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TNO report

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Emissions testing of a Euro VI LNG-diesel dual fuel truck in the Netherlands

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Samenvatting

In het kader van het ‘Steekproefcontroleprogramma voor vrachtwagens en bussen’ voor het Ministerie van Infrastructuur en Waterstaat zijn door TNO praktijkemissietesten uitgevoerd aan een lange-afstandsvrachtwagen met een Euro-VI tweebrandstoffenmotor (LNG-diesel) om het niveau van de uitstoot van schadelijke stoffen en de uitstoot van broeikasgassen te bepalen. Het voertuig werd geïntroduceerd in 2018 en vertegenwoordigt daarmee de nieuwste LNG technologie voor vrachtwagens voor de lange afstand. De resultaten worden in dit rapport gepresenteerd naast eerder in het kader van het programma onder vergelijkbare Nederlandse rijcondities verkregen emissieresultaten van een groep soortgelijke trucks met Euro VI dieselmotoren en motoren die enkel op LNG draaien. Voor het bepalen van de broeikasemissies zijn naast de CO_2 emissies uit de uitlaat ook de CH_4 emissies uit de uitlaat gemeten. Tijdens het meetprogramma is ook de boil-off uit de tank gemeten en gemonitord om een indicatie te krijgen van de bijdrage van deze bronnen aan de broeikasgasemissie op voertuigniveau. Er zijn zeer indicatieve metingen gedaan aan de uitstoot van het sterke broeikasgas N_2O. Aanvullend zijn formele testen uitgevoerd om de conformiteit van het in gebruik zijnde voertuig te controleren ten aanzien van de gereguleerde uitstoot van schadelijke gasvormige stoffen.

De belangrijkste conclusies:

- Het voertuig met een tweebrandstoffenmotor, met LNG als hoofdbrandstof en diesel als hulpbrandstof, slaagt voor de Europese emissietest voor de conformiteit van in gebruik zijnde voertuigen.
- Voor een gemiddelde langafstandsrit liggen de gemeten emissies van NO_x en deeltjesaantallen op een vergelijkbaar niveau als van een groep van reeds geteste Euro VI trucks met een dieselmotor.
- Voor een gemiddelde langafstandsrit liggen de broeikasgasemissies CO_2 en CH_4, wanneer deze samen worden uitgedrukt in een CO_2 equivalente uitstoot, gemiddeld lager dan een groep voertuigen met dieselmotoren (n=5) van een wat ouder modeljaar (rond 2013), met een gemiddeld verschil van rond de 19%. Het verschil is een paar procent hoger op de snelweg en mogelijk wat lager in de stad. In de uitstoot van CO_2 en CH_4 uit de uitlaat is het aandeel van de CH_4 emissie (ook wel methaanslip genoemd) wanneer deze wordt uitgedrukt in CO_2 equivalenten ongeveer 2-3%. Ook wanneer voertuigen van een nieuwer modeljaar (2018-2019) een paar procent minder CO_2 zouden uitstoten door technologische verbeteringen, zou het verschil in de CO_2 uitstoot significant zijn. Er is enige spreiding in de individuele testresultaten voor zowel de LNG-vrachtauto’s als de dieselvrachtauto’s. Dit kan het gevolg zijn van verschillen tussen de voertuigen maar ook van variatie in de testcondities bij het rijden van ritten op de weg. De reproduceerbaarheid van een wegtest met PEMS is voor CO_2 +/- 5%.

Indicaties ten aanzien van de overige potentiele broeikasgasemissies
Indicatieve metingen lieten zien dat het broeikasgas N_2O aanwezig is in het uitlaatgas van het voertuig. Motoren met een diesel uitlaatgasnabehandelingssysteem stoten mogelijk het sterke broeikasgas N_2O uit. Er is weinig bekend over het niveau van de uitstoot van dit gas.

Een gericht onderzoek met speciale meetapparatuur is nodig om meer inzicht te krijgen in de mogelijke bijdrage van de uitstoot van N_2O van vrachtwagens met diesel uitlaatgasnabehandeling.

Wanneer de LNG tank methaan afblaast (boil-off), is de bijdrage aan de broeikasgasemissies laag. Er zijn nog geen meetgegevens beschikbaar van de frequentie waarmee het afblazen plaatsvindt. Het testvoertuig is daarom uitgerust met een sensor om dit te meten. De resultaten komen naar verwachting halverwege 2019 beschikbaar.

Het monitoren van de vervuilende emissies en de broeikasgasemissies van zware bedrijfswagens over de levensduur van de voertuigen geeft inzicht in de trends van deze emissies, levert de gegevens voor het bepalen van de Nederlandse emissiefactoren en geeft inzicht in de effectiviteit van de Europese emissiewetgeving in het behalen van duurzaam lage emissies van de voertuigen op de openbare weg.

Summary

In the framework of the in-service testing programme of trucks and buses, for the Ministry of Infrastructure and Water Management by TNO, an on-road emissions testing programme was conducted to determine the criteria pollutants and greenhouse gas (GHG) emissions of a Euro VI long haulage truck with a dual fuel engine running on LNG (liquefied natural gas) as the primary fuel and diesel as the secondary fuel. Introduced in 2018, the tested vehicle represents the newest of LNG technology for long-haulage trucks sold in the Netherlands and uses a diesel-like emissions control system.
The results of the measurement programme are used to make a comparison with the emissions of baseline Euro VI diesel trucks that were tested earlier in the framework of the programme under comparable Dutch driving conditions on the public road. Besides tailpipe CO_2 emissions, methane slip and boil-off from the tank were measured to estimate the contribution to the tank-to-wheel (TTW) GHG emissions of the vehicle. Very indicative measurements of the greenhouse gas N_2O were conducted. Additionally, in-service conformity tests were conducted to check the regulated pollutant emissions of the vehicle with a Euro VI certified HDDF (heavy-duty dual fuel) engine.

From the measurements the following main conclusions can be drawn:

- The vehicle passed the formal European in-service conformity test for the regulated pollutant emissions.

- For an average long haulage trip, the emissions of the criteria pollutants NO_x and particulate number of the test vehicle were at a comparable level as for a group of tested comparable Euro VI diesel heavy-duty vehicles.

- For an average long haulage trip the greenhouse gas emissions CO_2 and CH_4 from the tail pipe of the test vehicle were on average significantly lower than the average of the group (n=5) of a somewhat older model year (around 2013) counterpart diesel vehicles, in the order of about 19%. The difference is a few % larger for motorway operations, but seems somewhat lower for urban and low load operations. The share of CH_4 emissions in the emission of CO_2 and CH_4 is about 2-3 % when expressed in CO_2 equivalents. There would still be a significant difference with newer model year diesel trucks when these newer diesel trucks (MY2018-2019) would emit a few percent less CO_2 due to technological improvements. There is some spread between individual measurement results of both the LNG as well as the diesel trucks. This can be caused by differences between vehicles but also by differences in test conditions on the road. The reproducibility of a road test with PEMS is for CO_2 about +/-5%.

Indications regarding other potential greenhouse gas emissions
Indicative measurements showed the presence of the greenhouse gas N_2O in the exhaust. N_2O emission from the tail pipe is a potential generic issue for engines with diesel exhaust gas aftertreatment such as also used by the tested vehicle. Therefore, the possible emission of N_2O of engines with diesel aftertreatment in general deserves further investigation by means of dedicated measurements.

When boil-off from the LNG tank occurs, the contribution is low. There are no measurement data available of the frequency of boil-off events. To collect data about the frequency of boil-off events, the vehicle has been equipped with an instrument that records this frequency. Results will be reported later in 2019.

Continuation of the monitoring of the pollutant and GHG emissions of heavy-duty vehicles during the life time of the vehicles reveals trends of these emissions and the effectiveness of EU emissions legislation in achieving sustainably low emissions over the life time of the category of heavy-duty vehicles.

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A Test fuel: LNG

1 Introduction

1.1 Background

The Ministry of Infrastructure and Water management has contracted TNO to conduct the in-service emissions testing programme for heavy duty vehicles.
In this programme TNO measures on an annual basis the emissions of a selection of vehicles.

The data is used to:

- Determine the Dutch emissions factors for heavy commercial vehicles.
- Determine trends over the different EU standards and steps:
  - Are the vehicles getting sufficiently cleaner each generation/step in the real world?
  - Use the data and insights in Brussels in discussions about the improvement of the test procedures.
- Screen the in-service conformity.
- Assess new/alternative technologies.
- Provide information to stakeholders. To help make purchase decisions for cleaner and more fuel efficient transport.

