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TNO report

TNO 2017 R11336

Emissions testing of two Euro VI LNG heavy-duty vehicles in the Netherlands: tank-to-wheel emissions

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Copy no	2017-STL-RAP-0100309761
Number of pages	39 (incl. appendices)
Number of appendices	2
Sponsor	Dutch Ministry of Infrastructure and Water Management
Project name	I&M HD steekproef 2015-2017
Project number	060.04301

Samenvatting

In het kader van het in-service testprogramma voor vrachtauto's en bussen voor het Ministerie van Infrastructuur en Waterstaat zijn emissiemetingen uitgevoerd aan twee Euro VI vrachtauto's op vloeibaar aardgas (liquefied natural gas, LNG).
De twee geteste vrachtauto's vertegenwoordigen de huidige stand (2017) van de LNG-technologie van in Nederland verkochte lange-afstandstrucks. In metingen op de weg zijn de emissies bepaald van luchtverontreinigende stoffen en broeikasgassen, en is het praktijk-brandstofverbruik vastgesteld. De resultaten worden vergeleken met die van eerder in dit kader geteste Euro VI dieselvrachtauto's. Alle testen zijn uitgevoerd onder vergelijkbare, Nederlandse praktijkcondities. Naast de gemeten CO_2-emissies uit de uitlaat zijn ook de directe emissies van andere broeikasgassen in een beknopte scenarioanalyse ingeschat.

Resultaten: luchtverontreinigende stoffen
Over een test voor de conformiteit van in gebruik zijnde voertuigen liggen de NO_x-, THC- en CO-emissies van beide geteste Euro VI LNG-voertuigen ruim onder de daarvoor geldende limiet van de conformiteitsfactor 1,5 keer de limietwaarde op de typekeuringstest voor Euro VI motoren.

De uitstoot van NO_x en fijnstof van beide geteste LNG-voertuigen ligt voor een gemiddelde lange-afstandsrit ongeveer gelijk met het niveau van de geteste dieselvoertuigen. Het niveau van de gemeten NO_x-uitstoot van beide LNG voertuigen verschilt in de stad. Bij één voertuig is de NO_x-uitstoot bij een stadsrit met een koude start 2,9 g/km en neemt dit niveau verder toe tot 4,5 g/km voor een rit met meer rijdynamiek in de stad, zoals een supermarktbevoorradingsrit. Voor het andere voertuig is de NO_x-uitstoot over dezelfde stadsrit met een koude start 1,8 g/km. De gemeten NO_x-emissies over de stadsrit met koude start liggen voor de dieselvoertuigen gemiddeld lager (1,2 g/km) dan voor de twee geteste LNG-voertuigen, maar ook de dieselvoertuigen laten een spreiding zien.

Het aandeel NO_2 in de totale NO_x-uitstoot is voor de geteste LNG-vrachtauto's veel lager dan voor de dieseltrucks. Daarom vallen de absolute NO_2-emissies van de gemeten LNG-trucks met gemiddeld 0,005 - 0,05 g/km laag uit in vergelijking met die van de geteste dieselvrachtwagens (0,1 - 0,4 g/km). Omdat NO in de buitenlucht wordt geconverteerd naar NO_2 heeft de NO/NO_2 verhouding in de directe emissies van voertuigen een beperkt effect op de (achtergrond)concentraties van NO_2 van een stad of een regio. Op het niveau van een straat, hangt de invloed van de inzet van voertuigen met lagere NO_2 emissies af van het aantal voertuigen met hoge NO_2 emissies in het verkeer ter plaatse dat daardoor vervangen wordt.

De aantallen geëmitteerde deeltjes (particle number emissions, PN) zijn voor zowel de geteste diesel- als LNG-trucks laag en liggen onder het niveau van de Euro VI norm die geldt voor een motortest. Vier geteste Euro VI dieselvrachtauto's stoten ca. $1x10^8$ tot $1x10^{12}$ deeltjes per kilometer uit, terwijl bij de twee geteste vrachtwagens met aardgasmotor een niveau van $1x10^{11}$ tot $1x10^{12}$ deeltjes/km is vastgesteld. Voor diesels wordt dit niveau bereikt door toepassing van roetfilters (vanaf Euro VI, 2014, noodzakelijk voor het halen van de limietwaarde voor de deeltjesaantallen).

LNG-motoren met vonkontsteking hebben door de brandstof en de aard van het motorprincipe minder deeltjesuitstoot, waardoor een roetfilter niet nodig is om de lage niveaus te halen. De geteste LNG-trucks waren derhalve niet uitgerust met een roetfilter.

Resultaten: tank-to-wheel broeikasgasemissies (directe emissies)
Om inzicht te krijgen in de mate waarin de uitkomsten uit dit onderzoek invloed hebben op de vergelijking tussen lange-afstandsvrachtwagens op LNG en diesel voor wat betreft tank-to-wheel (TTW) broeikasgasuitstoot, zijn de meetresultaten gecombineerd met informatie uit de literatuur voor de overige voertuig-gebonden bronnen van broeikasgasemissies en is een indicatieve vergelijking gemaakt met de gemiddelde TTW broeikasgasemissies van dieselvoertuigen.

Overige voertuig-gebonden bronnen van broeikasgasemissies omvatten bij LNG-en dieselvoertuigen de uitstoot van N_2O uit de uitlaat, en voor LNG-voertuigen boil-off en blow-off van methaan uit de brandstoftank en emissies door carterventilatie en lekkage van methaan. In dit onderzoek zijn de CO_2- en methaanemissie uit de uitlaat door TNO gemeten. De mogelijke bijdrage van de overige genoemde bronnen van broeikasgasuitstoot is voor een indicatieve vergelijking op basis van literatuurdata uitgewerkt in een beknopte scenarioanalyse.

Wanneer behalve de emissie van N_2O alle genoemde factoren op basis van metingen of inschattingen worden meegenomen, komt de TTW-uitstoot van broeikasgassen door de geteste LNG-vrachtwagens gemiddeld ruwweg 3 - 6% lager uit dan die van vergelijkbare dieseltrucks. Dit cijfer is onzeker, omdat de werkelijke bijdrage van lekkage, blow-off en boil-off onbekend is. Beschikbare literatuur geeft een sterke aanwijzing dat moderne dieseltrucks meer N_2O, een sterk broeikasgas, uitstoten dan de geteste LNG-trucks. Door de zeer beperkte beschikbaarheid van testresultaten voor Euro VI dieseltrucks en de grote spreiding in die resultaten is het op dit moment niet verantwoord om een uitspraak te doen over de verhouding van TTW broeikasgasemissies door Euro VI LNG- en dieseltrucks inclusief N_2O-emissies.

In aanvulling op bovenstaande zijn voor de vergelijking van TTW broeikasgasemissies van Euro VI LNG- en dieseltrucks de volgende overwegingen van belang:

- De metingen aan de uitlaat van beide LNG-trucks laten een 5-10% lagere CO_2-uitstoot zien dan voor vergelijkbare dieselvoertuigen. Dit geldt dus voor de directe uitstoot van CO_2 uit de uitlaat, de overige broeikasgassen buiten beschouwing latend. Dit resultaat impliceert dat het lagere rendement van een aardgasmotor met vonkontsteking, zoals gebruikt in beide voertuigen, een groot deel van het emissievoordeel van aardgas per eenheid energie compenseert. Per eenheid van energie is de directe CO_2-emissie van de verbranding van LNG namelijk ca. 25% lager dan van diesel.
- 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 is voor CO_2 +/- 5%.
- Een eventueel CO_2-voordeel voor de LNG-truck lijkt ook af te hangen van de inzet. Rijdend op de snelweg is de directe CO_2-emissie uit de uitlaat circa 10% lager dan het gemiddelde voor vergelijkbare dieseltrucks. In de stad echter,

waar meer stationair gedraaid wordt en wanneer gereden wordt met een lagere beladingsgraad, lijkt de efficiëntie lager te worden en is de directe CO_2-emissie van de LNG-wagens een paar procent hoger dan het gemiddelde voor vergelijkbare dieseltrucks. Ook is geconstateerd dat de rijstijl een significante invloed heeft op het brandstofverbruik en daarmee op de CO_2-emissie van de LNG-trucks, maar hetzelfde geldt voor vrachtauto's met een dieselmotor.

- De methaanslip van de geteste LNG-voertuigen was erg laag gedurende de testen, en bedraagt 0,3% van de CO_2-equivalente TTW broeikasgasemissies. De geteste voertuigen, en dus ook de katalysatoren, zijn betrekkelijk nieuw. Als het gemeten niveau gelijk blijft over de levensduur van het voertuig dan draagt methaanslip nauwelijks bij aan de totale van tank tot wiel gerekende broeikasgasemissies.
- Een betere indicatie van de gemiddelde bijdrage van boil-off gasemissies aan de TTW broeikasgasemissies van LNG-voertuigen kan worden verkregen door gerichte monitoring in de praktijk.
- De onzekerheid met betrekking tot N_2O-emissies kan met een specifiek meetprogramma worden verkleind. Dit is vooral relevant voor dieselvoertuigen.
- Voor een volledige evaluatie van de emissie van broeikasgassen door vrachtwagens op diesel en LNG zou ook het well-to-tank (WTT) gedeelte van de energieketen moeten worden meegenomen in de scope. Het gaat dan om de keten van brandstofwinning, -productie- en distributie. Relevante parameters zijn energiegebruik en broeikasgasemissies bij de winning van olie en gas, bij de productie van diesel en LNG en bij lange-afstandstransport van de beide brandstoffen.

Tot slot

De statistische significantie van tests aan twee voertuigen is te laag om algemeen geldende conclusies te kunnen trekken over de vergelijking tussen LNG en dieseltrucks in verschillende toepassingen. Het is de verwachting dat op korte termijn nieuwe voertuigmodellen op de markt zullen verschijnen die gebruik maken van LNG als hoofdbrandstof voor de motor. Door nieuwe typen LNG vrachtwagens te testen, zodra deze op de markt komen, kan een beter en betrouwbaarder beeld worden verkregen van de milieuprestaties van deze techniek.

Summary

In the framework of the in-service testing programme of trucks and buses, carried out by TNO for the Ministry of Infrastructure and Water Management, an on-road emissions testing programme was conducted to determine the criteria pollutants, greenhouse gas (GHG) emissions and fuel consumption of two modern Euro VI trucks running on LNG (liquefied natural gas). The tested vehicles represent the current state (2017) of development of LNG technology for long-haulage trucks sold in the Netherlands. The results 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 the same Dutch real-world conditions. Besides tailpipe CO_2 emissions, other possible sources of direct GHG emissions have been estimated in an indicative scenario analysis of tank-to-wheel (TTW) GHG emissions.

Criteria pollutants
Over an in-service conformity test the emissions of NO_x, THC and CO of the two tested Euro VI LNG vehicles are comfortably below the EU limit value for this test, which equals a conformity factor of 1.5 times the limit for the type approval test for Euro VI engines.

