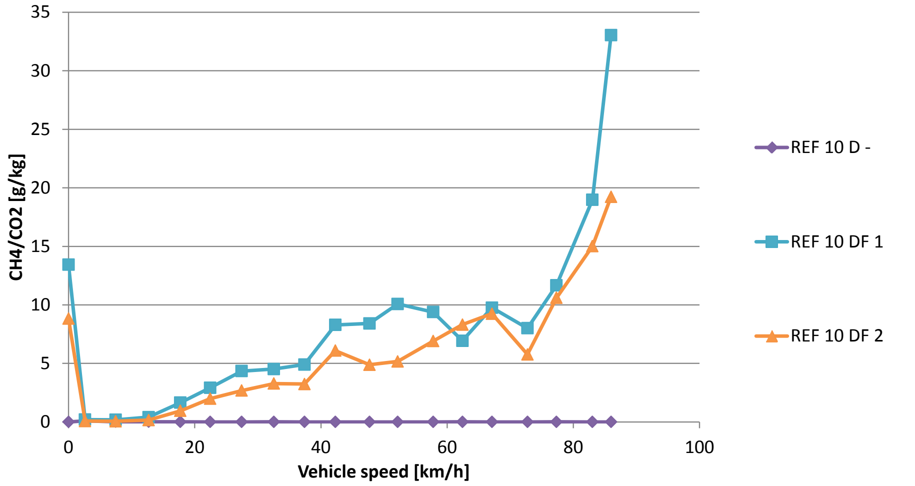

Figure 4: CO_2 specific CH_4 emissions averaged per speed interval of 5 km/h over the speed range for reference trips (10% payload) in diesel mode and dual-fuel mode (blend rate variant 1 and blend rate variant 2).

For 10 and 55% payload the CO_2 specific CH_4 emission is comparable. For 100% payload this is somewhat lower. Several mechanisms may play a role here. At very high loads during acceleration no gas is injected. This is caused by the injection strategy which has to limit the maximum engine power to the power achieved in diesel mode. When driving a constant speed, however, the blend rates may be higher for the 100% payload situation. Thermal effects may play a role as well, at higher loads the temperatures in the combustion chamber are higher, hence, the mixture may be combusted more complete, leading to less CH_4 emitted.

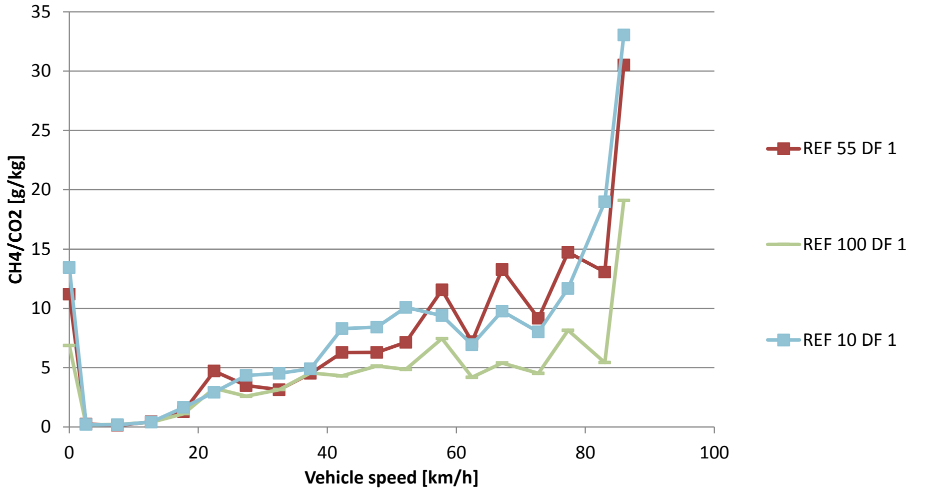

Figure 5: CO_2 specific CH_4 emissions averaged per speed interval of 5 km/h over the speed range for Reference trips in dual-fuel mode with different payloads.

3.4 Results: Conformity Factors

Below the results are presented as Conformity Factors calculated according to the evaluation method as defined in 582/2011/EC. Formally, an averaged Conformity Factor of a group of three vehicles may not exceed 1,5. Therefore, the results presented here are indicative only. Also, according to the In-Service Conformity requirements, [EC[(EU)582/2011], the trip needs to be driven conform certain specifications for payload and trip content of urban, rural and motorway driving see Table 3. In the next figures only the Euro VI trips (marked E6N3) are conform these requirements.

In dual-fuel mode the Conformity Factors for NO_x are somewhat lower than in diesel mode.