Follow-up on recommendations of TNO report R11336
In 2017, in the framework of this programme, TNO has tested two articulated trucks that are running on LNG. This was done to determine the level of criteria pollutants and the tank-to-wheel greenhouse gas emissions of the vehicles on the public road in the Netherlands. The tests and results have been reported in TNO report R11336, [TNO 2017]. One of both vehicles was retested outside the framework of the programme and reported in TNO report R10885 [TNO 2018].
At that time only few types of tractors with a spark ignited engine running on LNG were offered. It was therefore recommended to test additional vehicles when they would arrive on the market. Since September, 2018 Volvo Trucks offers a tractor with a different technology compared to the earlier tested LNG vehicles and uses a dual fuel engine running on LNG as the main fuel and diesel as a pilot fuel to start combustion. A vehicle was obtained from a private transport company to measure the emissions with PEMS on the public road.

A number of PEMS tests have been performed on the truck. The test programme contained in-service conformity tests according the applicable PEMS test requirement for testing the in-service conformity as well as additional tests that were focussed on typical representative driving conditions. The results of the in-service conformity tests that were performed over the applicable N3 test cycle are extensively reported in TNO report R10014 [TNO 2019].

This report presents an overview of the results of all PEMS tests that were performed on the vehicle and also presents those results next to the results of earlier tested comparable vehicles running on LNG and diesel.

1.2 Goals

The goals of the measurements are to determine the real world emissions levels of tank-to-wheel greenhouse gas emissions, the pollutant emissions and the in-service conformity, of a Euro VI dual fuel truck driving on the public road in the Netherlands and to present the results next to results obtained earlier in the framework of the heavy -duty in-service testing program for a number of comparable Euro VI diesel vehicles and two Euro VI LNG vehicles.

1.3 Approach

The following environmental indicators needed to be determined for the test vehicle with a Euro VI certified heavy-duty engine with dual fuel technology:

- TTW GHG emissions CO_2 and CH_4, including boil off from the tank (CH_4) and N_2O screening.
- TTW Gaseous pollutant emissions NO_x, NO_2, Particle Number (PN), CO, THC with a focus on NO_2, NO_x and PN as the most important criteria pollutants.
  - Emissions in g/km and g/kWh.
  - Emissions for typical Netherlands public roads containing urban, rural and motorway driving and a representative distribution trip with a stop representing delivery of goods.
- In service conformity factors of the regulated gaseous emissions NO_x, CO and THC according EC regulation nr. 582/2011 as amended by EC regulation nr. 2016/1718.

In-service conformity testing was conducted with the Portable Emissions Measurement System (PEMS) according to the prescribed test procedures to determine the in-service Conformity Factors for the regulated emissions.
The Conformity Factor is the ratio of the emissions value as determined by the pass-fail evaluation method to the limit value of the WHTC engine test for type approval. The pass-fail evaluation method uses moving averaging windows on the emissions data of the PEMS test and excludes a number of the windows according to some defined criteria. PEMS is also used to determine the emissions under normal Dutch driving conditions on the public road in the Netherlands on a vehicle that is normally in-service by a transport company and that was made available by the transport company for the purpose of the test programme.

2 Measurement programme

2.1 Test vehicle

The vehicle has Vehicle Identification Number YV2RZ70A3JA829953. This vehicle is an N3 vehicle with a dual fuel class 1A[1] engine Euro VI Step-C certified engine running on LNG-Diesel and is a vehicle designed for long haulage.
The vehicle has an odometer reading of 19.990 km at intake of the vehicle.
The tested vehicle is shown in Figure 1.

Figure 1: The test subject, a Volvo FH420 tractor with a Euro VI step C certified ‘1A’ HDDF heavy-duty dual-fuel engine with LNG as the main fuel.

[1] Class 1A means an engine running with a Gas-Energy-Ratio of >90%.

2.2 Vehicle specification

Table 1: General information.

TNO test vehicle code	**VO180**
Model	Volvo FH420
Vehicle owner	Peter Appel Transport B.V.
License plate no.	77-BLB-4
EEC Type approval	595/2009*2016/1718C
Date of registration	04-07-2018
Odometer reading at intake vehicle	19990 km
Maximum technically permissible laden mass	21.000 kg
Gross Train Weight (GTW)	50000 kg
Registered mass running order truck	8.131 kg
Registered mass running order trailer	7400 kg
Loading capacity combination	34489 kg
Combination weight during test	31920 kg
Axle configuration	4 x 2
VIN (chassis number)	YV2RZ70A3JA829953
Vehicle class	N3
Gearbox make + type	Volvo Sweden - AT2612F
Number of forward gears	12
Tyre make and type rear axle	Continental Hybrid HD3
Tyre size drive axle	315 / 70 / R22,5
Tyre test pressure	8.5 bar
Axle reduction ratio	2.47
Fuel tank capacity Diesel	195 l
Fuel tank capacity LNG	205 kg / 575 l
AdBlue tank capacity	64 l

Table 2: Engine information.

Engine type	**G13C420** (**HDDF engine class 1A**)
Fuel injection system	Combined Diesel/Gas Injector
Engine serial number	805066
Number of cylinders	6
Displacement	12.777 l
Euro Class Emissions limits	Euro VI, step C, HDDF class 1A WHTC limits NO_x 0.46 g/kWh CH_4 0.5 g/kWh NMHC 0.160 g/kWh PN $6x10^{11}$ NH_3 10ppm ISC PEMS test CF(CO, CH_4 and NO_x) 1.5
Turbo	Yes
Intercooler	Yes
EGR	Yes (Uncooled)

Table 3: Aftertreatment information.

Aftertreatment system (downstream)	Diesel Oxidation Catalyst (DOC)
	Diesel Particulate Filter (DPF)
	Selective Catalytic Reduction (SCR)
	Ammonia Slip Catalyst (ASC)
Consumable reagent	AdBlue

The vehicle received a regular scheduled software update at the local dealer daily before the test programme.

Table 4: Software versions and identifications.

	Engine Control Module	**Aftertreatment Control Module**
Software version	23338503	23240315
Software ID	23154053	23154361
Calibration ID	23154058	23154435

2.2.1 *Test fuel*

Before and during the tests the vehicle was fuelled with market fuel LNG at gas station ‘Truckstop 8’ in Eindhoven. See Annex A.

2.2.2 *Vehicle payload*

An artificial payload is used to load the combination with 16389 kg. The load consisted of concrete blocks, a container filled with water and the measurement equipment. The payload is shown in Figure 2.

50t is the maximum for a tractor semi-trailer or tractor-trailer combination in the Netherlands. Usually, the maximum GCW for a given combination is lower when the tractor is 4x2, because the axle load limits, limit the total allowed weight. For this vehicle, the maximum axle loads are 8, 11.5, 9 , 9 and 9 ton respectively meaning that the total weight of the combination shall not exceed 46.5t when payload would be ideally distributed. In that case the payload percentage is higher and is 53%. This means that the payload percentage can differ and depends on the exact configuration of the combination of vehicle and semi-trailer.

Table 5: Overview of vehicle and payload mass as used for the different PEMS tests. Weighting scale tickets can be found in [TNO 2019].

Payload	**Empty mass in running order [kg]**	**Payload[1] [kg]**	**Gross Train Weight [kg]**
Low (10%)	15531	3229	18760
Medium (53%)	15531	16389	31920
Full (100%)	15531	30909	46440

[1]Typical payload for the transport company is about 15.5t. 660 kg of extra mass was added to the payload to bring the weight at about the level of a closed trailer. Weight falls 200 kg short from target. 660kg represents the difference in weight between the curtain side semi-trailer that was used for the tests and the closed panel semi-trailer that is normally used by the transport company.

Figure 2: The vehicle payload inside of the trailer.

2.3 Equipment used

2.3.1 Gaseous emissions

The analyser that was used for measuring the gaseous emissions is the OBS-ONE-GS12 (PEMS) with serial number 63JNMN52. Detailed information about the checks performed for the calibration of the gaseous analysers can be found in [TNO 2019].

Figure 3: The PEMS analyser mounted in the cabin of the truck.

2.3.2 *Exhaust flow meter*

The exhaust mass flow, pressure and temperature are measured with a Pitot Flow Meter Unit (PF) and flow tube as shown in Figure 4, for its specifications see Table 6. Detailed information about the calibration of the pitot flow module and tube can be found in [TNO 2019].

Table 6: Horiba Pitot Flow Meter specifications.

PF serial number	**PG7RUL35**
Flow tube serial number	150502F
Flow tube diameter	4 inch (F-tube)
Flow measurement range	0 – 30 m³/min
Flow measurement accuracy	Within ±0.5 % of full scale or ±2.0 % of readings (whichever is larger)
Exhaust temperature measurement range	0-800°C
Exhaust temperature accuracy	Within ±2.0 % of full scale
Exhaust pressure measurement range	70-115 kPa (abs)
Exhaust pressure accuracy	Within ±2.0 % of full scale
EFM Cable	Exhaust H/L Tube and Thermocouple Cable

Figure 4: The flow tube connected to the exhaust of the truck.