For the criteria pollutants NO_x and particles from the tailpipe, the emissions levels of the two tested LNG heavy-duty vehicles are almost the same as for the tested Euro VI diesel heavy-duty vehicles for an average long haulage trip. The NO_x emissions over an urban trip vary between the two LNG vehicles. For an urban trip with a cold start one LNG vehicle emits 2.9 g/km. This level increases to 4.5 g/km for a trip with more dynamical driving, such as a supermarket supply trip. For the other vehicle the NO_x emission is 1.8 g/km over the urban trip with the cold start. The NO_x emissions of the diesel vehicles that were measured over the same trip are on average lower (1.2 g/km), but also show some spread.

The share of NO_2 emissions in the total NO_x emissions from the tailpipe of the LNG trucks is much lower than for the tested diesel vehicles. The absolute NO_2 emissions of the tested LNG vehicles are in the range of 0.005 to 0.05 g/km. This is significantly lower than the NO_2 emissions of the tested diesel trucks, which on average are in the range of 0.1 to 0.4 g/km. As NO is converted in the air to NO_2, the NO/NO_2 ratio in the direct emissions of vehicles has a limited impact on the overall NO_2 concentrations at the city or regional level. On the street level, the impact depends on the amount of vehicles with high NO_2 emissions which would be replaced by vehicles with lower NO_2 emissions in the traffic on those streets.

The real-world particle number emissions of the LNG vehicles as well as the diesel vehicles are on average very low and are lower than the level of the Euro VI limit that applies to an engine test. The particle number emission of four tested diesel heavy-duty vehicles is about $1x10^8$ to $1x10^{12}$ particles/km, while for the two tested LNG vehicles the level is about $1x10^{11}$ to $1x10^{12}$ particles/km. For diesel engines this is achieved by the application of diesel particle filters, which are needed to fulfill the EU particle number requirements that entered into force as of Euro VI (2014). Spark ignited LNG engines emit less particles than diesel engines, which means that no particle filter is needed to achieve low particle emission levels. The tested LNG vehicles were therefore not equipped with a particle filter.

Tank-to-wheel greenhouse gas emissions (direct emissions)
The measurement results have been combined with data from literature in order to get an indication whether other direct GHG emissions from the vehicle influence the outcome of this study regarding the comparison of tank-to-wheel (TTW) GHG emissions of LNG and diesel long haulage trucks.

In addition to the TTW CO_2 emissions from the tailpipe also methane slip from the tail-pipe, tailpipe N_2O emissions, fuel tank boil-off gas (BOG), crankcase venting, leakage and blow-off were taken into account for the comparison between LNG and diesel. Tailpipe CO_2 and methane slip were measured. Estimates for the other possible TTW GHG sources are included in an indicative scenario analyses based on available literature.

When all factors except the emission of N_2O are taken into account, the TTW GHG emissions from LNG trucks are on average around 3 - 6% less than those of comparable diesel trucks. This figure is uncertain because the actual contribution to these emissions of boil-off, blow-off gas and leakage is not well known. Available literature indicates that modern diesel trucks emit more N_2O, a powerful greenhouse gas, than the tested LNG trucks. As a result of the extremely limited availability of test results and the large spread in these results, it is at this stage not justified to draw conclusion on the comparison the TTW greenhouse gases of Euro VI LNG and diesel trucks including the N_2O emissions.

In addition to the above the following considerations are relevant for the comparison of TTW GHG emissions of Euro VI LNG and diesel trucks:

- The measurements of the direct tailpipe CO_2 emissions of both tested LNG trucks show 5-10% lower CO_2 emissions compared to the diesel trucks. This result implies that the lower efficiency of a spark ignition engine, as used for both LNG trucks, to a large extent compensates the CO_2 benefit that natural gas has per unit of energy. Per unit of energy the direct CO_2 emissions from combustion of LNG are about 25% than for regular diesel fuel.
- There is some spread between the individual results for the tested diesel as well as LNG trucks which may be caused by differences between the vehicles but also by variations in performing emission tests on the road. The repeatability of an on-road test is about +/- 5%.
- The tailpipe CO_2 emission of LNG trucks also seems to depend on the operation. Driving at the motorway, the CO_2 emission is about 10% lower than for comparable diesel trucks but in the city, with more idling and driving with low a payload, the efficiency seems to drop. Under those conditions CO_2 emissions are on average a few percent higher than for comparable diesel trucks. Also driving style proved to significantly impact the fuel consumption and hence the CO_2 emissions, but this also accounts for diesel trucks.
- The tailpipe methane slip of the tested LNG vehicles amounts to 0.3% of the TTW CO_2 equivalent emissions. When the measured levels would remain the same over the lifetime of the vehicles, then methane slip would hardly contribute to TTW greenhouse gas emissions.
- A better estimation of the impact of the TTW GHG emission of boil-off gas can be obtained by monitoring these emissions in real-world operation.

- The uncertainty with respect to the TTW GHG emission of N_2O can be reduced by means of a dedicated test programme. This especially applies to the diesel vehicles.
- For a complete evaluation of the greenhouse gas emissions associated with using heavy-duty vehicles running on diesel and LNG, the well-to-tank (WTT) GHG emissions and energy use of the ‘fuel pathway’ need to be taken into account. This includes the oil and gas production, the production of the fuels and the (long-distance) transport of the fuels.

The statistical significance of tests on two LNG vehicles is too low to draw generally valid and firm conclusions on the comparison of Euro VI trucks on LNG and diesel in various applications. It is expected that new truck models, running on LNG as main fuel, will be introduced in the short term. By testing new models, as soon as they arrive on the market, a better and more reliable view can be obtained of the environmental performance of this technology.

Contents

1 Introduction

Background

Contracted by the ministry of Infrastructure and Water Management, TNO runs an in-service emissions testing programme for heavy-duty trucks and buses. On a regular basis selected heavy duty vehicles are tested to investigate their environmental performance in the real-world and to check if they comply with the formal European requirements. Data obtained over the years provides valuable insights in the effectiveness of European emission legislation and new technologies in reducing pollutant and greenhouse gas emissions (GHG) from heavy duty vehicles.

Within the framework of the programme the Ministry of Infrastructure and Water Management has invited stakeholders to have measurements performed by TNO so that these stakeholders can base their purchase decisions for new clean vehicles upon information obtained from real-world emission tests[1]. This is especially important because today stakeholders are offered a range of options for making their fleet greener. Based on results of the tests, well-founded purchase decisions can be made with regard to real-world emissions performance, including GHG and noxious emissions.

Ahold and affiliated transporters have requested TNO to test Euro VI heavy goods vehicles running on LNG (Liquefied Natural Gas). Vehicles running on natural gas are claimed to be clean and silent and to have lower tank-to-wheel (TTW)CO_2 emissions than their diesel equivalents. In combination with the relatively lower fuel tax of LNG in the Netherlands this would make the fuel an attractive alternative to diesel. Current fleet data[2] shows 378 registered LNG heavy-duty vehicles in the Netherlands of which 171 have Euro VI certified engines and 334 are tractor semi-trailers. Various literature sources[3] report a potential for fuel savings and CO_2 emission reduction. These findings, however, include a large uncertainty as the actual effect of substituting vehicles running on diesel with vehicles running on LNG may depend on a number of conditions. The transporters also report some variability in the fuel economy of LNG trucks. For instance, by educating drivers in driving style the fuel economy is significantly improved during training, however it deteriorates again during regular daily operation. Furthermore, possible tail-pipe methane emissions and boil-off gas from the tank may, due to the larger GWP (Global Warming Potential) potential of methane, further reduce the CO_2 benefit of the fuel.

In addition, the Ministry of Infrastructure and Water Management wanted to update their emissions database with data of LNG trucks so that new factsheets and emission factors can be based on a more reliable set of real-world emissions data.

Goal of the LNG emissions testing programme

The goal of the measurements is to determine the real-world direct TTW (Tank-To-Wheel) emission levels of criteria pollutant and greenhouse gases of Euro VI heavy-duty vehicles running on LNG.

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[1] Kamerbrief actieplan luchtkwaliteit, 26 november 2015
[2] RDW database 8-11-2017, count of N2 and N3 vehicles with fuel=LNG
[3] See e.g. Factsheets brandstoffen voor het wegverkeer, juni 2014

The measurements are intended to provide updated insights in the emission behaviour of trucks running on this fuel in comparison to the emissions levels of equivalent heavy-duty vehicles running on diesel.

Approach
Two Euro VI tractor semi-trailer combinations have been equipped with a mobile emissions measurement system (PEMS, Portable Emissions Measurement System) to measure the emissions and fuel consumption over various real-world trips. The results are compared with the results obtained from similar emission tests on Euro VI diesel heavy-duty vehicles, carried out previously by TNO (see [TNO, 2014] and [TNO 2016a]).

For the comparison of TTW GHG emissions information on other possible TTW GHG emission sources of HD vehicles running on LNG, such as boil-off gas and methane emissions from the tail-pipe, have been obtained from literature.

2 Emissions measurement programme

To be able to compare the environmental performance and energy consumption of Euro VI heavy-duty vehicles running on LNG with heavy-duty vehicles running on diesel, a programme was set-up to measure the pollutant emissions, GHG emissions and fuel consumption of two LNG tractor semi-trailers at the vehicle level (TTW) in the real-world. The results of the measurements can be compared to the results of Euro VI heavy-duty vehicles on diesel that were tested earlier in the framework of the programme (see [TNO, 2014] and [TNO, 2016a]).

Table 1: Overview of types of emissions data obtained for the comparison between LNG and diesel within the framework of the Netherlands in-service testing programme for heavy-duty vehicles.

	Diesel Euro VI	LNG Euro VI
Vehicles	5 tractor semi-trailers 1 rigid + trailer	2 tractor semi-trailers
Gaseous emissions measured with PEMS	CO_2, NO_x, NO_2,THC, CO	CO_2, NO_x, NO_2,THC, CO
Particle measurement	Data set with anonymised results of PN measurements of chassis dyno measurements with 4 Euro VI HDVs (Source: JRC)	PN emissions measured with PEMS
Fuel consumption measurement	– carbon balance	– carbon balance – Coriolis fuel meter
Real-world trips and payloads	Reference trip N3 trip 10% and 55% payload	Reference trip N3 trip Representative trip for supermarket supply 10% and 55% payload

Other possible direct TTW GHG emissions of LNG and diesel vehicles are:
- tail-pipe N_2O emissions

For LNG-vehicles the following sources are also relevant:
- fuel tank boil-off gas (BOG),
- fuel system leakage,
- tank blow-off and
- crank case venting.

These emissions have not been measured but are included in an indicative analyses in chapter 3 where tractor semi-trailers running on LNG are compared with baseline tractor semi-trailers running on diesel for total TTW GHG emissions.

2.1 Measurement programme LNG vehicles

The emissions of two Euro VI LNG tractor semi-trailer combinations were measured on real-world test routes with Portable Emissions Measurement Equipment. A number of different routes were driven and two different payloads were used, as indicated in Table 1.

Equipment

European regulation[4] stipulates measurement equipment to assess the conformity of gaseous emissions of in-service heavy-duty vehicles and engines. This equipment (PEMS = Portable Emissions Measurement System) is the standard to measure the NO_x (NO and NO_2), CO, THC emissions and measures CO_2 emissions and fuel consumption as well.