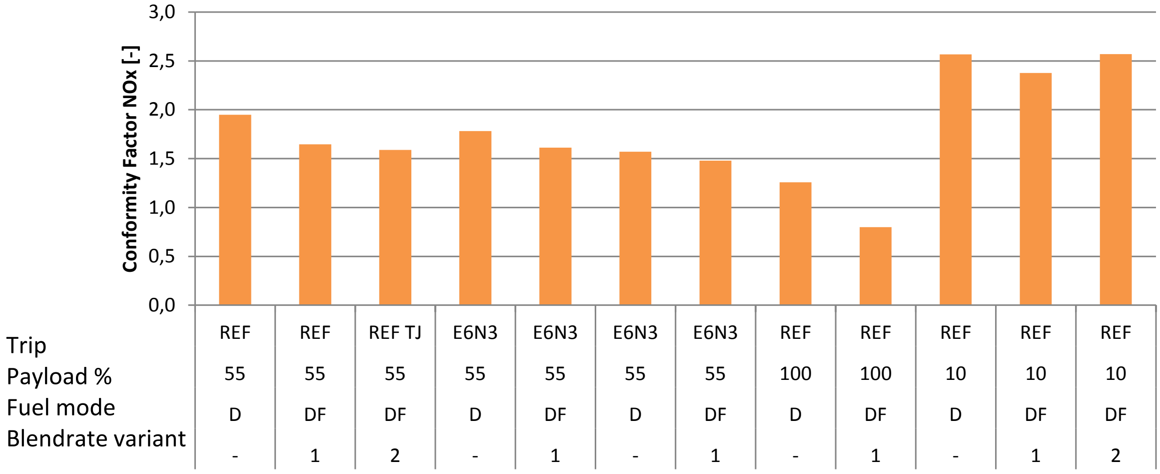

Figure 6: NO_x Conformity Factors calculated with EMROAD.

In dual-fuel mode the Conformity Factors for THC are much higher than in diesel mode and also much higher than 1,5.

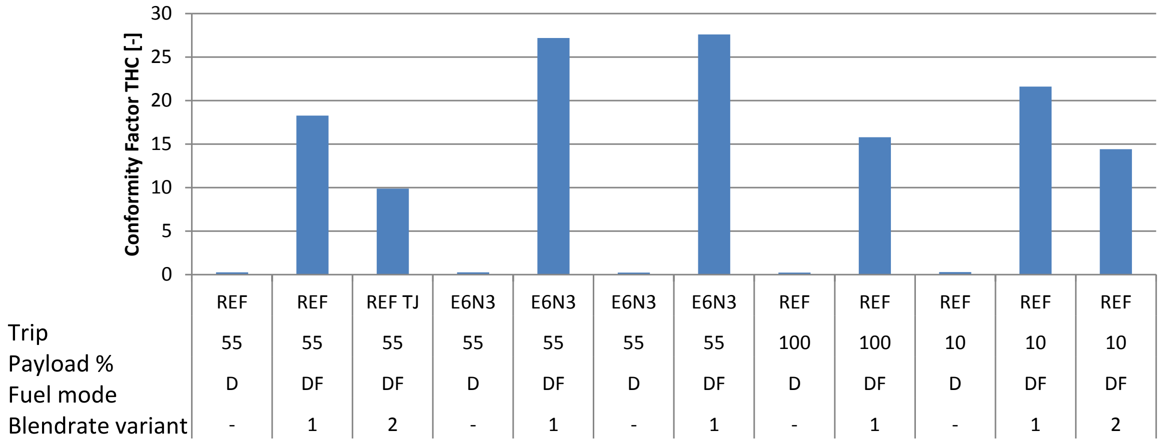

Figure 7: THC Conformity Factors calculated with EMROAD.

In dual-fuel mode the Conformity Factors for CO are higher than in diesel mode and in some cases exceeding 1,5.

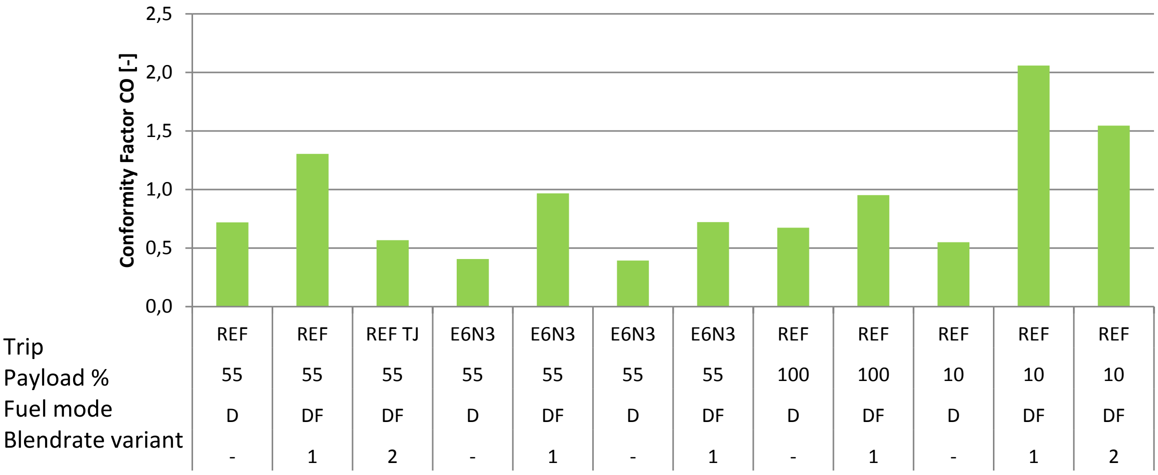

Figure 8: CO (Carbon monoxide) Conformity Factors calculated with EMROAD.