2.3.3 *Other equipment SEMS*

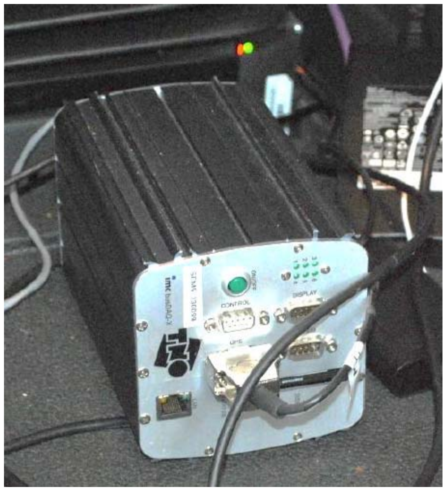

Figure 5: Smart Emissions Measurement System. SEMS was installed to measure boil-off frequency during normal operation at the Transport Company. Results yet to be published.

2.3.4 *Particle Number Measurement*

The Particle Matter Number emissions have been measured during the campaign using a PN-PEMS module. Table 7 shows its specifications. Detailed information about the checks performed for the calibration of the particle counter can be found in [TNO 2019].

Table 7: OBS-ONE-PN specifications.

Detectable particle	Limited to 1 µm by inlet cyclone
Detection efficiency	<60% at 23 nm >60% at 50 nm
Particle concentration	Single particle counting (nominal 100:1 dilution) 1 000 : 50 000 000 particle/cm³
Condensing liquid	99.5% isopropyl alcohol
Catalytic stripper	Efficiency >99.9% of 30 nm
Particle concentration accuracy	±15% compared to the standard
Environmental operating conditions	Temperature -10 – 40 °C Pressure 86 – 106 kPa
Sample interval	2 Hz

2.3.5 *Other equipment*

A Horiba OBS1-ONE-PN was used to measure the not yet regulated PN emissions.

A dual fuel flow meter was mounted in the feed and return diesel fuel lines at the diesel tank. Due to the low diesel consumption, up to few l/h, the measurement is not accurate.

Table 8 lists the remaining equipment that was used to operate the measurement system.

Table 8: Other equipment.

System software	1.3.6
Horiba Post Processing software version	2.12.0
Power supply	Honda 20i EAAJ-1820185
Power terminal	24V Power supply
Power cable	Power Cable BATT24V to DC3 + DC4 to DC3 extension cable
GPS sensor	U-Blox ANN-MS-1-005 GPS Antenna
Weather station	Temp and RH sensor Horiba 61361448
Protocol adapter	Kvaser Leaf Light v2 73-30130-00685-0
Heated line	Single Heated Line 191°C
System battery	2x 12V 170 Ah 1000 A (EN)
Silverscan software version	6.22.36.28520
Silverscan CAN interface	Kvaser Leaf Light v2 018504
Diesel flow	AIC 6004 Swissline
SEMS	UniNOx NOx sensor, Delphi NH3 sensor, GPS, k-type thermocouple, CAN/OBD connection, 1Hz data logger, 4G data server connectivity, pressure switch sensor.

2.4 Test schedule

Table 9: Overview of tests performed.

Test nr.	**Test type/route**	**Test date**	**Payload**	**Remarks**
01	Commissioning	11-10-2018	~53%	
02	Euro VI N3 #1	12-10-2018	~53%	
03	Euro VI N3 #2	15-10-2018	~53%	
04	Distribution	16-10-2018	~53%	
05	Euro VI N3	17-10-2018	~53%	OLD version of N3 route
06	Euro VI N3	18-10-2018	~10%	
07	Euro VI N3	11-10-2018	~100%	Test error
08	Euro VI N3 #3	22-10-2018	~100%	
09	Idle	23-10-2018		
10	N_2O	23-10-2018		Test error
11	Euro VI N3	24-10-2019	~%53%	
12	N_2O concentration @idle	25-10-2019		Stationary test measuring N_2O concentration in the tail-pipe
13	Diesel only test	26-10-2019		Check OBD fuel rate in ‘diesel only’ running mode
14	Boil-off	Weekend		Measurement of boil-off flow
15	SEMS tests during real operation	Period sept. 2018-May 2019. Ongoing		Not reported here

2.5 Test routes

A number of different test routes were driven in case of one route with different payloads. An overview of the routes, more detailed information is presented below:

- N3 route: the PEMS test route that is prescribed by EU emissions legislation for the tested vehicle of EU category ‘N3’, GCW>12t. The route was driven with low, medium and full payload and was repeated three times to determine the total repeatability of the test (variability of vehicle, instruments and conditions of test).
- Old N3 route: Old version of the N3 route, as used for earlier tested vehicles.
- Representative route: This route is added to represent typical use of the vehicle.

N3 route
For the N3 test route, a trip was selected that meets the following requirements for a N3 category vehicle:

1. Target time share of urban, rural and motorway operation : 20, 25 and 55% (±5%) respectively;
2. A total cycle work between 4-7 times reference work (World Harmonized Transient Cycle work) or a total CO_2 mass between 4-7 times reference CO_2 mass (World Harmonized Transient Cycle CO_2 mass);
3. The assessment of trip composition shall start after the engine coolant temperature has reached 343 K (70°C) for the first time or after the coolant temperature is stabilized within ±2 K over a period of 5 minutes whichever comes first but no later than 15 minutes.

All tests started with a cold engine(engine coolant temperature below 303 K(30°C)) as required in point 2.6.1. of EU 2016/1718.
The new version of the E6N3 route that was driven and that was use for the in-service conformity tests is shown in Figure 6. To determine the start of the rural and motorway parts, the first acceleration method has been used. This means that the first acceleration above 55km/h indicates the beginning of the rural part, and the first acceleration above 75km/h indicates the start of the rural part.

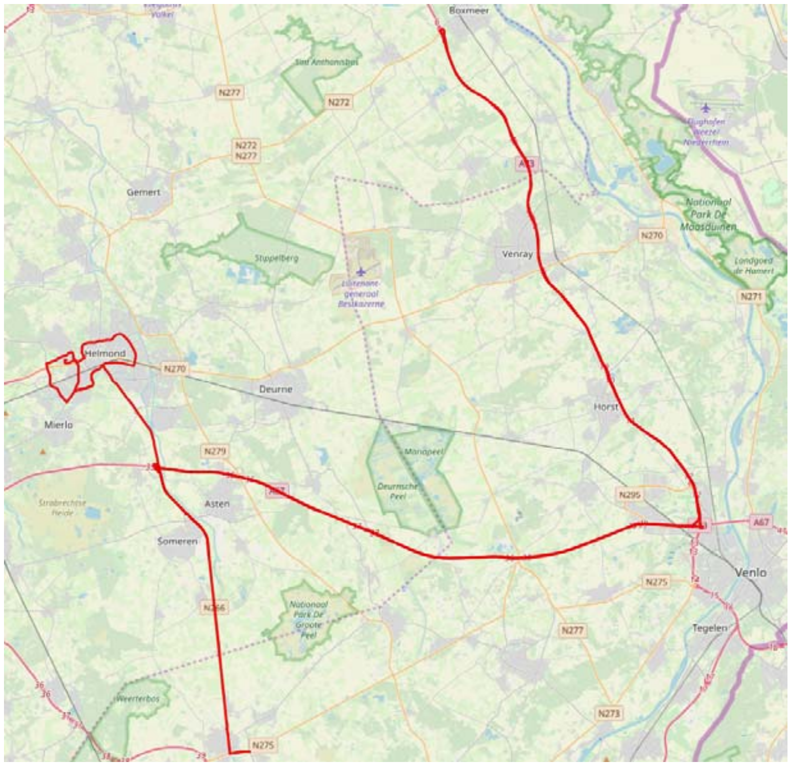

Figure 6: The N3 test route as also used for the in-service conformity tests.

Old N3 route

In addition, the old version of the N3 trip was driven. This route does not meet the requirements of EC 2016/1718. Because the trip was used for earlier measurements on LNG trucks and diesel trucks, this trip was added to the programme to serve as a reference.

Representative route

Because the vehicle is used in the Netherlands to distribute goods between distribution centres and to supermarkets the selection of test routes was extended with a route that was developed to simulate this particular duty. The route consists of highway driving simulating inter DC operation for conditioning, bringing engine and drive line on working temperature, followed by a stop for loading, driving from DC via highway into the city centre, a stop to simulate unloading of goods and driving from the city centre to the highway again.