Particle mass is very hard to measure with PEMS on-board of a vehicle at the very low PM concentrations in the exhaust of LNG engines and HDV engines with a particle filter. The most promising method to measure particle emissions with PEMS is based on the measurement of particle number emissions. This method has been added to the test programme. The instrument used to measure the particle number is one of the instruments being evaluated in an EU pilot programme for the measurement of particle numbers on-board of heavy-duty vehicles (2017) and as such it has not been fully verified for use in a legislative test procedure to test on-road emissions with PEMS.

To determine the contribution of tail-pipe methane emission to the TTW GHG emissions of the LNG vehicles the result of the THC (total hydrocarbons) analysis is used to get a good approximation of the methane emissions. In the case of an LNG engine the majority of THC emissions, i.e. more than approximately 85%, consists of methane.

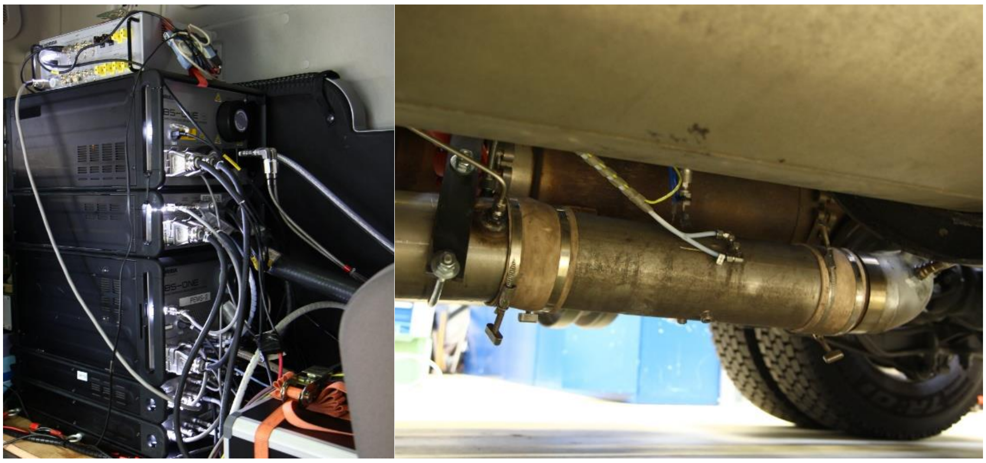

Figure 1: Left: PEMS gas analysers and PN analyser in the cabine.
Right: Exhaust flow meter with sampling lines mounted to the exhaust.

Test routes

Each LNG vehicle has been tested along a series of trips that are representative for the typical deployment of the vehicle. EURO VI ISC trips as prescribed by European emission regulation (N3) have also been included. In addition, also a reference trip developed by TNO was driven. This trip is driven with each vehicle that is tested with PEMS at TNO [TNO, 2016b].

[4] PEMS, Portable Emissions Measurement System, as specified for type-approval and in-service conformity emissions testing in EC regulation nr. 582/2011 and amendments.

Test trips:
- Reference trip, round trip Helmond – Eindhoven, with 55% payload, warm start (Helmond, about 2 hours);
- Reference trip, round trip Helmond – Eindhoven, with 55% payload, only the cold start part until the engine has warmed up (Helmond, 30 minutes);
- Euro VI trip (N3), conform EU regulation specifications, cold start with 55 and 10% payload (Helmond, about 3 hours);
- Representative trip for supermarket supply with 55 and 10% payload (Eindhoven, about 3 hours);
- To assess the possible effect of driving style for one of the vehicles, two trips with different driving styles have been measured for the vehicle with a manual gearbox. Additionally, with the same vehicle a test was done with larger diameter wheels to simulate ‘longer’ gearing, i.e. a lower overall reduction ratio.

<u>Vehicles</u>

The two LNG vehicles tested in the programme are
- Iveco Stralis Hi-road Euro VI 400hp with an automated gear box;
- Scania G340 Euro VI 340hp with a manual gear box.

Specifications are given in Table 2. The vehicles are obtained from transport companies that have the vehicles in regular service. The vehicles represent the current state (2017) of development of LNG technology of the best sold LNG tractors in the Netherlands. With 8050 and 27173 km on the odometer the vehicles, engines and aftertreatment are relatively new.

Iveco notes that the Stralis Hi-Road has been optimized for long-haulage. Long haulage typically includes mainly motorway driving, rural driving and a small share of urban driving. In the Netherlands, however, LNG trucks are used for both regional and urban distribution. Because gas engines have lower noise emissions than regular diesel engines, they are granted longer access to Dutch city centres. The transporters of Ahold use Euro VI LNG vehicles of two different brands in inter-distribution centre transport as well as for supply trips between distribution centres and supermarkets.

Both vehicles were tested at payloads that are typical for their use. About 15.5 tonnes is a typical average payload for a fully loaded semi-trailer for inter-DC operation. A payload of about 2 tonnes is typical for empty operation only carrying ‘emballage’. These two payloads represent respectively approximately 55 and 10% of the maximum allowed payload.

Table 2: Overview of test vehicle specifications for the two tested Euro VI LNG trucks.

	Iveco Stralis Hi road	**Scania G340**
	Cornelissen Transport	Peter Appel Transport
License plate nr.	28-BHX-4	47-BHT-3
Vehicle type / axle configuration	Tractor / 4x2	Tractor / 4x2
Type	AS440S40T/P	G340
Engine max. power [kW] / torque[Nm]	294 / 1700	250 / 1600
Engine capacity [cm^3] / nr. cylinders	8710 / 6	9291 / 5
Registered mass in running order [kg]	7760	7342
Fuel, tanks Type Net volume per tank [l] Total approx. fuel mass @ 0.37 kg/m^3[kg]	LNG two tanks Chart HLNG158 511 378	LNG, one tank Chart HLNG119 410 152
Legislative category, Euro class	N3, Euro VI, (595/2009/EC*627/ 2014EC)	N3, Euro VI, 595/2009/EC*627/ 2014/EC
Gear box	Automated 12s	Manual
Odometer at test start [km]	8050	27173
Semi-trailer	Jumbo OL-02-RR	
Registered mass in running order [kg]	7400	
Test mass truck scale, ~10% payload [kg]	17860	17840
Test mass truck scale, ~55% payload [kg]	31440	31180

<u>Fuel</u>
The trucks have been operated with regular market fuel and were refilled multiple times during the test programme. The test vehicles were fuelled at LNG station Doornhoek Veghel. This station has a relative high throughput so as to ensure the least risk for possible degradation of the LNG fuel in terms of its composition. Test certificates of the fuel have been provided by the fuel supplier of the batches that have been deposited before the vehicle was refilled.

2.2 Database with results from PEMS tests on Euro VI diesel trucks

Diesel Euro VI trucks have been tested by TNO with PEMS since 2013. Table 3 shows a selection from the complete database of tested Euro VI diesel vehicles that are comparable to the LNG trucks in terms of type and performance.

Table 3: Overview of 6 Euro VI diesel heavy goods vehicles in the PEMS database that are comparable to the LNG trucks tested in the programme covered by this report.

TNO vehicle code	MB113	SC116	MA118[1]	DA122	IV123	VO124
Vehicle type	Tractor semi-trailer	Tractor semi-trailer	Rigid-trailer	Tractor semi-trailer	Tractor semi-trailer	Tractor semi-trailer
Brand type	Mercedes Actros	Scania R	MAN TGM	DAF XF	Iveco Hi-way	Volvo FH
Axles	4x2	6x2	4x2	4x2	4x2	4x2
Power [kW]	312	353	251	340	312	345
Final reduction ratio	2.61	2.71	n.a.	2.69	2.64	2.64

[1]Not used for the comparison of CO_2 emissions because the vehicle configuration, being a rigid-trailer, is different compared to the LNG tractors semi-trailers. Levels of criteria pollutants are expected to be comparable between the vehicle configurations, so for these pollutants all 6 diesel vehicles were taken into account in the comparison.

The diesel vehicles have high final reduction ratios. These are higher than one would use on a diesel tractor that is mainly used for Dutch national supermarket supply and inter-distribution centre operation. A higher end reduction ratio results in a higher engine speed at cruising speed. This in turn increases the fuel consumption. This effect is taken into account for the comparison between LNG and diesel.

2.3 In-service conformity

The in-service conformity with respect to regulated emissions was evaluated for the two LNG vehicles. Both vehicles have emissions on the ISC test that lead to conformity factors (CF) which are well below the applicable limit of 1.5 for Euro VI vehicles and engines. This means that there are no indications to assume that the vehicles would not be in proper technical condition.

Although one vehicle had relatively high NO_x emissions in urban operation (see section 2.4.3), this did not lead to a CF above the limit. The reason is that according to the formal evaluation method of the real-world in-service conformity test, a certain amount of the emission data with higher emissions has to be discarded from the evaluation. According to EU regulation for in-service conformity, Euro VI engines are not necessarily required to perform well under all representative driving conditions.

The PN emissions were measured but not evaluated over the formal pass-fail method for PEMS testing as PN is not yet regulated. The PN emission levels are, however, on average lower than the applicable limit for the engine test ($6x10^{11}$ #/kWh over a WHTC engine test) under all tested driving conditions.

Table 4: Results of the ISC test performed for the two Euro VI LNG trucks, expressed by means of a Conformity Factor relative to the WHTC limit, compared with applicable limit of 1.5 times the WHTC limit value.

	CF IV162	CF SC163	CF limit	(WHTC limit) mg/kWh P.I.	(WHTC limit) mg/kWh C.I.
CO	0.25	0.13	1.5	4000	4000
THC	0.11[1]	0.03[1]			160
NMHC			1.5	160	
CH_4	<0.11[1]	<0.03[1]	1.5	500	
NO_x	0.92	0.30	1.5	460	460
PM				10	10
PN				6.0×10^{11}	6.0×10^{11}

[1]For natural gas vehicles (P.I. = positive ignition) formally a NMHC limit and a CH_4 limit apply. However, because for the PEMS no dedicated methane analyser was available at the moment of the testing programme, only the THC emission was measured and evaluated. As a result, for the pass-fail evaluation, the THC emission was evaluated against the THC limit for C.I. (diesel) engines (160 mg/kWh instead of 500 mg/kWh). Still this leads to the conclusion that for CH_4 and NMHC, the CFs for these substances are comfortably below the limit.

2.4 LNG and diesel heavy-duty vehicle emissions under a range of driving conditions

2.4.1 Tailpipe CO_2 emissions

For both LNG vehicles the test results for tailpipe CO_2 emissions, and the comparison with the average results for 5 comparable diesel vehicles, are depicted in Figure 2 to Figure 4.

Averaged over urban, rural and motorway driving the tailpipe CO_2 emissions of both tested LNG vehicles are clearly lower than the average tailpipe CO_2 emissions of the 5 tested diesel vehicles. The difference on the motorway and on rural roads is about 10%. For urban driving the average difference is about 5%, but the behaviour of the two LNG vehicles is different. At low payloads one of the vehicles emits more CO_2 in urban driving than the average for the tested diesels.