In dual-fuel mode the Conformity Factors for CH_4 which would account for a dedicated natural gas vehicle are much higher than in diesel mode and much higher than 1,5.

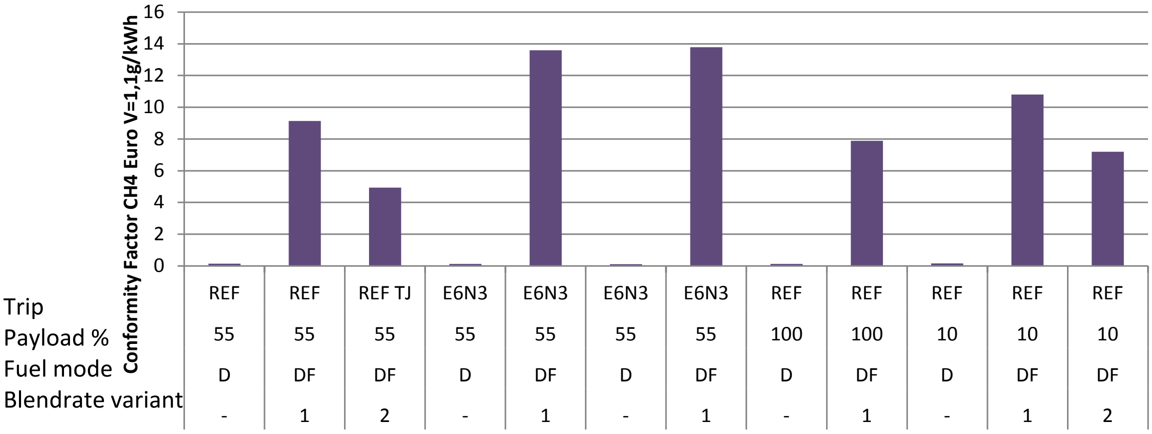

Figure 9: CH_4 Conformity Factors calculated with EMROAD. This Conformity Factor is calculated from the CH4 limit of a dedicated natural gas vehicles for Euro V (1,1g /kWh).

4 Conclusions and recommendations

A Euro V N3 heavy-duty truck with a dual-fuel retrofit system, running on diesel and natural gas, was tested with PEMS on the road driving various trips in diesel mode and dual-fuel mode. An evaluation of the exhaust gas emissions over the trips lead to the following conclusions.

- In dual-fuel mode the NO_x and NO_2 emissions are somewhat lower than in diesel mode.
- In dual-fuel mode the CH_4 emissions are very high. The high CH_4 emissions are the highest during the for the vehicle typical motorway operation. The CH_4 emissions decrease at a lower blend ratio but are still high.
- In dual-fuel mode the CO_2 emissions are lower, as could be expected from the lower energy specific CO_2 emission of natural gas. However, when the high CH_4 emission and its Global Warming Potential of 25 in CO_2 equivalents are considered, the total CO_2 emissions are 14-40% higher in dual-fuel mode than in diesel mode, depending on the trip and the blend ratio.
- With a high payload (100%) the CO_2 specific CH_4 emission decreases somewhat compared to lower payloads (55 and 10%).

It is recommended to investigate a vehicle with a semi-OEM solution for the dual-fuel system to see how this technology performs with regard to the methane emissions. The semi-OEM solution has interaction with the vehicles engine control system and has a methane catalyst to reduce the methane emissions.

5 References

[2005/78/EC] Directive 2005/78/EC of 14 November 2005 implementing Directive 2005/55/EC of the European Parliament and relating to the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles, and the emission of gaseous pollutants from positive ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles.

[(EU)582/2011] Commission Regulation (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009

[Ligterink et al, 2009] Ligterink, N.E., Lange, R., Vermeulen, R.J., Dekker, H.J., "*On-road NOx emissions of Euro-V trucks*", TNO Science and Industry, Report number MON-RPT-033-DTS-2009-03840, Delft, 2 December 2009

[Verbeek et al, 2010] Verbeek, R, Vermeulen, R.J., Vonk, W., Dekker, H.J. "*Real World NOx emissions of Euro V vehicles*", TNO Science and Industry, Report number MON-RPT-2010-02777, 11 November 2010

[Vermeulen et al, 2012] Vermeulen, R.J., Dekker, H.J., Vonk, W.A., *Real-world NO_x emissions of Euro V and Euro VI heavy-duty vehicles,* TNO-report TNO-060-DTM-2012-01193, May 2012.

6 Signature

Delft, 26 April 2013

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