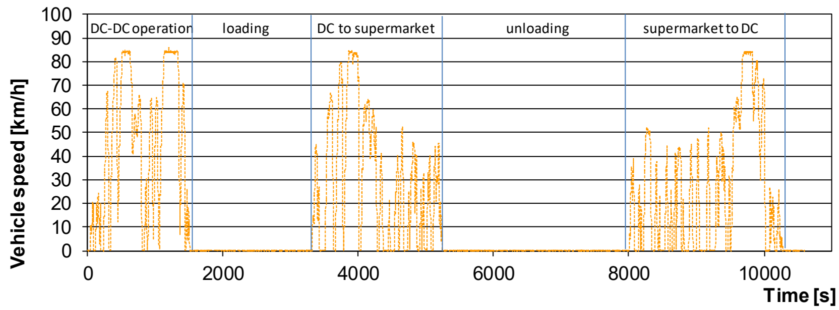

Figure 7: Example of supermarket delivery trips, with parts for inter-distribution centre operation and distribution centre to super market and back.

Overview of test route specifications

Table 10: Test trip specifications

Test cycles	**Distance**	**Approximate average speed**
	[km]	**[km/h]**
DC-DC operation conditioning	21	45
Supermarket supply trip DC-supermarket part	16	28
Supermarket supply trip supermarket-DC part	16	28
N3 trip urban	23	23
N3 trip rural	41	57
N3 trip motorway	114	80

2.6 OBD error check

An OBD error check was performed by TNO prior to the first PEMS test. No active error codes were found in the vehicle.

Software: Silver Scan-Tool 6.22.36.28250
Adapter: Kvaser Leaf Light v2 73-30130-00685-0

2.7 Data processing

HoribaPP (Post Processing) version 2.11.1 has been used as data processing tool.

2.8 Test procedure

Further details of the test procedure have been elaborated in [TNO 2019].

3 Measurement results

3.1 Tank-to-wheel greenhouse gas emissions

3.1.1 CO_2 and CH_4 tail pipe

The table below presents the GHG emissions CO_2 and CH_4 from the tailpipe as measured over the different routes and route parts. The CO_2 emissions were measured directly with PEMS. The CH_4 emissions were estimated based on the total hydrocarbon (THC) emissions that were measured with PEMS. About 85 to 100% of THC emissions are emitted as CH_4 for an engine that mainly runs on LNG. For the calculations it is assumed that the THC emission is 100% CH_4. IPCC[2] presents a Global Warming Potential of Methane of 34. This value is used to express the methane emissions as CO_2 equivalent emissions.

Table 11: Overview of greenhouse gas emissions CO_2 and CH_4 (measured as THC) in g/km and g/kWh. The THC emission is assumed to be 100% CH_4. In practise, most of the THC emissions of a gas fuelled engine are CH_4. Usually, the methane fraction is somewhat lower than 100% and in the range of about 85-100% as the THC emissions may still contain some heavier hydrocarbons. A GWP of 34 is used to calculate the CO_2 equivalent emissions of CH_4.Total, urban, rural and motorway parts are selected from the 1Hz dataset to represent comparable trips and trip parts.

Test nr._type_payload _ cold or warm start_remarks		CO_2	THC (CH_4 eq.)[1]	CH_4 Fraction $CO_{2\ eq}$	$CO_{2\ eq}$		CO_2	THC) CH_4 eq.)
		[g/km]	[g/km]	[g/km]	[g/km]		[g/kWh]	[g/kWh]
02_E6N3_53C	Total	684	0.40	2.0%	698		550	0.32
	Urban	1199	0.89	2.5%	1229		592	0.44
	Rural	760	0.45	2.0%	775		547	0.32
	Motorway	550	0.29	1.8%	560		535	0.28
03_E6N3_53C	Total	662	0.38	1.9%	675		571	0.33
	Urban	1307	0.99	2.6%	1341		597	0.45
	Rural	745	0.39	1.8%	759		554	0.29
	Motorway	526	0.27	1.7%	535		568	0.29
04_REP_53W	Total	917	0.51	1.9%	935		518	0.29
	Motorway warm up	857	0.42	1.7%	871		522	0.26
	DC-winkel	955	0.55	2.0%	974		519	0.30
	Winkel -DC	941	0.56	2.0%	960		513	0.31

[2] The Global Warming Potential (GWP) for methane is 34 according to the 2013 IPCC AR5 (p. 714) for a 100 year time horizon, meaning that the contribution of 1 kg of CH_4 to global warming is equivalent to that of 34 kg of CO_2.

05_E6N3_53C_OLD N3	Total	618	0.40	2.2%	632		535	0.35
	Urban	1227	1.10	3.0%	1265		617	0.55
	Rural	737	0.48	2.2%	753		534	0.35
	Motorway	504	0.29	2.0%	514		516	0.30
06_E6N3_10C	Total	543	0.44	2.8%	558		566	0.46
	Urban	929	0.95	3.5%	962		626	0.64
	Rural	587	0.47	2.7%	603		575	0.46
	Motorway	450	0.33	2.5%	461		540	0.40
08_E6N3_100C	Total	825	0.46	1.9%	840		524	0.29
	Urban	1547	1.13	2.5%	1585		567	0.41
	Rural	929	0.51	1.9%	946		511	0.28
	Motorway	638	0.30	1.6%	648		512	0.24
11_E6N3_53C	Total	664	0.46	2.4%	680		526	0.37
	Urban	1263	0.98	2.6%	1296		569	0.44
	Rural	734	0.52	2.4%	752		519	0.37
	Motorway	526	0.35	2.2%	538		512	0.34

[1]an ugas of 0.000565 of CH_4 was used for the calculation of mass emissions based on tabulated values (ECE-R49).

3.1.2 Boil off

No measurement data are available of the amount of boil-off of LNG tanks of vehicles. Boil-off is the release of gas from the fuel tank when the pressure rises to the threshold of the pressure relieve valve, which is required to prevent further build-up of pressure in the tank. This venting usually only occurs after a certain period of time when the vehicle hasn't consumed fuel from the tank or consumed little fuel from the tank as a result of which pressure in the tank rises. To get an indication of the level of boil-off emission, two factors are of importance; 1) how much do these events occur over the lifetime of the vehicle in normal operation and 2) if it occurs, how much is vented to the air.

Measurements have been performed to obtain an indication of the amount of boil off once the boil-off was initiated, i.e. the pressure in the tank reached the pressure relief valve threshold of 16 bars. Overnight and over one weekend the boil off flow was measured with a gas flow meter that was connected to the venting pipe behind the cabin of the vehicle.

It was observed that the boil-off starts after about two days of standstill when the vehicle was prepared for the measurements. R110 certified LNG tanks have a required hold time of 5 days when the tank is full. There are different LNG systems on the market. The tested vehicle has an LNG system that is designed for so-called low pressure, cold LNG. In the Netherlands most fuel stations provide LNG at a higher pressure of around 8 bar. This could be a reason for the observed hold times of about two days.

Because the LNG system uses liquid fuel from the tank, the tank pressure that is caused by the gaseous part of the fuel, is not immediately reduced when the vehicle starts to consume fuel from the tank.

For the situation boil-off occurs after a certain time, the boil-off is estimated to be about 0.3 kg/day. This would account for an equivalent CO_2 emission of about 9 kg/day. To get an indication of the significance, the equivalent CO_2 emissions can be compared to the CO_2 emissions of the combustion engine. With a CO_2 equivalent emission of 0.65 kg/km from combustion this would equal about 15 km of driving.

Table 12: Measured boil-off flow after boil-off has initiated and estimation of CO_2 eq. emission per day.

Begin time	**End time**	**Hours**	**[Litre]**	**[l/h]**	**Approximate emission LNG / CO_2 eq. [kg/day][1]**
We 18:45	Thu 8:15	14.5	228	16	0.3 / 10.0
Fr 16:00	Mo 10:00	66	892	14	0.25 / 8.5

[1]Based on 0.76 kg/m(n)^3 and assuming standard temperature and pressure of the gas from the boil-off vent.

To obtain insight in real world boil off frequency during normal operation a datalogger was installed that counts the number of times a pressure induced switch switches on and off. The switch indicates the occurrence of venting. Data is collected from September 2018 onwards. Results are not yet available.

Other methane sources not measured on this particular vehicle type are:

- System to vent the gas from the gas control module, when the engine is switched off this gas is vented to the tank.
- Crankcase venting. The tested vehicle probably has an open crankcase with an oil separator. It means emissions should be added to the emission results of the WHTC and WHSC engine test and under those test conditions tail pipe and crankcase emissions shall not exceed the limits.

3.1.3 *N_2O*

Literature [TNO 2017] indicates that diesel vehicles with SCR emit the strong greenhouse gas N_2O. IPCC[3] presents a GWP of 298 CO_2 equivalents. Little information is available on the N_2O emission of diesel and gas-fueled trucks. It was recommended in [TNO 2017] to measure the N_2O emissions of diesel trucks.
The tested vehicle uses diesel aftertreatment with comparable specifications as regular Euro VI diesel aftertreatment and therefore an indicative measurement of the tail-pipe N_2O concentration was performed at the engine running idle, high stationary engine speeds and the engine revving up and down. N_2O concentrations were measured with a QCL (Quantum Cascade Laser) instrument. The QCL instrument isn't suitable to perform on-road tests so the vehicle was positioned next to the lab analyzer to perform a quick measurement.