Looking at the spread in results for the diesel vehicles (the error bars in Figure 2 to Figure 4) it can be concluded that the tested LNG vehicles have lower CO_2 emissions than equivalent diesels in rural and motorway driving. This also applies to the average result based on a weighting of 15%/25%/60% for urban/rural/motorway. Looking at the variation in the results for the LNG as well as the diesel vehicles in urban driving, the test results do not justify a firm conclusion. The difference strongly depends on which LNG vehicle is compared to which diesel vehicle. Also the measurement repeatability needs to be taken into account which for PEMS measurements of CO_2 emissions and fuel consumption is about 5%.

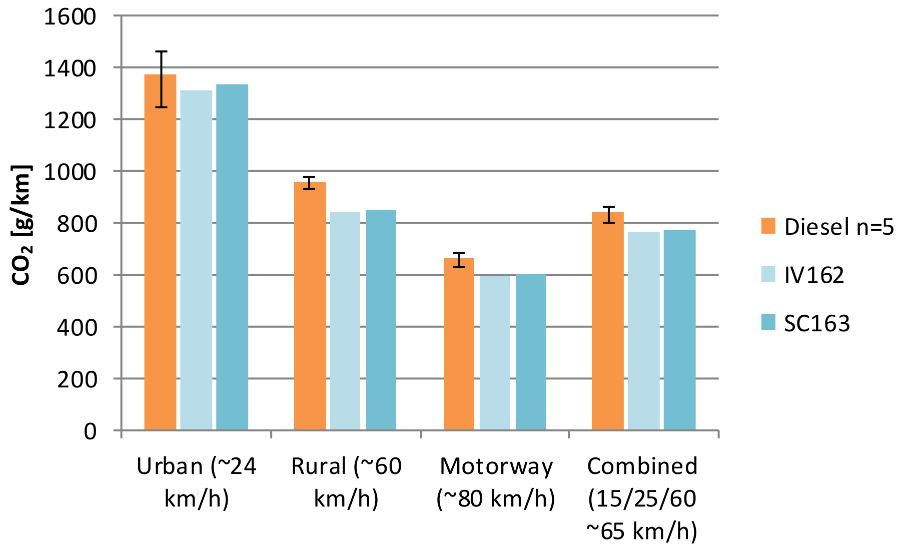

Figure 2: CO_2 emissions of the two tested LNG vehicles at 55% payload (~15.5t) compared to the average results for 5 tested diesel vehicles. The error bars represent the minimum and maximum values from the database.

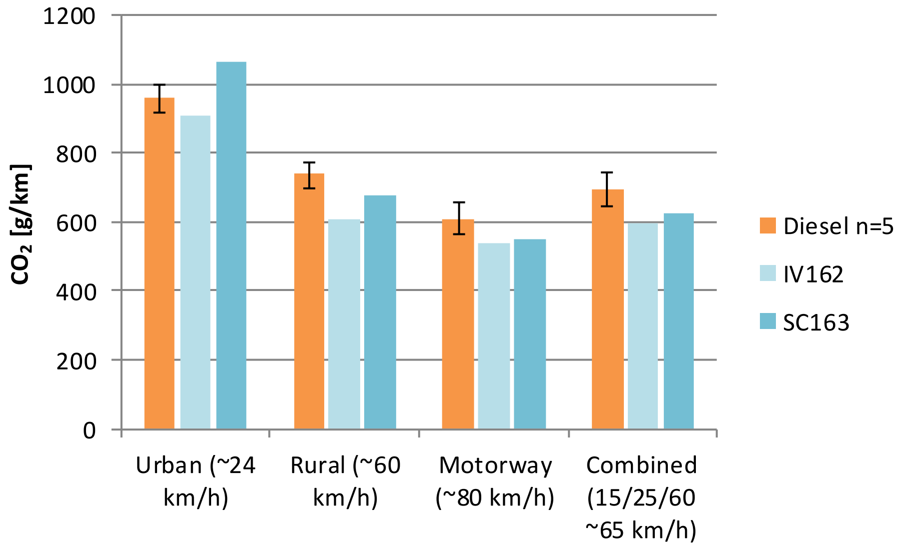

Figure 3: CO_2 emissions of the two tested LNG vehicles at 10% payload (~2t) compared to the average results for 5 tested diesel vehicles. The error bars represent the minimum and maximum values from the database.

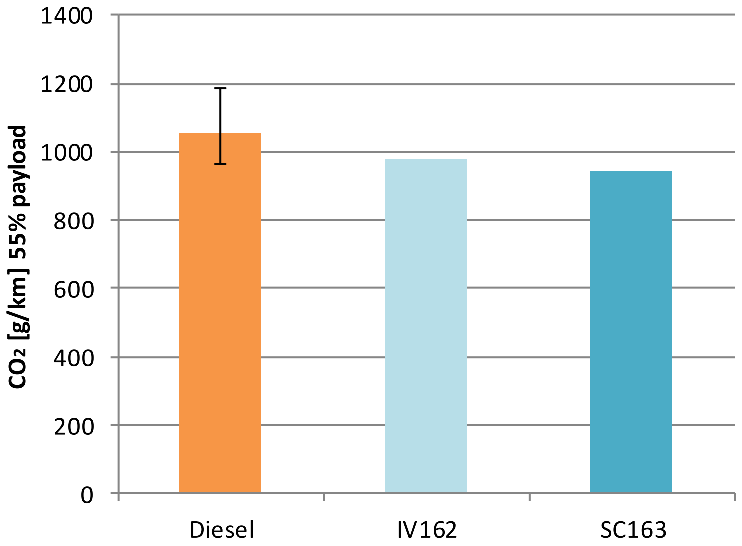

Figure 4: CO_2 emissions of the two tested LNG vehicles over the TNO reference trip with 55% payload (~15.5 t), compared to the average results for 5 tested diesel vehicles. The trip contains a mix of urban, rural and motorway driving (trip length 72 km, average speed ~40 km/h). The error bars represent the minimum and maximum values from the database.

2.4.2 *Impact of driving style on tailpipe CO_2 emissions*

During the on-road emission tests, reported in Figure 2 to Figure 4, the LNG vehicles as well as the diesel comparator vehicles have been driven with what is considered a normal defensive, fuel efficient driving style. This is characterised by looking ahead and keeping distance and anticipating decelerations by getting of the throttle early. In this way hard braking is avoided. Shifting was performed at moderate engine speeds in the torque band of the engine.

For the LNG vehicle with manual transmission one trip was repeated with a more dynamic, or aggressive driving style. This means shifting up at a higher engine speed for a faster acceleration and less defensive driving so that the driver needed to brake more. The result is presented in Figure 5. Over a complete test trip containing urban, rural and motorway driving, the CO_2 emission (and thus fuel consumption) of the LNG truck clearly increases with the more dynamic driving style. This is mainly caused by the higher energy demand of the driving style, where more energy is dissipated through braking. On the motorway, the effect is small. This is to be expected, because there is less need for braking under stable cruising conditions.

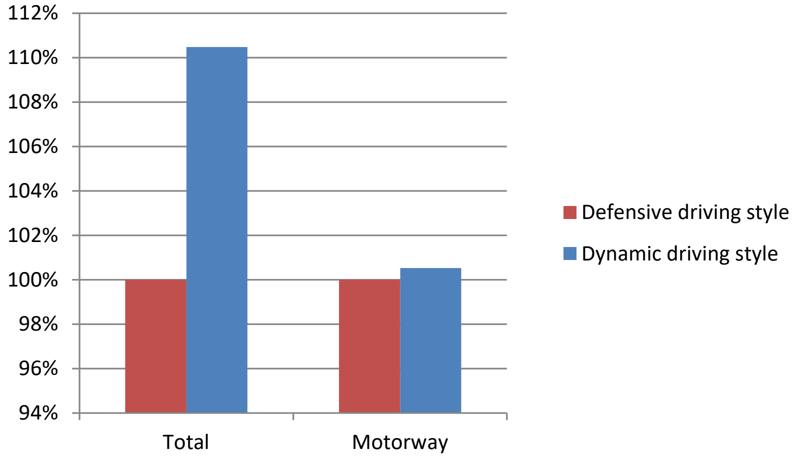

Figure 5: Impact of a dynamic driving style on the CO_2 emissions of the LNG vehicle with manual gearbox over the TNO reference trip with 55% payload (~15.5 t). This trip contains a relative low share of motorway driving compared to typical long haulage operation. The CO_2 emissions measured over the 'which was driven with a normal, fuel efficient driving style are set at 100%.

2.4.3 *NO_x emissions*

For both LNG vehicles the test results for NO_x emissions, and the comparison with the average results for 6 comparable diesel vehicles, are presented in Figure 6.

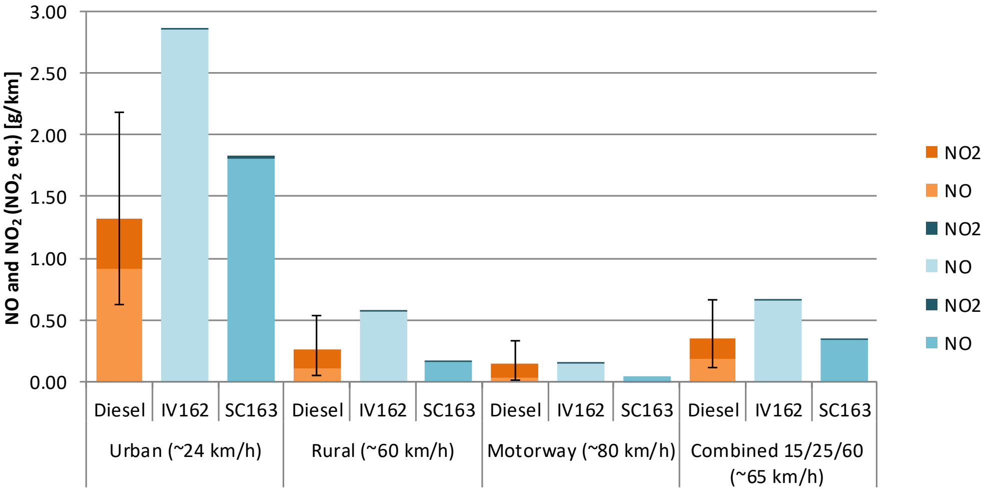

Figure 6: NO and NO_2 emissions of the two tested LNG vehicles at 55% payload (~15.5t) over the N3 ISC trip compared to the average results for 6 tested Euro VI diesel vehicles over the same trip. The urban trip was started with a cold engine. The error bars represent the minimum and maximum values from the database.

For the individual trip parts and the combined result the following can be observed:

- During motorway driving the average emission levels of LNG and diesel trucks are both very low, with the two tested LNG vehicles having emissions equal to or below the average for the six tested diesels.
- On rural roads the NO_x emissions of both LNG vehicles are higher than on the motorway and show a similar spread as observed for the 6 tested diesels.

- All tested diesel and LNG trucks emit substantially more NO_x over the urban trip than over the other trips. The NO_x emissions of both LNG trucks differ strongly. Diesel trucks also show a large spread. For one of the LNG vehicles the NO_x emissions in urban driving were higher than for all of the tested diesel vehicles (see error bars in Figure 6).
- When the results for urban/rural/highway driving are combined with a 15%/25%/60% ratio, to represent average driving of these vehicles, one of the LNG vehicles is found to have average emissions which are similar to the average for the 6 tested diesels, while the other LNG vehicle has NO_x emissions that equal those of the highest emitting vehicle in the sample of diesel trucks.