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[3] see IPCC AR5 p714, 2013

The measurement confirms the presence of N_2O in the exhaust. Measured concentrations range from 0 to 100ppm. No conclusion can be drawn about the level of CO_2 equivalent emissions of N_2O for this vehicle. It is recommended to measure the N_2O mass emissions of vehicles with diesel aftertreatment over representative routes either on chassis dynamometer with lab instruments or on the public road with suitable equipment for on-road testing.

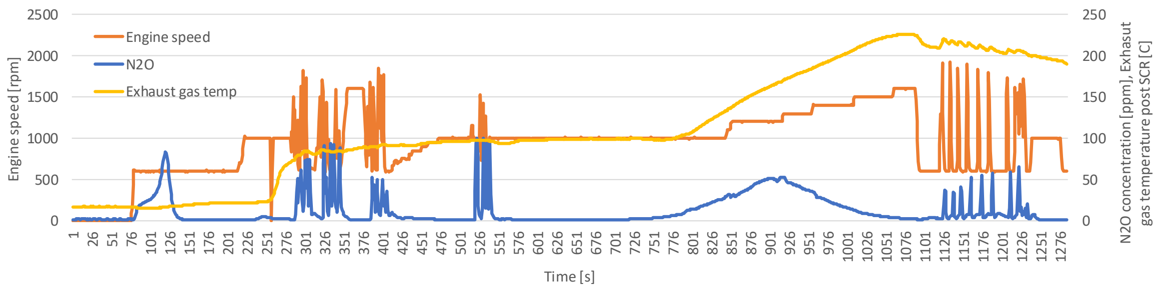


Figure 8: Measured tail pipe N_2O concentration at idle, revving up and increased stationary engine speeds.

3.2 Pollutant emissions

3.2.1 Real world emissions

The criteria pollutant emissions NO_x, NO_2, PN number (PN) and CO are presented in the table below. Generally, the emissions of NO_x and PN are at a level of Euro VI diesel engines when driving on the public road in normal driving conditions. The NO_x and PN emissions are on average routes below the levels of the limits that are set for a formal WHTC engine test (0.46 g/kWh for NOx and 6.0 x 10^{11} for PN) with exception of the urban parts that have a cold start were NO_x is higher and the motorway trip with full payload were PN is higher.

Table 13: Overview of criteria pollutant emissions NO_x, NO_2, PM number (PN) and CO in g/km and g/kWh. The total hydrocarbon (THC) emission is presented in Table 11.

		CO	NO_x	NO_2	PN		CO	NO_x	NO_2	PN
		[g/km]	[g/km]	[g/km]	[#/km]		[g/kWh]	[g/kWh]	[g/kWh]	[#/kWh]
02_E6N3_53C	Total	3.9	0.32	0.17	6.8E+11		3.2	0.26	0.14	5.5E+11
	Urban	14.2	1.22	0.67	2.4E+11		7.0	0.60	0.33	1.2E+11
	Rural	2.8	0.18	0.10	7.8E+10		2.0	0.13	0.07	5.6E+10
	Motorway	2.2	0.18	0.10	9.9E+11		2.1	0.18	0.10	9.6E+11
03_E6N3_53C	Total	3.7	0.26	0.14	3.7E+11		3.2	0.22	0.12	3.2E+11
	Urban	14.8	1.42	0.74	1.2E+11		6.8	0.65	0.34	5.6E+10
	Rural	2.5	0.17	0.10	5.3E+10		1.8	0.13	0.07	3.9E+10
	Motorway	2.2	0.09	0.05	5.1E+11		2.3	0.10	0.05	5.5E+11
04_REP53W	Total	5.0	0.50	0.37	3.9E+11		2.8	0.28	0.21	2.2E+11
	Motorway warm up	4.8	1.10	0.85	1.1E+11		2.9	0.67	0.52	6.6E+10

	DC-winkel	4.5	0.15	0.07	7.8E+11		2.5	0.08	0.04	4.3E+11
	Winkel -DC	5.7	0.16	0.14	3.2E+11		3.1	0.09	0.07	1.8E+11
05_E6N3_53C _OLD N3	Total	3.7	0.34	0.18	5.7E+11		3.2	0.30	0.16	4.9E+11
	Urban	14.5	2.64	1.27	8.8E+11		7.3	1.33	0.64	4.4E+11
	Rural	3.5	0.22	0.15	5.6E+11		2.6	0.16	0.11	4.1E+11
	Motorway	2.5	0.12	0.07	5.3E+11		2.6	0.13	0.07	5.5E+11
06_E6N3_10C	Total	3.5	0.40	0.29	6.5E+10		3.7	0.42	0.31	6.7E+10
	Urban	9.6	1.93	1.34	3.1E+11		6.4	1.30	0.91	2.1E+11
	Rural	2.9	0.43	0.40	3.7E+10		2.8	0.42	0.39	3.6E+10
	Motorway	2.6	0.09	0.05	2.7E+10		3.1	0.10	0.06	3.2E+10
08_E6N3_100 C	Total	3.2	0.46	0.27	1.3E+12		2.0	0.30	0.17	8.0E+11
	Urban	11.9	1.95	1.20	1.4E+11		4.4	0.72	0.44	5.0E+10
	Rural	2.3	0.38	0.22	8.6E+11		1.3	0.21	0.12	4.7E+11
	Motorway	1.7	0.19	0.10	1.6E+12		1.3	0.15	0.08	1.3E+12
11_E6N3_53C	Total	3.5	0.48	0.32	2.2E+11		2.8	0.38	0.25	1.7E+11
	Urban	10.0	3.04	2.03	8.9E+10		4.5	1.37	0.92	4.0E+10
	Rural	2.7	0.19	0.15	9.8E+10		1.9	0.13	0.10	6.9E+10
	Motorway	2.6	0.11	0.06	2.9E+11		2.5	0.11	0.06	2.8E+11

3.2.2 In-service conformity

The CF (Conformity Factor) results for NO_x emission, for both work- and CO_2 window based methods are shown in Table 16 and Table 15.

Data was processed according to EU 2016/1718 [2], which means that:

- Windows are marked valid when the average engine power exceeds the minimum power threshold of 20%. When the resulting share of valid windows is below 50%, the power threshold is lowered in steps of 1% (to a minimum of 15%) until the amount of valid windows exceeds 50%;

- From the resulting valid windows, per emission component the 10^{th} percentile of the windows with the highest calculated emissions are discarded;

- The conformity factor is determined by dividing the resulting highest emission by the legislative limit (for NO_x this is 0.46 g/kWh).

Table 17 and Table 15 show that the CF results for NO_x, CH_4 and CO for both the work and CO_2 based window results are below the limit (CF 1.5) as demanded by EU 582/2011.

The CF for PN does not yet have to be measured for the determination of in-service conformity and yet there is no limit value either.

For all regulated emissions that are to be tested with PEMS (NO_x, CH_4 (THC based) and CO), the Conformity Factors are well below 1.5. The average Conformity Factors of the three tests is therefore also well below the applicable limit of 1.5.

Table 14: Test results: 90% cumulative percentile of the work-based exhaust emission conformity factors of the engine system tested. The Conformity Factor of CH_4 is based on the measurement of THC. There is no CF limit for PN yet.

	Work based window					
Test #	**CO**	**CH_4 (THC based)**	**NO_x**	**PN**	**Valid windows**	**Power threshold**
	CF	**CF**	**CF**	**CF**	**%**	**%**
1	0.57	0.65	0.50	2.33	93.5	20
2	0.65	0.63	0.33	1.39	93.9	20
3	0.77	0.77	0.32	0.53	91.2	20

Table 15: Test results: 90% cumulative percentile of the CO_2-based exhaust emission conformity factors of the engine system tested. The Conformity Factor of CH_4 is based on the measurement of THC. There is no CF limit for PN yet.

	CO_2 based window					
Test #	**CO**	**CH_4 (THC based)**	**NO_x**	**PN**	**Valid windows**	**Power threshold**
	CF	**CF**	**CF**	**CF**	**%**	**%**
1	0.57	0.65	0.52	2.41	91.1	20
2	0.64	0.61	0.33	1.30	93.3	20
3	0.83	0.81	0.33	0.57	89.4	20

3.2.3 *Test repeatability*

To determine repeatability of the test, (vehicle, instruments and test conditions determine repeatability), the N3 test with medium payload was repeated three times. Variations are thought to be normal variations for PEMS measurements on public roads.

Table 16: Emissions results of three repeated tests over the same N3 route expressed as g/km and g/kWh.