For diesel the high emissions in urban driving are mainly caused by the cold start in the urban trip and the fact that the NO_x emission reduction system (SCR) needs to warm-up. NO_x emissions from warm diesel engines are on average around 0.5-1.0 g/km. But after prolonged driving under low load conditions and with low average speeds, as may occur in urban conditions, the SCR catalyst may cool down and as a result the NO_x emissions may increase. This effect is widely reported.

For the tested LNG vehicles a detailed analysis of the NO_x emissions, recorded as function of time, shows that just a small share of the higher NO_x emission in urban driving is caused by the cold start. Also for these vehicles high NO_x concentrations are emitted just after a cold start, because the three-way catalyst needs to warm up to operating temperature. But generally, three-way catalysts heat up rapidly, which leads to a small contribution of the cold start itself. However, for both LNG trucks higher NO_x emissions have also been observed in urban trips during accelerations when the engine and three-way catalyst are warm. For both LNG vehicles this leads to average NO_x emissions under urban driving conditions (with a warm engine and catalyst) that are higher than the average for comparable diesel vehicles.

NO_2 emissions
Figure 6 also provides a comparison of the tailpipe NO_2 emissions of the vehicles under different driving circumstance. The NO_2 share in the tailpipe NO_x emissions is relevant for the direct contribution of vehicles to the NO_2 concentration at street level, which is subject to European air quality legislation. To what extent vehicles with low direct NO_2 emissions can contribute to lowering NO_2 concentrations in specific streets depends on the extent to which these vehicles can replace vehicles with higher NO_2 emissions in the traffic on those streets. As NO is converted in the air to NO_2, the impact of the NO/NO_2 ratio in direct emissions of vehicles has a limited impact on the overall NO_2 concentrations at the city or regional level.

The tailpipe NO_2 emissions of both LNG vehicles are significantly lower than the average for the diesel vehicles. The higher NO_2 emissions of diesel vehicles is caused by the nature of the catalytic aftertreatment system of Euro VI diesel engines. The oxidation catalysts applied directly after the engine promote the formation of NO_2. A part of that is reduced in the SCR catalyst but on average for the 6 diesel vehicles still a substantial fraction of NO_x is NO_2 (30 to 70%). The gas engine and the three-way catalysts used on spark-ignition LNG engine, on the other hand, produce very little NO_2 which results in a very low faction of NO_2 in the NO_x emissions.

Other observations
As can be seen in Figure 7, one LNG vehicle has NO_x emissions up to around 1.5 g/km at lower average speeds on a range of urban trips with a warm start, while the other vehicle's NO_x emissions on the same trips were 2 to 4.5 g/km at the lower average speeds. After examination of the emission results for this vehicle, the manufacturer concluded that the observed behaviour of the vehicle can probably be attributed to the emission control which would not be optimized for dynamic driving using an automated gear box. According to the manufacturer the vehicle is typically optimized for long-haulage operations which constitutes mainly of motorway driving and only a minor share of urban driving. Because for urban trips the driving pattern is more dynamic and gear shifting is more frequent, more NO_x peaks occur which leads to a higher average NO_x emissions under those conditions.

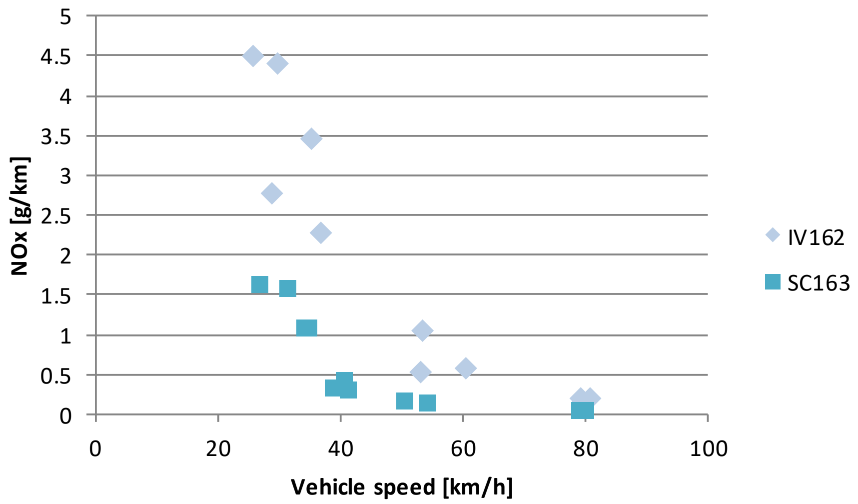

Figure 7: NO_x emissions of the two LNG vehicles on all trips with 55% payload performed with a warm start.

On average, urban driving only constitutes a minor share in the total mission profile for long haul tractor semi-trailer combinations, but for individual vehicles the actual shares of urban driving depend on the specific usage and application. As mentioned before, in the Netherlands the companies providing transport services for Ahold use the tested vehicle models not only for inter-distribution centre operation with a large share of motorway, but also for supply trips to supermarkets. These vehicles therefore do drive a significant share of their kilometres in cities.

Test results for a representative supermarket supply trip
The two LNG trucks have also been tested on a trip which represents the urban part of a DC-to-supermarket trip. To make the results representative for the average DC-to-supermarket trip of the companies where these trucks are used, the test results obtained on the urban DC-to-supermarket trips in the test programme need to be combined with the results obtained on the rural and motorway parts of the ISC N3 trips with weighting factors of respectively 45, 25 and 30%. This leads to an overall average speed of 52 km/h, which is consistent with the average speed indicated by the transport companies for their DC to supermarket operations, but actual shares of sub trips are not accurately known.

For the given operation, the average NO_x emissions for one LNG vehicle are found to be 2 g/km while for the other vehicle the NO_x emissions are 0.5 g/km.

For the diesel comparator vehicles no data is available from supermarket supply trips, so NO_x emissions levels for this typical type of operation could not be estimated. The DC-to-supermarket trips used in the tests contain simulated unloading time. During this time the engine is turned off. Due to the nature of the NO_x reduction system based on SCR, for diesel vehicles the NO_x emissions may be elevated after engine start because the SCR catalyst has cooled down since the engine was stopped. The contribution of such a ‘semi-warm’ start on NO_x emissions of Euro VI diesel trucks is not known.

Test results for inter-distribution centre trips
When the test results obtained on the urban, rural and motorway parts of the ISC N3 trip are used (see Figure 6) and are weighted with shares of 15, 25 and 60% for the respective parts, this leads to an approximate average speed of 65 km/h, which is indicated by the transport companies as the typical average speed for inter distribution centre transport. The average NO_x emissions on this combination of urban, rural and motorway driving are 0.35 g/km for one LNG vehicle and 0.66 g/km for the other vehicle, compared to an average of 0.4 g/km for the six tested diesels.

2.4.4 Particle number emissions

For both LNG vehicles and the sample of tested diesel vehicles the particle number emissions, as depicted in Figure 8 are very low. One vehicle emits a PN level which is on average around the applicable type approval limit value (6.0×10^{11} #/kWh, which is equivalent to ~ 6.0×10^{11} #/km at 1 kWh/km for motorway driving) and the other one emits less. [Giechaskiel, 2012] reports an emission level of 6×10^{13} for a non-DPF Euro III HD engine and [Giechaskiel, 2015] reports an emission level of about 2×10^{13} for a Euro V HD vehicle with a DPF, that did not yet have to fulfil the EU particle number requirements.

On average the LNG engines were found to emit more particles than the average for the diesel counterparts, but there is also a large spread between the four Euro VI diesel vehicles for which PN was measured. Further caution in the interpretation of the results is necessary as the diesel vehicles were tested in the lab while for the LNG trucks particle numbers were measured on the road.

For the Iveco truck the air compressor dumps its excess air in the tailpipe after the catalyst. This could, in theory, bring about some additional particle emissions from the lubrication oil of the compressor. In terms of particle number emissions however, this vehicle emitted the least particles of both LNG vehicles.

At the time of writing this report there is not much experience yet with particle number testing on heavy-duty vehicles on the road. It is therefore not possible to draw firm conclusion on the possible significance of the differences observed between vehicles and technologies at these low emission levels. Overall the conclusion should therefore be that the particle number emission levels of the measured Euro VI LNG and diesel trucks are on a comparable low level.

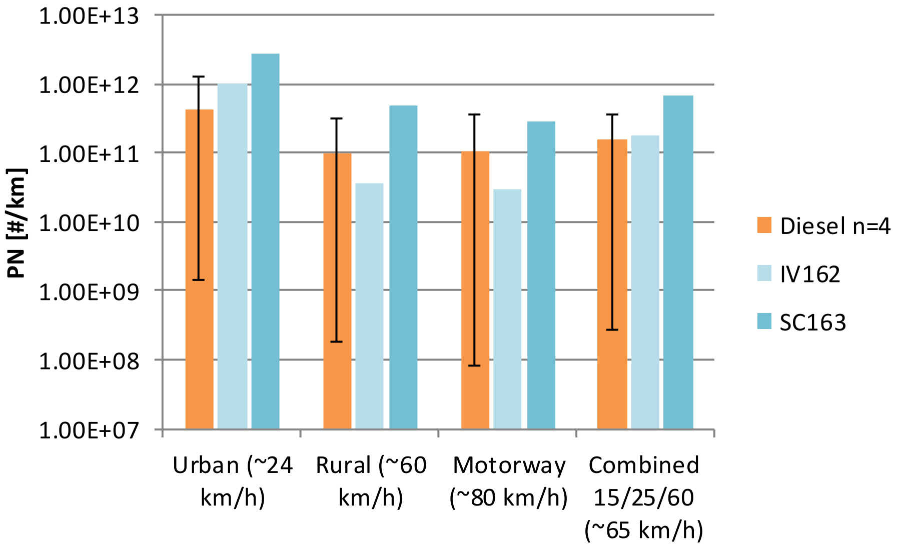

Figure 8: Particle number emissions of the two tested LNG vehicles at 55% payload (~15.5t) compared to the average results for 4 tested diesel vehicles (Source: JRC). The error bars represent the minimum and maximum values from the database.

2.4.5 *Total hydrocarbon and CH_4 emissions*

As can be seen from Figure 9, the two LNG vehicles have higher total hydrocarbon emissions than their diesel counterparts under urban driving conditions. This is caused by the cold start. For LNG engines, however, most of the total hydrocarbons (>85%) are methane. Methane has limited impact on local air quality but is a powerful greenhouse gas[5]. LNG engine exhaust gas contains unburned methane, which is not oxidized in the three-way catalyst until it is warmed up. The additional emissions of total hydrocarbons of the tested LNG engines during a cold start at ambient temperatures around 0-5 °C are found to be about 10 grams, which is equivalent to about 340 gram CO_2. When the engine and aftertreatment are warm, the total hydrocarbon emissions, and thus also the methane emissions, are very low. This means that, averaged over the length of a complete trip, the cold start emissions of methane contribute very little (about 2 gCO_{2eq}/km) to the total GHG emissions of the tested LNG vehicles. As the tested LNG vehicles were relatively new, with relatively little ageing of the three-way catalysts, results may not be valid for older vehicles. This deserves further study.

[5] 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.

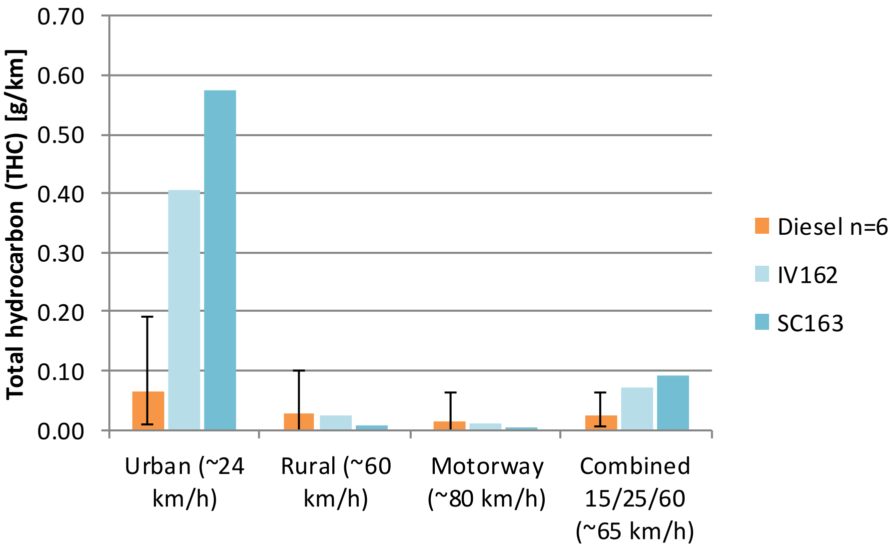

Figure 9: Total hydrocarbon emissions of the two tested LNG vehicles at 55% payload (~15.5t) compared to the average results for 6 tested diesel vehicles. For the LNG engines the total hydrocarbon emissions will be composed of more than 85% CH_4 (methane). The error bars represent the minimum and maximum values from the database.

3 Possible contributions of other tank-to-wheel GHG emissions

Engines running on natural gas potentially have lower greenhouse gas emissions than diesel engines. For methane the amount of CO_2 emitted per unit energy content of the fuel is about 25% lower than for diesel. The net benefit is also dependent on the energy efficiency of the gas engine however. In addition, methane emissions in the exhaust gas (so-called methane slip) and emissions from the LNG tank and the engine carter may further reduce the GHG emission benefit of natural gas engines.

In section 2.4.1 it was shown that the two tested Euro VI LNG engines have 5 to 10% lower direct CO_2 exhaust emissions than the average for a sample of 5 comparable diesel trucks. In order to investigate if other tank-to-wheel GHG emissions influence the comparison between Euro VI heavy goods vehicles running on LNG and comparable vehicles running on diesel, data from literature sources was combined with the measured tail-pipe CO_2 and CH_4 emissions as reported in chapter 2.

3.1 Sources of TTW greenhouse gas emissions

For the TTW GHG emissions, besides CO_2 and CH_4 emissions from the tail-pipe, some other sources of the vehicle may contribute to the direct TTW GHG emissions. These GHG emissions have not been measured. A literature study was performed and additional vehicle information was retrieved in order to estimate the possible levels of these sources.

Not included in this analyses are the GHG emissions from the well-to-tank (WTT) part of the energy chain. To make a complete analyses of the GHG emissions of heavy goods vehicles on diesel and LNG, it is recommended to take account of the entire fuel pathway which includes emissions of production and transportation of the fuel.

The possible sources of TTW GHG emissions:

Diesel and LNG trucks:

- CO_2 as a product of the combustion process;
- N_2O, a strong greenhouse gas that can be produced in a catalyst and is emitted from the tail-pipe.

LNG trucks:

- Methane from incomplete combustion of LNG that is not oxidized in the catalyst and is emitted from the tail-pipe. Also known as methane slip. These methane emissions may have several causes (engine design, fuel mixture control, catalyst efficiency and ageing, cold start and malfunctions such as misfire);
- Boil-off gas (BOG), is fuel gas containing methane that may be vented from the LNG tank once the pressure rises above a certain threshold due to the gas gradually absorbing heat in the tank. The amount of BOG events depends on the number of periods with prolonged vehicle parking. For a full tank this is beyond the prescribed maximum holding time of 5 days;
- Leakage, in the event piping is not gas tight;
- Blow-off, deliberate venting of gas which is necessary to lower the pressure in the tank, empty the tank for repair, to release tank residue gas or for dismantling the vehicle at the end of life ;
- Crank case venting of methane from incomplete combustion that slips past the pistons and piston rings into the crankcase and is vented to the air. For the modern LNG engines crank case gases are rerouted to the intake to take part again in the combustion process and as such do not bring about additional TTW GHG emissions.

The Global Warming Potentials (see IPCC AR5 p714, 2013) in CO_2 equivalent for those gases are:

- CO_2 1
- CH_4 34
- N_2O 298

3.1.1 TTW CO_2 emissions from combustion

For LNG about 25% less CO_2 is emitted per unit of energy than for diesel fuel. How much of this energy is eventually used in an LNG or diesel engine during normal operation, and consequently how much CO_2 eventually is emitted, depends on a number of factors.

In terms of driving resistances LNG and diesel trucks are very much alike. In principle aerodynamics do not differ and weight and rolling resistance differ not so much either. What does differ, however, is the efficiency of the engines. A compression ignition engine running on diesel is more efficient than a stoichiometric spark ignition engine running on LNG. This causes the advantage of LNG in terms of lower CO_2 emissions per unit of energy to be offset by the lower energy efficiency of the gas engine. The real-world measurements on Euro VI diesel and LNG trucks of this investigation seem to confirm this effect.

Averaged over the two tested vehicles, the results presented in paragraph 2.4.1 still show a lower CO_2 emission for the LNG vehicles of about 10% for motorway and rural driving and 5% for urban driving. At urban driving with a low payload the efficiency of one of the engines seems to further decrease resulting in higher emissions than the average for the diesel vehicles used as comparison.
The diminishing advantage of the gas engine over the diesel engine under those circumstances is to be expected as the spark ignited engine becomes progressively less efficient at low load engine operation, e.g. approximately below half throttle and at idling.

What not has been accounted for in the measured values and averages calculated, is the effect of the final reduction ratio of the rear axle, which for the sample of diesel trucks was relatively high. For application in super market delivery and interdistribution centre operations, such diesel trucks would normally use lower reduction ratios which would result in about 1 to 2 percent less fuel consumption. This effect is taken into account in the scenario analyses presented further on in this chapter, in which also other possible TTW greenhouse gas emissions are included.

3.1.2 Methane slip

Combustion gases of engines running on LNG may contain unburned methane. When this unburned methane passes the catalytic emissions reduction system, this methane is emitted in the air and contributes to the TTW GHG emissions of the vehicle. This methane emission from the tail-pipe is often referred to as 'methane slip'. Normally, the three-way catalyst, when warmed-up, oxidizes most of the engines methane emissions.

The methane emissions of two LNG trucks have been determined with PEMS. The measured methane emission levels can at least be considered representative for relatively new vehicles (odometer readings of the two tested vehicles were 8,000 and 25,000 km respectively) with fresh three-way catalysts. It is not known if and how much these catalysts age. In addition, it is not known if and how much engine malfunctions such as engine misfires occur. These two factors, which could lead to increased methane emissions with increasing age of the vehicles, have not been taken into account here, as there is no generic data available. Generally, the methane emissions of the two tested trucks are of the order of 2 gCO_2-eq./km, and therefore contribute very little to the TTW GHG emissions (see section 2.4.5).

3.1.3 Boil-off, leakage, blow-off

In the case of heavy-duty vehicles running on LNG, boil-off is gaseous fuel venting from the fuel tank to the air. This may happen by heat influx into the fuel tank which causes the pressure of the gaseous part of the fuel to rise above a certain threshold. For LNG vehicles boil-off means that methane is released to the air. Possible boil-off is included in the analyses of the GHG emissions of LNG trucks by different taking scenarios into account for the amount of boil-off events that could happen in normal use.

ECE Regulation 110 requires a minimum holding time of the gas in the fuel tank of 5 days:

"...Annex 3B paragraph 2.7. Vehicle LNG tank(s) shall have a design hold time (build without relieving) minimum of 5 days after being filled net full and at the highest point in the design filling temperature/pressure range..."

Both tested vehicles use Chart HLNG type tanks which comply with Regulation 110. This means that according the requirements the vehicles are not allowed to emit BOG with a full tank within the first 5 days after being filled. Two literature sources report about BOG from modern LNG trucks. [Gunnarsson, 2015] reports, based on estimates of BOG supplied by Scania, a boil-off of 2 to 4% per day from a 320 kg LNG tank fill after 5 days, which represents about 10 kg per day. [Ursan, 2011] determines the theoretical BOG quantity, based on a physical calculation and estimates BOG at 2.6% of the initial amount of fuel mass per event for a tank pressure drop from 15.9 to 14.8 bar. During the testing programme, the tank pressures of both trucks were closely monitored. The test vehicles have been parked indoors at 20 °C for three days during the test preparation and over the weekend. Indeed, the pressure gradually increases, but did not rise above the threshold of the pressure relief valve of 16 bar.

For full tanks, taking account of the designed holding time of 5 days, the amount of BOG vented over the lifetime of an LNG truck depends on the number of instances where the holding time of 5 days is exceeded.

The instances over the lifetime of a LNG truck where holding times may be close to or exceed 5 days are at:

- the factory,
- transportation to the distributor,
- the distributor depot,
- the bodybuilder,
- regular service or repair at the workshop
- longer stand-stills when in use by the transport operator and
- at the end of life when the vehicle is dismantled.

According to the Dutch Scania importer the tank is filled with about 5-6 kg when a vehicle leaves the factory. This means that after manufacturing and during transportation no or almost no BOG days would occur. For all of the other instances, where higher amounts of gas may be in the tank, it is hard to predict the vehicle stand still time, and thus whether or not and for how long the holding time of 5 days is exceeded [Gunnarsson, 2015]. Therefore, for the analyses, the CO_2 equivalent emission of BOG is calculated for different numbers of BOG days to determine whether the level of an event is significant compared to the tail-pipe emissions.

In addition to boil-off, theoretically also leakage of the fuel system may occur. Also deliberate blow-off of gas from the tank may occur, for instance to vent gas residue from the tank that has a relative bad quality, or at the vehicle’s end-of-life when the remaining fuel needs to be vented from the tank before dismantling the vehicle.

For boil-off a sensitivity evaluation was done with assumed different amounts of boil-of days per year and one full tank blow-off. This is done for respectively 1 and 5 boil-off days per year, hereby assuming that at least once per year the holding time of 5 days is exceeded. 5 days of boil-off per year would occur when a vehicle is parked 5 days longer then the holding time or when for instance over the year holding times of 5 days are exceeded 5 times. The latter seems very unlikely. It is not known whether these amounts are realistic, but an indicative assessment of the possible relative contribution of BOG and blow-off and leakage to the GHG emissions of an LNG truck over its life time. Based on this assessment the contribution of boil-off methane to the LNG vehicle's TTW GHG emissions could be between 0.4 and 4% of the direct CO_2 emissions over the vehicle's lifetime.