	CO	**CO_2**	**THC (CH_4 eq.)**	**NO_x**	**PN**
	[g/km]	**[g/km]**	**[g/km]**	**[g/km]**	**[#/km]**
N3 test #1	3.9	684	0.40	0.32	6.8E+11
N3 test #2	3.7	662	0.38	0.26	3.6E+11
N3 test #3	3.5	664	0.46	0.48	2.2E+11
average, n=3	**3.7**	**670**	**0.42**	**0.35**	**4.2E+11**
2 sigma (2*stdev)	0.4	24	0.09	0.23	4.7E+11
2 sigma [%]	11%	4%	21%	65%	112%

	CO	**CO_2**	**THC (CH_4 eq.)**	**NO_x**	**PN**
	[g/kWh]	**[g/kWh]**	**[g/kWh]**	**[g/kWh]**	**[#/kWh]**
N3 test #1	3.2	560	0.33	0.26	5.6E+11
N3 test #2	3.2	578	0.33	0.23	3.2E+11
N3 test #3	2.8	534	0.37	0.39	1.8E+11
average, n=3	**3.1**	**557**	**0.35**	**0.29**	**3.5E+11**
2 sigma (2*stdev)	0.4	44	0.05	0.17	3.8E+11
2 sigma [%]	15%	8%	14%	57%	109%

4 Presentation of results next to other Euro VI vehicles tested with a Portable Emissions Measurement System

In the framework of the Netherlands in-service testing program, heavy-duty vehicles are tested on a regular basis. To date, six Euro VI diesel trucks and two trucks with spark ignited LNG engines were tested with PEMS on N3 test routes and are in the dataset. Specifications of the vehicles in the dataset and emissions levels are presented in TNO report R11336 [TNO 2017].

The Euro VI diesel tractors from the dataset represent the first generation vehicles with main stream step-A Euro VI engines of MY 2013 and are configured for long haulage. TNO report R11336 [TNO 2017] mentioned that the final rear axle reduction of these vehicles were higher (2.61 to 2.71, on average 2.66 for the dataset) than what would normally be used at time of reporting in 2017. For current MY diesel trucks, with a Euro VI step C engine, the reduction would be on average around 2.5. A lower ratio generally results in a lower fuel consumption and CO_2 emissions. Taking account of lower axle ratios, current diesel tractors for long haulage would consume 1-2% less fuel and emit proportionally less CO_2. The fact that the dataset of diesel trucks represents older model years has to be taken into account for the comparison.

The test vehicle (VO180) was tested over the ‘old N3 route’ which is the route that was also used for earlier tested vehicles from the dataset. Results over the comparable tests are plotted with for each test urban/rural and motorway operation distinguished. To obtain an average emission figure that indicates average usage of a long haulage truck in the Netherlands, the parts were weighted with a distribution of 15, 25 and 60% respectively.

4.1 Tail pipe greenhouse gas emissions

For CO_2 equivalent emissions the results for medium payload are presented (Figure 9). The results of the VO180 dual fuel truck include the tail pipe CH_4 emission which is around 2% expressed in CO_2 equivalents, see 3.1.1. The dataset of reference diesel vehicles only has data from older MY 2013 vehicles with high rear axle ratios. This means that the CO_2 emissions of current vehicles (MY2018) could be some percent lower which has to be taken into account for the comparison.

Over the ‘OLD N3 route’ with medium payload the VO180 with a dual fuel engine clearly has lower tail-pipe CO_2 equivalent emissions than the five diesels and the two vehicles with spark ignited engines from the database. For medium payload and the combined route, the difference with the average diesel from the dataset is about 19% (+/- 5% point). The observed difference is a few percent point higher for the motorway and the lowest for the urban trip (about 8% +/- 5% point). Also over the ‘new N3 route’ the CO_2 emissions are clearly lower than the diesels and the two SI LNG vehicles, but the routes are not the same. When newer diesel vehicles would emit a few percent less CO_2 then the measured older MY counterparts, the VO180 would emit significant less CO_2.

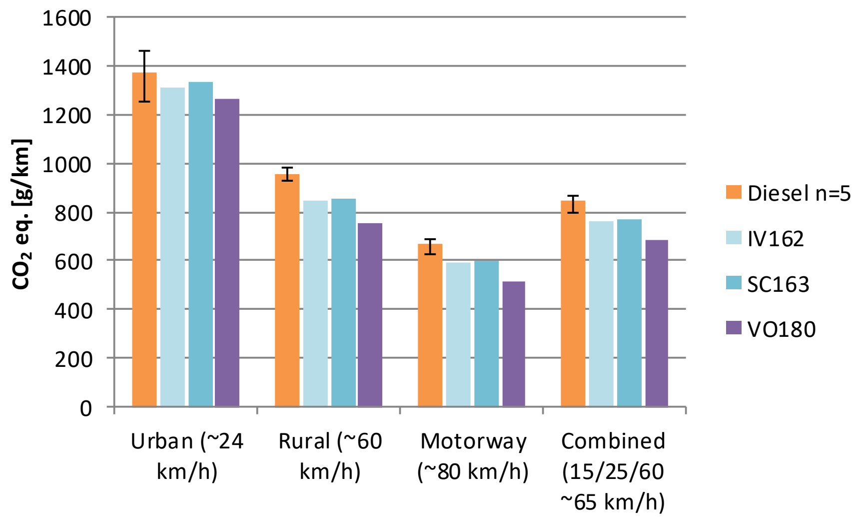


Figure 9: CO_2 equivalent emissions (including tail pipe CH_4) of the LNG-diesel truck at medium payload compared to the average results for 5 tested diesel vehicles (MY around 2013) and the two LNG vehicles (MY around 2016) with SI engines (TNO 2017 R11336). The error bars for the diesel trucks represent the minimum and maximum values from the database.

For the route with low payload the difference with the diesels is comparable with the results of the tests with medium payload, although for urban driving the CO_2 equivalent emissions is at the same level as the diesel average. These results are indicative as test routes for the low payload situation are not directly comparable with the tests of the diesel vehicles.

Work specific CO_2 emissions

When the work specific CO_2 emissions are observed it can be seen that to produce the same amount of work, the dual-fuel engine emits significant less CO_2 (3.1.1) than typically found for diesel counterparts. For the dual fuel engine about 520 to 570 gram CO_2 per kWh was measured over the combined, weighted routes, whereas typical diesel engines emit around 650 gram CO_2 per kWh. This difference is due to the lower CO_2 intensity of the LNG per unit of energy compared to regular diesel fuel and the fact that the dual-fuel engine is based on a diesel-like combustion concept which has an efficiency that is comparable to that of a diesel engine as opposed to the conventional stoichiometric LNG spark ignition engine that run at lower efficiencies.

Reproducibility of PEMS tests

Results obtained from PEMS tests performed on the public road show variation, see also 3.1.1, that is caused by traffic, weather conditions driver, vehicle and measurement equipment. Generally, fuel consumption and CO_2 emissions measurement of PEMS tests reproduce within 5%, but in individual tests or parts of test deviations may be higher due to occasional disturbance (traffic, traffic lights, wind gusts, …) which can all lead to lower or higher work to be produced by the engine hence affecting CO_2 emissions and fuel consumption. This variation has to be taken into account for the comparison of measurement results tests performed on the public road with PEMS.

CH_4 emissions

As expected, for the test vehicle VO180 with dual fuel engine the CH_4 emissions are higher than the diesels (THC emissions of Euro VI diesel engines are generally low and <0.1 g/km and probably contain little CH_4) and are also higher than the two vehicles with spark ignited engines. The latter emit most CH_4 after a cold start. The somewhat elevated CH_4 emissions level of the test vehicle can be attributed to the combustion and aftertreatment concept of the dual fuel engine used. Emissions levels are higher after a cold start when combustion chamber is cold and aftertreatment is not yet at working temperature. The contribution of CH_4 to CO_2 equivalent emissions is around 2% and somewhat higher at urban driving (2.6-3%) due to the cold start and at the route with low payload (2.8%), see paragraph 3.1.1.

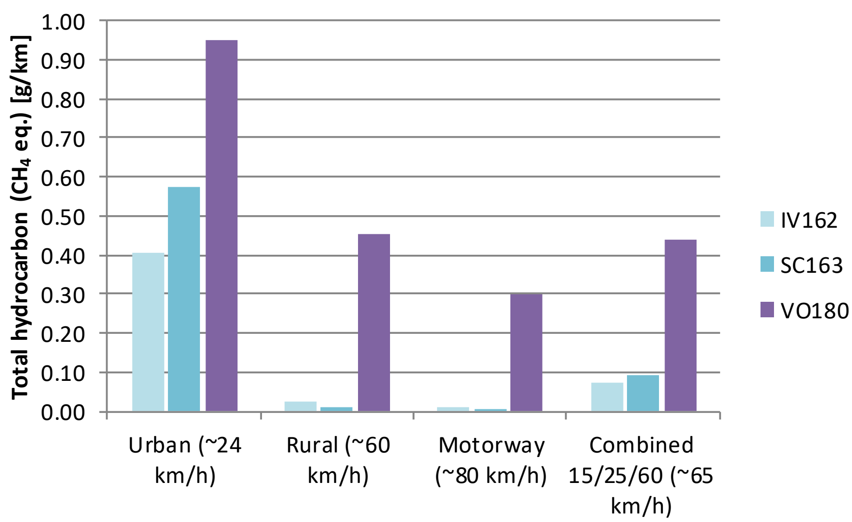


Figure 10: Total hydrocarbon emissions expressed as methane equivalent of the LNG-diesel truck and 2 vehicles with an LNG SI engine (TNO 2017 R11336). For the LNG fuelled engines the total hydrocarbon emissions will be composed of more than 85% CH_4 (methane).

4.2 Tail pipe pollutant emissions

4.2.1 *NO_x and NO_2 emissions*

Average rural and motorway NO_x emissions of the test vehicle are within the spread of the diesel vehicles. In urban driving the NO_x emissions is with 2.6 g/km somewhat higher than the highest diesel. The higher NO_x emissions after a cold start are mainly caused by the fact that the SCR system has to reach it's working temperature in this period. At the applicable 'new' N3 trip, see paragraph 3.2.1 on page 22, the average urban NO_x emission was 1.9 g/km but for this new N3 trip the urban part is longer, hence the contribution of the elevated NO_x emissions after a cold start is averaged out over a longer urban trip part for the new N3 route.

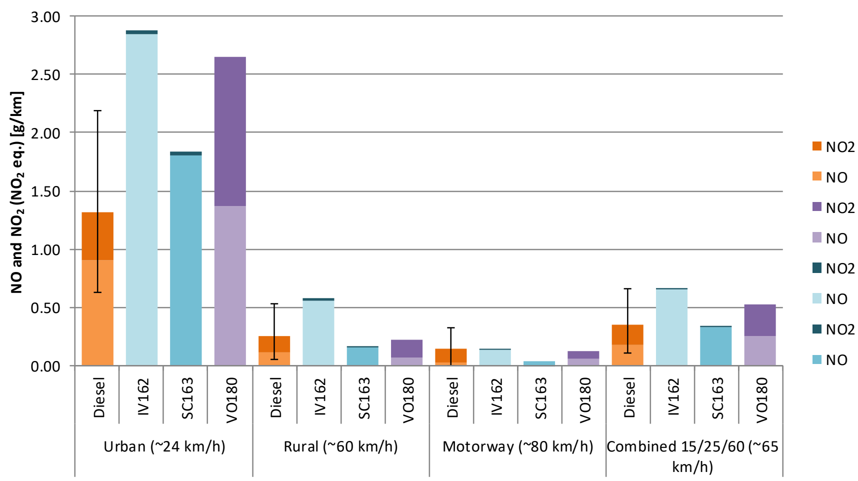


Figure 11: NO_x, NO (NO_2 equivalent) and NO_2 emissions of the LNG-diesel vehicle at medium payload over the 'Old N3 route' compared to the average results for 6 tested Euro VI diesel vehicles over the same trip and two vehicles with LNG SI engines (TNO 2017 R11336). The urban trip was started with a cold engine. The error bars represent the minimum and maximum values from the database for the diesel vehicles.

The supermarket supply route does not show deviating NO_x emissions. Looking at the instantaneous NO_x emissions of the N3 route, it can be concluded that the high levels of NO_x emissions are mainly produced after a cold start. When the engine and aftertreatment are at operating temperature NO_x emissions are kept low.

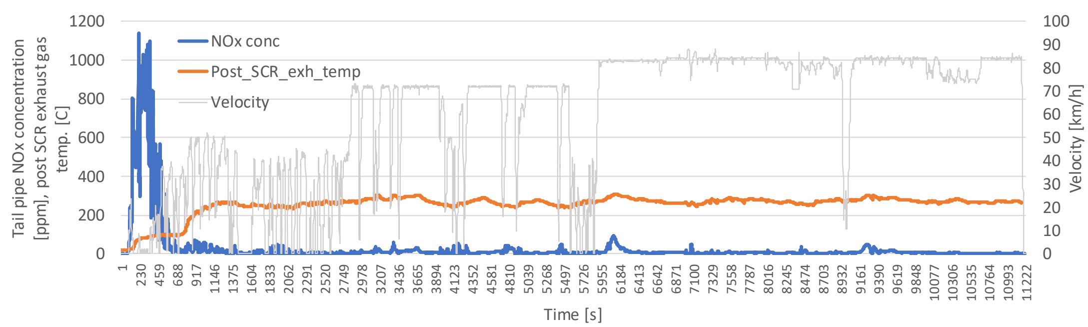


Figure 12: Tail pipe NO_x concentration after a cold start and over a complete N3 route.

4.2.2 *Particulate Matter Number emissions*

The measured PM number emissions of VO180 are at a comparable level of the four diesel vehicles that are in the dataset from JRC as presented in [TNO 2017] and the two LNG vehicles. The results represent low concentrations (post DPF) and are in most cases, except the motorway trip of the first N3 ($9.6x10^{11}$), lower (see paragraph 3.2.1) than the level of the applicable limit value of 6.0×10^{11} #/kWh for an engine WHTC test. No conclusions can be drawn about the observed differences between vehicles or fuels as the diesel vehicles were tested in the lab while for the three LNG trucks particle numbers were measured on the road. Also the test trips were not the same and the number of tests and vehicles is too low to draw generalised conclusions. Also the instruments of road and lab test differ.

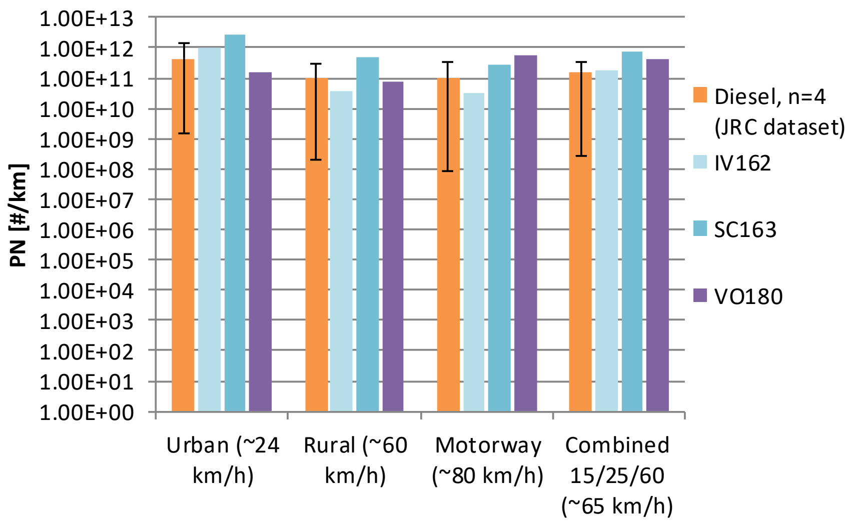


Figure 13: Particle number emissions of the LNG-diesel vehicle and two vehicles with LNG SI engines at medium payload as measured with PEMS (TNO 2017 R11336) and average results for four diesel vehicles as tested on a chassis dynamometer (Source: JRC chassis dyno measurements) over different trips that also contain urban, rural and motorway operation. Due to differences in the measurements and instruments, the results of individual vehicles can't be compared. The error bars represent the minimum and maximum values from the four diesel vehicles.

5 Conclusions

Emissions measurements have been performed with a Portable Emissions Measurement System (PEMS) on a Euro VI dual fuel, LNG-diesel, dual fuel truck to determine the real world emissions levels of tail pipe greenhouse gas emissions, the pollutant emissions and the in-service conformity, driving on the public road in the Netherlands. Measurement results were compared with results that were obtained from six diesel trucks and two trucks with spark ignited LNG engines in an earlier testing program as reported in TNO report R 11336 [TNO 2017]

In-service conformity
Three on-road emission tests were performed with PEMS on a N3 Euro VI Step-C truck conform Regulation EU No. 582/2011 [1] as amended by EU 2016/1718 [2] to verify that the vehicle meets the requirements concerning heavy duty vehicle in-service conformity emission regulations.

- For the three valid tests the 90% cumulative exhaust emissions conformity factors for NO_x, CH_4 (based on the THC measurement) and CO are below the maximum allowed value of 1.5.
- The 90% cumulative NO_x conformity factors for test 1, 2 and 3, determined according the work based method are 0.50, 0.33 and 0.32, and on average 0.38.
- The 90% cumulative NO_x conformity factors for test 1, 2 and 3, determined according the CO_2 based method are 0.52, 0.33 and 0.33, and on average 0.39.