Boil-off gas (BOG) and blow-off scenario

- The vehicle has 2 tanks with a total of 378 kg LNG;
- No boil-off during standstill events shorter than 5 days;
- After 5 days standstill the boil-off is 3% of the initial fuel mass per day [Gunnarsson, 2015], [Ursan 2011];
- This means a venting of 9.8 kg of CH_4 (GWP100 25) BOG/day after 5 days, equivalent to 332 kg CO_2 emission per day.

Average tailpipe CO_2 emission 50/50 mix 10 and 55% payload: 702 g/km
Average annual mileage for Dutch distribution services: 130.000 km / year
Approximate maximum useful mileage (Ahold transporter): 800.000 km (useful life of ~6.2 years)

Total life time tailpipe CO_2 emissions: 560 t

Total lifetime BOG in tonne CO_2 equivalent emission and as percentage of tailpipe CO_2 emissions for different BOG event frequencies (1 or 5 times per year or 1 full tank blow-off over the entire vehicle lifetime):

1 event/year:	2.0t	= 0.4 % of the lifetime tailpipe CO_2 emission
5 events/year:	10.2t	= 1.8%
1 full tank blow-off/life time:	11.1t	= 2.0%

3.1.4 *Crank case venting*

Combustion gases, which may contain unburned methane, slip past the pistons from the combustion chamber of an engine to the crank case. This leads to a pressure build up in the crank case. This over-pressure needs to be levelled, which means that crank case gases are to be vented. Usually, for modern heavy-duty engines these gases are vented to the air intake of the engine which means that the gases are cycled back to the combustion process and are not vented to the air. The two tested vehicles both have crank case gases vented to the intake of the engine. This means that, besides the emissions from the tail-pipe, there are no additional GHG emissions from the engine to the air.

3.1.5 *N_2O, nitrous oxide*

In addition to CO_2 and methane, an internal combustion engine with catalytic emission reduction systems may emit N_2O, a greenhouse gas which is about 298 times stronger than CO_2. This gas was not measured, but is included in this indicative analyses of the overall TTW GHG emissions.

Today's LNG trucks employ spark ignited stoichiometric engines, which means that these engines use a three-way catalyst to fulfil the Euro VI emission standard. Three-way catalysts are known to potentially produce nitrous oxide, especially during the short warm-up period and when they become aged [Gense, 2000].

One study [Willner, 2013b] reports the nitrous oxide emissions of a Euro VI CNG vehicle equipped with a three-way catalyst. For a cold WHVC (World Harmonized Vehicle Cycle) test average N_2O emissions of 0.07 to 0.08 g/km are reported. For the warm test no N_2O was detected (0.00 g/kWh). This is in line with the reported behaviour that N_2O of a fresh three-way catalyst is mainly produced in a temperature window during warm up of the catalyst. For the given WHVC test, the total amount emitted was about 480 g CO_2 equivalents, which is mainly attributable to the cold start. The contribution of N_2O to the total TTW GHG emissions thus depends on the number of cold starts. Taking account of two cold starts occurring per day, the contribution of N_2O to the total GHG emissions is small compared to the daily amount of tailpipe CO_2 emissions which may be about 200-300 kg.
The contribution of one or two cold starts per day adds 0.4 % to the total of tailpipe CO_2-equivalent GHG emissions. However, when a three-way catalyst ages the N_2O formation may increase [Gense, 2000].

Catalytic aftertreatment for diesel engines may also produce N_2O emissions. [Cummins, 2011] reports that modern diesel catalysts (oxidation catalyst, SCR (all types) and ammonia slip catalyst) produce small amounts of N_2O. Formation levels depend on exhaust gas composition, temperature, and catalyst formulation. Unlike three-way catalysts, diesel aftertreatment systems produce N_2O when warm. The US introduced standards for N_2O, and testing started as of model year 2015. The standard is 0.10 g/bhp.h for engine testing which equals to about 6% of the engine CO_2 emissions. Based on road-side tunnel measurements, [AGU, 2014] reports a significant increase of N_2O emissions of modern HDVs with aftertreatment compared to older types without aftertreatment. [Suarz-Bertoa et al., 2016] reports N_2O emission levels of 0.063 to 0.139 g/kWh for a Euro V diesel truck equipped with DPF and SCR. This represents about 3 to 6% of the tailpipe CO_2 emissions. [Vermeulen et al., 2010] reports N_2O levels of 0.01 to 0.02 g/kWh for 5 SCR equipped Euro V engines, equivalent to about 0.5 to 1% of the tailpipe CO_2 emissions. [TØI, 2013a and 2013b] report N_2O emission levels of two tested Euro

VI heavy-duty vehicles. One vehicle with a 9 liter engine emits about 0.06 g/km N_2O. This represents 17 gCO_2-eq./km or about 2% of the tailpipe CO_2 emissions. The other vehicle, with a 13 liter engine, emits about 0.7 g/km N_2O, which represents 220 gCO_2-eq./km or about 30% of the tailpipe CO_2 emissions. Because there is just a small amount of data available of the N_2O emissions of Euro VI diesel engines the level of these emission is very uncertain. For one tested vehicle very high N_2O emissions were reported, but without more data it is not possible to determine whether this is typical or an outlier. Given the possible importance for total TTW GHG emissions more data is necessary to more accurately estimate the contribution of N_2O.

3.2 Comparison of TTW GHG emissions

The TTW GHG emissions of the Euro VI diesel and LNG vehicles are compared taking account of the estimated contributions of possible other sources of GHG emissions at the vehicle as summarized in Table 5. In general, the contributions of these other sources are very uncertain. It is not known how many BOG events, leakage and blow-off of methane will take place over the lifetime of a vehicle. It largely depends on the usage of the vehicle and on BOG prevention measures taken pre-sales, during service, repair and maintenance and at the end of life. Also the data on the emission levels of the strong greenhouse gas N_2O are very uncertain and not representative. For N_2O a provisional effect of +6% (46 gCO_2-eq./km) of tail pipe CO_2 emissions is taken into account for the diesel vehicles in a separate scenario. This value is comparable to the US limit. Given the high N_2O emission, reported for one HDV in [TØI, 2013a and 2013b], it is strongly recommended to investigate whether this is an outlier or regular behaviour.

From Table 5 it can be concluded that the methane slip of the measured LNG vehicles is very low and hardly contributes to the GHG emissions. N_2O emission of Euro VI diesel may however significantly influence the comparison.

Table 5: Overview of the estimated additional TTW GHG emissions of Euro VI diesel and LNG trucks: boil-off gas, N_2O and crank case venting in % of the tail-pipe CO_2 emissions.

Emissions in % of tailpipe CO_2	Diesel Euro VI	LNG Euro VI
Tail-pipe CO_2	770 g/km	702 g/km
BOG [**3.1.3**]		
1 BOG event/year	0%	0.4%
5 BOG events/year+1 tank blow-off/lifetime	0%	3.8% (strongly depending on usage and parking times)
Methane slip [**2.4.5**] 2 cold starts/day, 9.5 gCH_4 per cold start	0%	0.3%
Crankcase venting [**3.1.4**]	0%	0%
N_2O [**3.1.5**]	0.5-30% (few data)	0.4% (few data)

In Table 6 the overall results for the indicative comparison of TTW GHG emissions is shown for a number of scenarios, depending on the emissions included in the comparison and the values used from the estimated bandwidths for the contributions of different GHG emission sources. For the diesel trucks, the high final reduction ratio of the test sample is accounted for by correcting with -2% for fuel consumption and CO_2 emissions. The estimate is based on internal engine friction change going from a reduction ratio i = 2.65 to i = 2.38.

After inclusion of all TTW emissions, except for N_2O and possible effects of ageing of three-way catalysts and engine malfunctions, LNG trucks are found to emit less TTW GHG emissions (in g/km CO_2-equivalents) than equivalent diesels. The difference is about -3% for the scenario ‘LNG high’ to -6% for the scenario ’LNG low’ as indicated in Table 6. When N_2O emissions of diesels are taken into account with an estimated value of 6% of the tailpipe CO_2 emissions, the difference is -9% for the ‘LNG high’ scenario and -12% for the ‘LNG low’ scenario.

Table 6: Indicative comparison of TTW GHG emissions of the tested Euro VI diesel and LNG trucks, based on the measured tailpipe emissions and estimated other vehicle-based GHG emissions

Emissions in g/km TTW CO_2-eq.		**Diesel Euro VI**	**LNG Euro VI**
(1) tailpipe CO_2[1]		770, n=5	702, n=2
(2) Final reduction ratio (-2%)		-15	-
Boil-off gas			(strongly depending on usage, parking times, BOG prevention)
(3) 1 BOG event/year		-	3
(4) 5 BOG events/year		-	13
(5) 1 tank blow-off/lifetime		-	14
(6) N_2O (high uncertainty)		46	3
(7) Methane slip		-	2
Diesel	(1), (2)	755	
Diesel incl. N_2O	(1), (2), (6)	801	
LNG ‘low’	(1), (3), (7)		706
LNG ‘high’	(1), (4), (5), (7)		730

[1] Based on a 50/50 mix of 10 and 55% payload (2 and 15.5t) and a mileage distribution of 15%/25%/60% for urban, rural, motorway driving, which represents an average speed (without loading / unloading) of ~ 65km/h.

4 Conclusions

Criteria pollutants

- Over an in-service conformity test with PEMS, driving an N3 trip, both LNG vehicles have conformity factors for CO, HC and NO_x comfortably below the limit value of 1.5.

- The tests show NO_x levels that vary between types of trips and between both LNG vehicles. One vehicle emits 0.15 g/km over a motorway trip up to 2.9 g/km for an urban trip with a cold start and this increases up to 4.5 g/km for a typical urban trip that contains operation for supermarket delivery. The other vehicle emits 0.04 g/km over a motorway trip and 1.83 g/km for the cold started urban trip. For a typical urban trip that contains operation for supermarket delivery the NO_x emissions are 1.6 g/km.
- On average the NO_x emissions of the two LNG vehicles are respectively 0.4 and 0.7 g/km for a case with mainly motorway driving. This level is comparable to the average NO_x emissions of diesel vehicles for this case (0.4 g/km)
- For a case which includes a substantial share of city driving with supermarket delivery, average NO_x emissions of the LNG vehicles are 0.5 and 2 g/km respectively. Emission data of diesel vehicles for supermarket delivery trips is not available and therefore a comparison could not be made for this specific application.
- The share of NO_2 in the NO_x emissions of the two tested LNG vehicles is low and results in absolute NO_2 emissions of 0.005 to 0.05 g/km. This is substantially lower than the NO_2 emission of the tested diesel vehicles (on average 0.13 g/km for motorway and rural operation and 0.4 g/km for an urban trip with a cold start).

- The tests show average particle number levels for the two LNG vehicles of $2x10^{11}$ and $7\ x10^{11}$ particles/km respectively.
- The emissions levels vary somewhat between the two vehicles and between types of operations. Especially, for the cold started urban trip the emissions are higher.
- The emissions remain below a level that is comparable to the limit that applies to a Euro VI engine certification test, and the levels are comparable to the average of four tested Euro VI diesel vehicles with a diesel particle filter.
- Given the experimental status of measuring particle number emissions in an on-road test, no hard conclusions can be drawn about possible differences between vehicles and technologies.

Tank-to-wheel greenhouse gas (GHG) emissions

- The measurements of tailpipe emissions of both tested LNG trucks show 5-10% lower CO_2 emissions compared to the diesel trucks.
- The tail-pipe CO_2 emissions of LNG trucks also depend on the operation. In general, CO_2 emissions are higher for urban driving than for motorway driving. For the comparison with diesel counterparts for driving at the motorway, the CO_2 emission is on average about 10% lower but in the city, with more idling and driving with low a payload, the efficiency appears to drop. Under those conditions CO_2 emissions are a few percent higher than for comparable diesel trucks.

- Driving style proved to significantly impact the fuel consumption and CO_2 emissions. A more dynamical driving style with more braking and accelerating at higher engine revolutions resulted in 10% higher fuel consumption. On the motorway part of the test the effect is small, probably because less accelerations and braking occur on the motorway. Hence the change in driving style impacts CO_2 emissions less under those conditions.
- The measurements show some spread between individual results which may be attributed to the vehicles but also to measurement variation of testing on the road which is typically up to 5%.

- Over the tests the methane emission, often referred to as methane slip, is low. Emission levels of measured total hydrocarbons, which are expected to consist mainly of methane, are below 0.05 g/km for rural and motorway driving and are 0.4 to 0.6 g/km for an urban trip with a cold start. For an average case the contribution of the methane emission tot the total TTW GHG emissions is 2 gCO_2-eq./km.

- The TTW GHG emissions of the Euro VI diesel and LNG vehicles are compared taking account of the estimated contributions of possible other sources of GHG emissions at the vehicle (boil-off, blow off, N_2O, methane slip). The tailpipe methane emissions were measured. The contributions of the other sources are very uncertain.
- When estimates of all factors that contribute to TTW GHG emissions are taken into account, except the emissions of the strong greenhouse gas N_2O, the LNG trucks emit from tank-to-wheel roughly 3 - 6% less GHG emissions than comparable diesel trucks for an average case.
- The comparison of TTW GHG emissions between LNG and diesel is uncertain because the actual contribution to the emissions of boil-off, blow-off gas and leakage is not known and additionally the emission level of the strong GHG N_2O of diesel vehicles is very uncertain.
- Especially, the limited amount of data on N_2O emissions from Euro VI diesel vehicles as available from literature shows a large spread with a potential minor to a very large impact on TTW GHG emissions.

Closing remarks

- The results of the analyses of the contribution of other possible sources of TTW GHG emissions show a high uncertainty. This is mainly caused by the lack of reliable data of boil-off, blow-off and leakage of LNG vehicles and the N_2O emissions of diesel vehicles. A better indication of the possible contribution of these emissions to the TTW GHG emissions could be obtained by dedicated measurements or monitoring.
- This study presents emissions test results of only two LNG vehicles, which means that the statistical significance for drawing generalized conclusion on the comparison with diesel is very low. New types of vehicles running on LNG are likely to be introduced on the market in the near future. By testing new models, as soon as they arrive on the market, a better and more reliable view can be obtained of the environmental performance of this technology.

5 References

[AECC, 2008] May et al. Heavy-Duty Engine Particulate Emissions: Application of PMP Methodology to measure Particle Number and Particle Mass, SAE paper 2008-01-1176

[AGU, 2014] Preble, C., Harley, R. Kirchstetter, T., *N_2O and NO_2 Emissions from Heavy-Duty Diesel Trucks with Advanced Emission Controls*, American Geophysical Union, Fall Meeting 2014, abstract #A33F-3260

[Chart, 2015] http://files.chartindustries.com/10834738_HLNGVehicleTanks_2015.pdf

[Cummins, 2011] Krishna Kamasamudram*, N_2O Emissions From 2010 SCR Systems*, Deer conference Detroit 2011

[Gense, 2002] N.L.J. Gense, R.J. Vermeulen, *N_2O formation in vehicle catalysts*, TNO report 02.OR.VM.017.1/NG, February 28 2002

[Giechaskiel, 2012] Giechaskiel et al., *Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review*, Aerosol Science and Technology, 46: 719-749, 2012

[Giechaskiel, 2015] Giechaskiel et al., *Vehicle Emissions Factors of Solid Nanoparticles in the Laboratory and on the Road using Portable Measurement System (PEMS)*, 22 December 2015

[Gunnarsson, 2015] Gunnarsson, L, Helander. E, *How to Handle Boil-off Gases from LNG Trucks*, Master thesis project, Linköping University, LIU-IEI-TEK-A—15/02235-SE, 2015-06-04

[Hallstrom et al. 2013]
Hallstrom, K., Voss, K., and Shah, S., "*The Formation of N2O on the SCR Catalyst in a Heavy Duty US 2010 Emission Control System*," SAE Technical Paper 2013-01-2463, 2013, doi:10.4271/2013-01-2463.

[LowCVP, 2017] Robinson B., *Emissions Testing of Gas-Powered Commercial Vehicles,* report prepared by Low Carbon Vehicle Partnership, January 2017

[Pérez et al., 2014] Pérez et al., *LNG Blue corridors, Euro V technical solutions*, seventh framework programme deliverable LNG-BC D2.1 14/3/2014

[Suarz-Bertoa et al. 2016]
Suarz-Bertoa et al., *On-road measurement of NH3 and N2O emissions from a Euro V heavy-duty vehicle*, Atmospheric Environment 139 (2016) 167-175

[TNO, 2010] Vermeulen, R.J. et al., *In-Service Testing Programme for Heavy-Duty Vehicle and Engine emissions; 2006-2009*, TNO report MON-RPT-2010-00969, 2 April 2010

[TNO, 2014] Vermeulen et al, *The Netherlands In-Service Emissions Testing Programme for Heavy-Duty 2011-2013*, , 26 May 2014

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

[TNO, 2016b] Heine, V.A.M. et al., *Assessment of road vehicle emissions: methodology of the Dutch in-service testing programmes*, TNO 2016 R11178, October 2016

[TØI, 2013a] Rolf Hagman, Astrid H. Amundsen, *Emissions from Euro 6/VI vehicles Test programme phase 2*, summary of TØI Report 1291/2013

[TØI, 2013b] Rolf Hagman, Astrid H. Amundsen, Utslip fra kjøretøy med Euro 6/VI teknologi, måleprogrammet fase 2, TØI Report 1291/2013

[Topsector logistics, 2017] *Outlook City Logistics 2017, Topsector logistics, April 2017*

[Ursan, 2011] Mihai Ursan PhD., P.Eng, Westport Power Inc., *What is boil-off?,* prepared for the LNG taskforce meeting in Brussels, November 3, 2011

[Willner, 2013a] Willner K., Danielsson D., *Testing of unregulated emissions from heavy duty natural gas vehicles*, SGC rapport 2013:289

[Willner, 2013b] Willner K., Danielsson D., *Testing of unregulated emissions from heavy duty natural gas vehicles Part 2*, SGC rapport 2014:297

6 Signature

The Hague, 10 November 2017

TNO

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A Test fuel LNG

Loading date	molar fractions						GHV/GCV
	CO_2	N_2	CH_4	C_2H_6	C_3H_8	other HC	[MJ/kg]
12-1-2017	n.a.	0.054	92.482	7.435	0.028	<0.05	54.9
15-1-2017	0.000	0.043	91.272	6.852	1.391	<0.05	54.8
17-1-2017	0.000	n.a.	91.193	6.921	1.404	<0.05	54.8
19-1-2017	0.000	0.030	91.124	6.977	1.418	<0.05	54.8
24-1-2017	0.000	0.022	92.191	7.551	0.193	<0.05	54.9

B Test cycles

Table 7: Test trip specifications

Test cycles	Distance	Approximate average speed
	[km]	[km/h]
Supermarket supply trip DC-supermarket	16.0	28
Supermarket supply trip supermarket-DC	16.0	28
N3 trip urban	16.5	22
N3 trip rural	48.2	55
N3 trip motorway	132.8	80
Reference trip	72.4	39

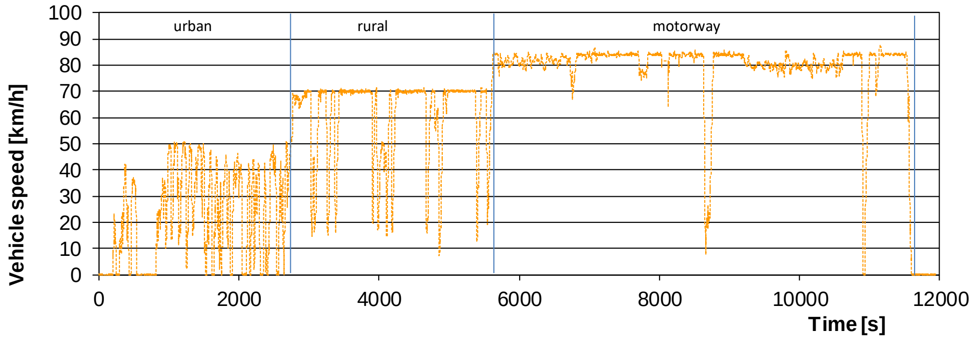

Figure 10: Example of an N3 trip for heavy-duty vehicles with a GVM higher than 12t.

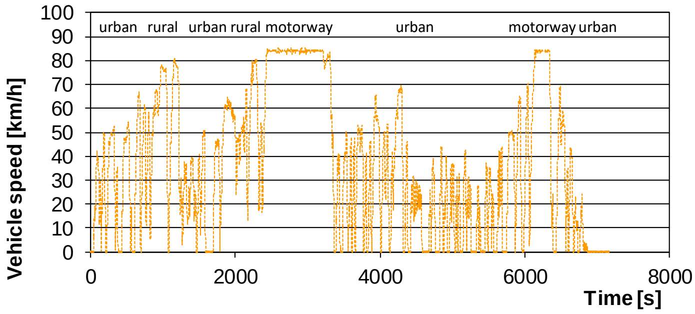

Figure 11: Example of the TNO reference trip.

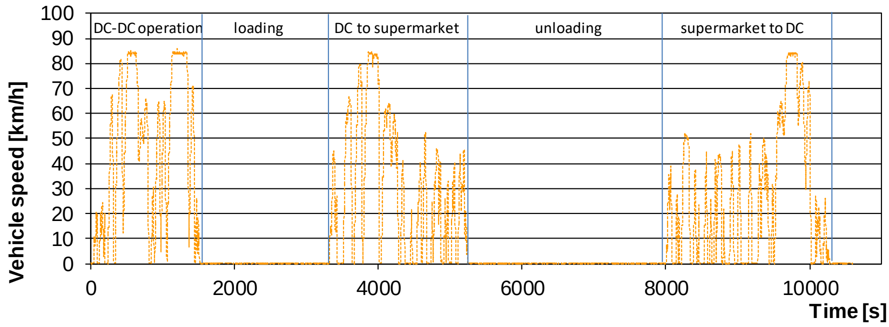

Figure 12: Example of supermarket delivery trips, with parts for inter-distribution centre operation and distribution centre to super market and back.