Real world pollutant emissions
- The emission of NO_x is for the average long haulage route around 0.5 g/km. The majority of this is emitted in the urban part just after the cold start. On the motorway and rural road the emission of NO_x is about 0.1 and 0.2 g/km respectively with somewhat higher emissions at the route with full payload (0.2 and 0.4 g/km).
- The NO_x emission was the highest at the urban trips and ranges from 1.2 to 3 g/km. This higher NO_x emission is clearly caused by the cold start and the period after, where engine and SCR catalyst need to warm up to reach stable working temperatures. The level of NO_x emission therefore depends strongly on the actual amount of cold starts compared to ‘warm’ driving.
- The NO_x emissions level is at the same level as the diesel counterparts although the urban trip with cold start shows somewhat higher emissions. This is mainly caused by the cold start and at warm urban operation NO_x emission are at a comparable level as the diesel counterparts. The vehicle uses a similar emissions control system as is normally used for a Euro VI diesel engine.
- The particulate matter number (PN) emissions are generally low and range from $6.5x10^{10}$ for the trip with low payload to $1.3\ x10^{12}$ for the trip with full payload and is typically around 2 to $7x10^{11}$ for average routes with medium payload and levels vary for the trip parts from $1x10^{11}$ to $1x10^{12}$. For all routes and parts, but the motorway driven at full payload, the measured average PN emission is below the limit value of $6.0\ x10^{11}$ g/kWh that is set for the WHTC emission test for the engine.

- Both the dual fuel engine and counterpart vehicles with a diesel engine have low PN emissions. Both engine types use a Diesel Particulate Filter to reduce the particulate emissions from the engine. The PN emissions level of the dual fuel engine is on a comparable low level as the data from four diesel trucks that were measured on a chassis dynamometer over a somewhat different test trip.

Tank-to-wheel real world greenhouse gas emissions

- The tail pipe GHG emissions CO_2 and CH_4 were measured. The CO_2 equivalent emission of these components from the tailpipe of the truck with the LNG-diesel engine is significantly lower than for comparable, but somewhat older (around MY2013) group of diesel counterparts. Over an average long haulage route, were the vehicle drives with a medium payload, the measured CO_2 eq. emissions is about 19% lower than the CO_2 eq. emission of the diesel counterparts. The measured difference is a few percent higher for motorway (23%) and the lowest for urban driving (8%). At a low payload the differences are about the same, with exception for urban driving were no difference was measured. There would still be a significant difference with newer diesel trucks when these newer diesel trucks would emit a few percent less CO_2 than the older measured trucks of around MY2013. Typically over the same route without major interferences of traffic situations and without large deviations in weather, the CO_2 emissions reproduce within roughly 5%. The statistical uncertainty is larger. Indicatively, for a repetition of three tests 2σ variation is 8%. Also it has to be noted that the vehicle was relatively new.
- The emission of CH_4 (measured as THC as CH_4 equivalent) was about 0.2 to 0.3 g/km for rural and motorway driving and goes up to 1 g/km for urban driving with a cold start. The contribution of this CH_4 emission to the CO_2 equivalent emission from the tail pipe is around 2% on average and 3% for the urban part with a cold start. The higher CH_4 emissions is observed just after the cold start and reduces to a lower but still significant level when engine and aftertreatment reach operating temperatures.
- The lower CO_2 emissions are confirmed by the lower work specific CO_2 emissions compared to diesel counterparts.
- Boil-off was measured during the test program. When boil-off occurs, typically during the testing program after about two days after fueling, it amounts approximately 0.3 kg/day which equals a CO_2 equivalent emission equal to 15km of average driving, assuming an average CO_2 emission of 650 g/km.
- Due to the time delay, the occurrence of boil-off depends on how fast the vehicle is refueled. It is not clear how often this boil-off occurs in practice, which means that the actual contribution to the TTW GHG emission could not be determined. To measure the frequency of boil-off events, a datalogger was installed on-board of the truck. Sufficient data will probably be available summer 2019.
- Measurements of the tail pipe exhaust gas concentration of N_2O indicate that this strong greenhouse gas is present in the exhaust. Because of the indicative character of the measurement, the level of the emission could not be determined. Concentrations peaks up to 100 ppm have been observed.
  The vehicle uses a diesel-like emissions control system which are known to potentially produce N_2O. It is therefore recommended to measure N_2O emissions of vehicles with diesel aftertreatment to determine the contribution of this component to the TTW GHG emissions.

- Other sources of GHG emissions are the open crankcase ventilation system of the engine and the control module venting system. Emissions levels of methane of these sources are unknown and it recommended to investigate what the possible contribution is to the TTW GHG emissions.

Continuation of the monitoring of the pollutant and GHG emissions of heavy-duty vehicles during the life time of the vehicles reveals trends of these emissions and the effectiveness of EU emissions legislation in achieving sustainably low emissions over the useful life of the category of heavy-duty vehicles.

6 References

[TNO 2019] Nijenhuis, M, *In-Service Conformity test on a Volvo FH420 LNG-diesel dual fuel truck with a Euro VI step C certified engine*, TNO report TNO 2019 R10014

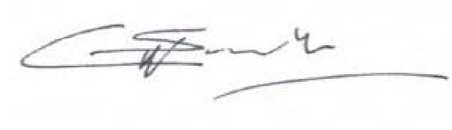
[TNO 2018] van Schaijk. J., *Iveco Euro VI LNG PEMS test report*, TNO report TNO 2018 R10885, 7 August 2018

[TNO 2016] Vermeulen R.J., et al., *The Netherlands In-Service Emissions Testing Programme for Heavy-Duty Vehicles 2015-2016 Annual Report*, TNO report TNO 2016 R11270, 10 October 2016

[TNO 2017] Vermeulen , R.J. et al., *Emissions testing of two Euro VI LNG heavy-duty vehicles in the Netherlands: tank-to-wheel emissions*, TNO report TNO 2017 R11336, 17 November 2017

7 Signature

The Hague, 8 April 2019 TNO



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A Test fuel: LNG

Gate terminal
Maasvlakteweg 993
Maasvlakte
Tel: +31 181 79 90 00

Slot start date-time:	2018-10-04 15:00:00
Slot end date-time:	2018-10-04 16:30:00
Slot ID nummer / Slot ID number:	**SNV_1008101**
Weegbrug volgnummer / Weighbridge sequence number:	2017003090

LNG Leverancier klant / Customer's LNG Supplier:
Shell Western LNG B.V.
Carel van Bylandtlaan 30 2596 HR The Hague The Netherland
NL

Klant / Customer:
Shell Nederland Verkoopmaatschappij B.V.
Weena 70 3012 CM Rotterdam
NL

Kenteken Truck / License plate truck:
36-BFF-7

Kenteken Trailer / License plate trailer:
ON-80-PG

Container ID (if applicable, e.g. HOYU 434433 3):
Not Applicable

Afleveradres 1 / Delivery address 1:
Shell retail station Waalwijk Nederland

Afleveradres 2 / Delivery address 2:
Shell retail station Eindhoven Nederland

Afleveradres 3 / Delivery address 3:

Naam & handtekening Chauffeur / Driver name & signature:
Peter Verkooijen

Naam & handtekening Operator / Operator name & signature:
A. Voogt

Product:
UN1972
Aardgas, Sterk Gekoeld, Vloeibaar, 2.1, (B/D)
Natural Gas, Refrigerated Liquid, 2.1, (B/D)

Ticket Datum / Ticket Date:	**Ticket Tijd / Ticket Time:**
2018-10-04	15:51:53

Compositie / Composition (Vol %):

Methane	93.846	Neo Pentane	0.002
Ethane	5.144	Iso Pentane	0.006
Propane	0.600	Hexane	0.000
Normal Butane	0.137	Carbon dioxide	0.000
Iso Butane	0.138	Nitrogen	0.126
Normal Pentane	0.002		

GHV (MJ/Kg):	**LHV (MJ/kg):**	**Methane nr:**	**Temp. LNG (°C):**
54.933	49.596	80.970 DIN EN 16726	-157.620
GHV (kWh/kg):	**WI (MJ/Nm3):**	**Dens. (kg/m3):**	**Dens. (kg/Nm3)**
15.259	54.583	437.491	0.764

Tot. energie geladen / Total energy loaded (MWh)	**S (mg/Nm3)**
297.248	0.000

Gewicht VOOR laden / Weight BEFORE loading:
21700 kg LB02 3914 2018-10-04 14:58

Gewicht NA laden / Weight AFTER loading:
41180 kg LB02 3915 2018-10-04 15:51

Netto gewicht geladen / Net weight loaded:
19480 kg

Cooldown service:
No

Commentaar / Comments: