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TNO report

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Tail-pipe NOx emissions of refuse collection vehicles with a Euro VI engine in daily operation in the Netherlands

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Samenvatting

In het kader van het Nederlandse steekproefcontroleprogramma voor vrachtwagens en bussen, dat TNO uitvoert in opdracht van het Ministerie van Infrastructuur en Waterstaat, zijn de stikstofoxiden (NO_x) emissies van negen Euro VI vuilnisauto's gemeten tijdens representatieve inzet in de dagelijkse praktijk met het Smart Emissions Measurement System 'SEMS' [TNO 2016a]. Het gaat om acht verschillende praktijksituaties met vuilnisauto's die een eerste generatie Euro VI dieselmotor hebben. Deze groep vormt een goede afspiegeling van de Nederlandse vloot Euro VI vuilnisauto's. Ook is één vuilnisauto met een Euro VI aardgasmotor getest. Dit aantal is te laag om algemeen geldende conclusies te trekken over het praktijkemissieniveau van vuilnisauto's met een Euro VI aardgasmotor.

Resultaat van het onderzoek is dat in vijf van de acht situaties, waarbij vuilnisauto's met een eerste generatie Euro VI dieselmotor in verschillende inzetprofielen werden gebruikt, de NO_x-uitstoot tijdens de dagelijkse inzet hoger lag dan de normwaarde die geldt voor de officiële Europese praktijkemissietest voor motoren van zware bedrijfswagens. In drie van de vijf situaties lag de NO_x-uitstoot fors hoger dan deze normwaarde.

Kanttekening is dat de norm geldt voor de condities van de officiële Europese praktijkemissietest. Praktijkinzet als vuilnisautomotor valt daar tot dusver niet onder. De officiële praktijkemissietest wordt zwaarder voor bedrijfswagens met Euro VI motoren die vanaf 2019 op de markt komen. Dit is onder meer het resultaat van Nederlandse inbreng in Brussel. Emissietesten zullen moeten uitwijzen wat het effect hiervan is op het emissieniveau tijdens dagelijkse inzet. Nederland heeft ook geprobeerd om voor vuilnisauto's de testcondities van de officiële praktijktest in lijn te brengen met het werkelijk gebruik als vuilnisauto. Dit is niet gelukt. In Brussel voorziet men dat dergelijke aanpassingen aan de praktijktest pas bij de volgende grote stap in de emissiewetgeving (Euro VII) gedaan kunnen worden.

Bij één voertuig lag het emissieniveau bij rijden in de stad op de normwaarde. Dit was een vuilnisauto die grote stalen bakken in de straat leeghaalde. De motor van dit type vuilnisauto's wordt zwaarder belast, waardoor de katalysator voor het reinigen van de emissies beter op temperatuur komt en het dus beter doet.

Achtergrond
In eerder onderzoek [TNO 2016b] heeft TNO de stikstofoxidenemissies van zware Euro VI bedrijfswagens gemeten tijdens dagelijkse inzet op de weg. Hierbij werd gevonden dat Euro VI vrachtauto's en bussen gemiddeld genomen fors minder schadelijke stoffen uitstoten dan voorgaande generaties. Metingen aan Euro VI vrachtwagens voor langeafstandsvervoer met een lage kilometerstand laten zeer lage praktijkemissies van stikstofoxiden zien. Ook in andere toepassingen zijn Euro VI dieselauto's gemiddeld schoner dan eerdere generaties.

Fabrikanten moeten voor de Europese toelating van vrachtauto's en bussen een formele praktijktest met mobiele meetapparatuur op de openbare weg uitvoeren, zowel bij de typegoedkeuring van op de markt te brengen voertuigen als bij de

controle van de conformiteit van in gebruik zijnde voertuigen. Deze praktijktest heeft ervoor gezorgd dat gewone Euro VI vrachtauto's bij de dagelijkse inzet op de weg voor de uitstoot van stikstofoxiden flink schoner zijn geworden.

Uit het voorgaande onderzoek kwam ook naar voren dat in stedelijke toepassing enkele voertuigen niet zo schoon waren als je op basis van de normstelling zou mogen verwachten. Een aanbeveling was om, voor het vaststellen van emissiefactoren, extra voertuigen te testen die in stedelijk gebied worden ingezet omdat juist dan de emissie van stikstofoxiden een wisselend beeld liet zien.
Met emissietesten aan voertuigen in stedelijke inzet kan worden getoetst of Euro VI effectief is voor de representatieve omstandigheden en of de stedelijke inzet van invloed is op het emissieniveau van stikstofoxiden. Aan deze aanbeveling is gevolg gegeven door de emissies van negen vuilnisauto's tijdens praktijkinzet te meten.

Conclusies en aanbevelingen
De officiële praktijkemissietest schiet voor vuilnisauto's vaak nog tekort voor het realiseren van lage emissie van stikstofoxiden in de praktijk. Met name door de lage rijsnelheid van vuilnisauto's in de dagelijkse inzet is de motorbelasting gemiddeld laag en komt de katalysator, die de uitlaatgassen van stikstofoxiden moet ontdoen, vaak niet goed op werktemperatuur. Hierdoor kunnen bij vuilnisauto's in de dagelijkse inzet hoge emissies van stikstofoxiden optreden. Door de toepassing van een door de fabrikant gemonteerd roetfilter liggen de emissies van roetdeeltjes van zware bedrijfswagens bij gebruik in de praktijk wel op een laag niveau [JRC 2018].
De meetgegevens van de vuilnisauto's op diesel worden gebruikt voor de jaarlijkse actualisatie van de Nederlandse emissiefactoren.

NO_x- emissies van acht vuilnisauto's met een dieselmotor
Het niveau van de gemiddelde NO_x-emissies varieert tijdens dagelijkse inzet sterk en hangt af van de manier waarop elke wagen wordt ingezet en de omstandigheden. Tijdens de inzet kunnen de NO_x-emissies tijdelijk sterk toenemen als de katalysator voor het reduceren van de NO_x-emissies afkoelt tot beneden zijn werktemperatuur. De gemiddelde NO_x-emissies variëren tussen de voertuigen en de bijbehorende inzetten van 0,4 tot 4,3 gram per kilometer. Wanneer deze cijfers worden uitgedrukt in gram per kilowattuur geleverde arbeid, dan variëren de NO_x-emissies tussen de 0,3 en 2,3 g/kWh voor de dieselvoertuigen. Ter indicatie, de limiet voor de formele praktijktest is 0,69 g/kWh[1]. Deze limiet deze geldt niet voor de dagelijkse praktijk maar slechts voor in de wetgeving vastgelegde testcondities voor de praktijktest. Bij één van de acht voertuigen werd witte aanslag geconstateerd in de uitlaat wat duidt op een mogelijk probleem met het uitlaatgasnabehandelingssysteem.
De resultaten van dit voertuig zijn niet meegenomen omdat de witte aanslag heeft geleid tot een foute meetwaarde van de gebruikte sensoren.

NO_x-emissies van een vuilnisauto met een aardgasmotor
Eén voertuig, dat op LNG (Liquefied Natural Gas) rijdt, had een gemiddelde NO_x- emissie van 1,5 g/km. Uitgedrukt in geleverde arbeid is dit 0,7 g/kWh.

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[1] De limiet voor de NO_x emissie over de praktijktest van zware bedrijfswagens is de conformiteitsfactor van 1,5. Deze factor wordt toegepast op de limiet voor de NO_x emissie over een WHTC motortest van 0,46 g/kWh: 1.5 x 0.46 = 0,69 g/kWh.

Ammoniak emissies
De gemiddelde ammoniakconcentraties in de uitlaat zijn vastgesteld voor de geteste voertuigen met behulp van een ammoniak sensor; deze concentraties bedragen gemiddeld 1 tot 8 ppm voor zes van de acht voertuigen. Voor twee andere dieselvoertuigen werden veel hogere concentraties gemeten, wat wijst op een mogelijk probleem met het SCR systeem of de regeling voor de AdBlue dosering. De gemeten waarden liggen echter hoger dan het nauwkeurige bereik van de sensor (>20ppm). Bij één van beide voertuigen werd witte aanslag in het uitlaatsysteem geconstateerd wat mogelijk duidt op een probleem met het SCR systeem.

Invloed van de inzet van de voertuigen op de NO_x-emissie
De gemiddelde snelheden van de geteste voertuigen variëren sterk, van 6,4 tot 26,5 kilometer per uur. Voor inzet met een lage gemiddelde snelheid, lager dan 15 km/u, neemt de NO_x-emissie voor enkele voertuigen toe.
De hogere NO_x-emissie bij lagere snelheden wordt veroorzaakt door de lagere belasting van de motor, waardoor de katalysator afkoelt tot beneden zijn werktemperatuur. Onder deze omstandigheden kan de NO_x-emissie uit de motor niet meer worden gereduceerd.

Bij vuilnisauto's neemt de vermogensvraag van de motor echter toe wanneer het hydraulische systeem voor het binnenhalen en samenpersen van het vuil wordt gebruikt. Dit kan ervoor zorgen dat bij lage gemiddelde snelheden de katalysator beter op temperatuur blijft. Het niveau van de NO_x-emissie hangt dus ook af van de geïnstalleerde systemen.

Na een koude start moeten motor en emissiebeheersingssystemen opwarmen tot hun optimale werktemperatuur. In de periode tot aan het bereiken van de werktemperatuur is de emissie van NO_x tijdelijk verhoogd. Omdat vuilnisauto's weinig koude starts maken per dag, is de bijdrage van de koude start aan de totale gemiddelde NO_x-emissies laag. De bijdrage van de koude start aan de gemiddelde NO_x-emissie is voor de geteste voertuigen 120 tot 310 mg/km en bedraagt typisch rond 5 tot 10% van de totale emissies, tot 23% voor een voertuig dat over het geheel lage emissies had.

Aanbevelingen voor de praktijktest
De NO_x-emissies van voertuigen met een eerste generatie Euro VI-gecertificeerde motor kunnen in de praktijk hoger zijn dan men op basis van de typegoedkeuringslimiet (0,46 g/kWh) en de limiet voor de conformiteit van in gebruik zijnde voertuigen (1,5 x 0,46=0,69 g/kWh) zou verwachten. Dat komt zeer waarschijnlijk doordat Euro VI-vuilnisauto's tijdens werkelijke inzet in de praktijk een groot deel van hun tijd (rond 50%) rijden onder condities die niet worden meegenomen in de EU 'praktijktest'. Uit de analyse van de praktijkgegevens blijkt namelijk dat de motoren zeer regelmatig met een gemiddeld vermogen lager dan 15 tot 20% van het maximumvermogen draaien. Dit niveau is de ondergrens waaronder voor de huidige formele praktijktest[2] de emissies niet worden meegenomen in de beoordeling.

[2] Step A tot en met C. Binnen de emissieklasse Euro VI wordt onderscheid gemaakt tussen de stappen A tot en met D, met elk verschillende eisen.

In 2019[3] wordt die ondergrens verder verlaagd naar 10% wat betekent dat voor vuilnisauto's een groter deel van het representatieve inzetbereik van de motor wordt meegenomen in de beoordeling van een formele praktijktest.

Voor de praktijktest voor de Europese toelating van vrachtauto's en bussen geldt een aparte testrit voor vrachtwagens en aparte testrit voor bussen. Voor de praktijktest voor bussen wordt langer in de stad getest (70% van de testtijd) dan bij de praktijktest voor vrachtwagens (20% van de testtijd). De praktijktest voor bussen biedt daarom een betere waarborg dat bij stadsgebruik lagere emissies worden gerealiseerd. Gebleken is dat bij Euro VI motoren, die ook in vuilnisauto's worden toegepast, de praktijktest voor vrachtauto's wordt uitgevoerd. Dit komt omdat de voertuigen die tot vuilnisauto worden omgebouwd, als gewone vrachtauto worden geleverd. Aanbeveling is dat de Europese regelgeving op dit punt wordt aangepast zodat motoren van zware voertuigen die typisch in de stad worden gebruikt altijd worden getest volgens de praktijkrit voor bussen. Ook voor motoren voor vuilnisauto's moet dan de praktijkrit voor bussen worden gebruikt.

Voor aanschaf van vuilnisauto's in de nabije toekomst kunnen kopers van vuilnisauto's bij de aanbesteding van nieuwe voertuigen vragen om een praktijktest voor gebruik als busmotor. Een praktijktest voor gebruik als busmotor geeft een betere waarborg dat bij rijden in de stad lagere NO_x-emissies optreden.
Ook kan een koper kiezen voor een vuilnisauto met een kleinere dieselmotor (lagere cilinderinhoud en vermogen). Hierdoor is de kans groter dat de emissiebeheerssystemen van de dieselmotor goed op temperatuur komen en blijven.
Voorts komen naast de motor op aardgas, het meest gangbare alternatief voor de dieselmotor, inmiddels mondjesmaat vuilnisauto's met nieuwe aandrijfconcepten op de markt. Deze concepten zijn interessant met het oog op lokale emissies, maar de brede inzetbaarheid van de concepten moet nog worden onderzocht. Het gaat onder meer om volledig elektrische vuilnisauto's, de waterstofvoorbereide hybride variant daarvan en de diesel-elektrische hybride variant die lokaal emissieloos kan worden ingezet.

[3] Step D.

Summary

In the framework of the in-service testing programme for heavy-duty vehicles for the Ministry of Infrastructure and Water Management, TNO conducted an on-road emissions testing programme with the Smart Emissions Measurement System 'SEMS' [TNO 2016a] to determine the NO_x emissions of nine Euro VI refuse collection vehicles in real-world operation during everyday' s' use. Eight of the tested vehicles run on diesel and are a good representation of the Dutch fleet of refuse collection vehicles with a first generation Euro VI diesel engine. One of the tested vehicle has a Euro VI LNG (Liquefied Natural Gas) engine. Based on the results of this single vehicle no general conclusions can be drawn about the real-world emissions level of Euro VI engines running on LNG.

Result of the investigation is that for five out of eight cases in which refuse collection vehicles with a first generation Euro VI diesel engine were employed in different representative conditions, NO_x emissions were higher than the limit value that accounts for the official European on-road emissions test for heavy-duty engines. For three out of the five cases the NO_x emissions was substantially higher than the limit value.

It must be noted that the limit value accounts for the conditions as prescribed for the official European on-road emissions test. To date, real-world usage as a refuse collection vehicle is not included in these prescribed conditions.
The official on-road emissions test will be more demanding for heavy-duty engines entering the market as of September 2019. This is, amongst others, the result of the Dutch contribution to the working group discussions in Brussels. Emission tests will be needed to determine the impact on real-world emissions levels.

It was also proposed to bring the official on-road PEMS test in line with real-world usage of refuse collection vehicles. In Brussels, one only foresees such adaptions of the PEMS on-road test for the next large future step in emissions legislation, being Euro VII.

For one vehicle the level of the NO_x emissions remains below the level of the limit of the on-road test while driving in the city. This was a vehicle that collects large steel containers in the street. The engine load of this vehicle was generally higher, hence emission control systems were able to remain at operating temperature, resulting in lower NO_x emissions.

Background
Previous investigation [TNO 2016b], showed that Euro VI heavy-duty vehicles on average have significant lower pollutant emissions than older generations of vehicles. Measurements on relatively new long haulage trucks have on average shown very low NO_x emissions and also in other types of use Euro VI diesel vehicles have become cleaner than earlier generations.

For the EU certification of heavy-duty vehicles manufacturers need to execute a real-wold test on the road with PEMS (Portable Emissions Measurement Equipment). Both for type-approval and to check the in-service conformity.

Because of this test, regular Euro VI trucks have become much cleaner regarding NO_x in daily operation on the road.

The investigation also showed that in urban use some vehicles are not as clean as one can expect based on the standard. It was therefore recommended to test the emissions of such vehicles in city application. The tests could point out whether Euro VI requirements are effective to achieve low NO_x emissions for all representative conditions of use. The recommendation was followed up by testing the NO_x emissions of nine refuse collection vehicles in daily operation.

Conclusions and recommendations
For refuse collection vehicles the real-world test still falls short and low NO_x emissions, especially in city operation, are often not achieved. Real-world operation of refuse collection vehicles exhibit typically low average driving speeds and consequently low engine loads. Mainly due to these circumstances the emission control system to reduce NO_x doesn't always reach its optimum working temperature and depending on actual operation, high NO_x emission may occur. Because on Euro VI diesel engines also efficient particulate filters are used, the emission levels of particulate matter are very low in the real-world [JRC 2018].

This information will be used by the Netherlands in the discussions about the test procedures with a goal to improve the procedures on this point. The obtained data is also used to update the national emission factors of heavy-duty vehicles.

NO_x emissions of eight diesel vehicles
The level of NO_x emissions of the measured refuse collection vehicles varies and depend on the way each vehicle is operated. During operation, NO_x emissions can rise strongly. Average NO_x emissions vary between vehicles and their operations from 0.4 g/km to 4.3 g/km. Expressed per unit of work delivered by the engine the emissions are 0.3 to 2.3 g/kWh for de vehicles running on diesel. The limit for the formal on-road test, which is only used as a reference is 0.69 g/kWh[4]. One of the eight vehicles had white deposits in the tail-pipe. This may have been caused by a problem with the SCR system. The results are excluded from the dataset because the deposit has resulted in false sensor values.

NO_x emissions of one LNG vehicle
One vehicle running on LNG (Liquefied Natural Gas) had an average NO_x emission of 1.5 g/km and 0.7 g/kWh.

Ammonia emissions
The ammonia emissions have been measured with an automotive sensor.
For most vehicles the average tail-pipe concentrations of ammonia are low and about 1 to 8 ppm on average. For two vehicles out of eight tested diesel vehicles, the measured ammonia concentrations were substantially higher, indicating an issue with the SCR system, but the measured levels are higher than the accurate range of the sensor (>20ppm). For one of the vehicles white deposits in the tail-pipe indicate a possible problem with the SCR system.

[4] The limit for the NO_x emission over an on-road test for heavy-duty engines and vehicles is the conformity factor of 1.5. This factor of 1.5 and applies to the NO_x limit of 0.46 g/kWh of the WHTC engine test: 1.5 x 0.46 = 0.69 g/kWh.

Influence of real-world usage of the vehicles on NO_x emissions levels
The average speeds vary strongly between the tested vehicles, from 6.4 to 26.5 km/h. At lower average speeds, below 15 km/h the NO_x emission of some of the tested vehicles tends to increase. This is caused by the lower average engine load under those conditions which in turn leads to cooling down of the SCR catalyst to below its working temperature. If the catalyst cools down depends mainly on the power demand of the engine. This phenomenon is known and widely reported.

For refuse collection vehicles, the engine power demand increases when the hydraulic system is activated to take in and compress the garbage. In some cases this can help to keep the SCR catalyst at its operating temperature even though the average speed of the vehicle is low. This means that NO_x emission also depend on the type of system installed.

After a cold start, the engine and the SCR catalyst need to warm up to their operating temperatures. Until reaching operating temperature the emission of NO_x is high. Because the amount of cold starts is low for refuse collection vehicles, the contribution of these cold start emissions to the total missions is relatively low. The contribution of the cold start to the average NO_x emissions is fort he tested vehicles 120 to 310 mg/km and respectively 5 to 23%.

Recommendations for the real-world test
The real-world NO_x emissions of Euro VI-certified engines can be higher than one might expect based on the type approval limit (0.46 g/kWh) and the limit for the on-road test (1.5 x 0.46 g/kWh). This is amongst others because refuse collection vehicles operate outside conditions (around 50%) controlled by the EU real-world test. An evaluation of the real-word data namely showed that engines regularly run with a low average power, lower than the threshold of 15 to 20% of maximum engine power. This is the level below which for the current[5] formal real-world PEMS test emissions are not taken into account fort the pas-fail evaluation. As of 2019[6] periods with an average power of 10 to 20% will be taken into account for the evaluation of the real-world PEMS test.

For the real-world test with PEMS there are separate trips for trucks and for buses. Because the test for buses has a long part of urban driving (70% of the test time), the test should be able to secure low emissions in urban use better than a trip with a very small part of urban driving as used for long haulage trucks (20% of the test time). For the real-world test, Euro VI engines of refuse collection vehicles are tested over a trip that is meant for long haulage trucks. This is because refuse collection vehicles are produced as regular trucks on which the special bodywork and auxiliaries are added later, often by a different manufacturer. This means that RCV’s are not tested in representative driving conditions. It is recommended that the EU regulation is adapted so that engines of heavy-duty vehicles that usually operate in urban driving are always tested with sufficient urban driving. For refuse collection vehicles the bus trip should be used.

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[5] Step A to C. Within Euro VI the four steps A to D are distinguished. Each comes with different requirements.
[6] Step D.

Customers who purchase refuse collection vehicles for typical use in cities could ask for a real-world bus test for the engine because that could be a better guarantee that NO_x emissions are low in city driving.
A customer may also consider the purchase of a vehicle with a smaller diesel engine because in that case the probability increases that the emission control systems remains at operating temperature.

Next to engines running on natural gas, which is currently the most common alternative for a diesel engine, refuse collection vehicles with new propulsion concepts gradually enter the market. These concepts may be interesting with respect to local emissions but still it must be investigated whether these concepts can replace a fleet of conventional vehicles. The concepts comprise amongst others full electric RCV's, the hydrogen-prepared hybrid variant and the diesel-electric hybrid variant that can be run in zero emission mode locally.

Contents

1 Introduction

Background

Contracted by the Ministry of Infrastructure and Water Management, TNO runs the in-service emissions testing program for heavy-duty trucks and buses.
In this program TNO measures on a regular basis the tail-pipe emissions of these vehicles, to investigate how clean they are in the real-world, to monitor the effectiveness of current EU emissions regulation and to screen the emissions of vehicles in-service. Data obtained within the programme leads to valuable insights in environmental performance of heavy-duty vehicles in the real-world and its trends.

Modern Euro VI engines have become clean on average. The emission of criteria pollutants NO_x and particulates has reduced drastically from Euro V to Euro VI [TNO 2016b], [JRC 2018]. This is due to the improved EU emission legislation, which requires real-world testing (PEMS) and particle number testing which has led to the development and application of very efficient emission reduction systems on board of heavy-duty vehicles. To reduce the NO_x emissions of a diesel engine, a generally very efficient Selective Catalytic Reduction (SCR) system is used. When such a system is working on operating temperature it is able to convert the NO_x in the exhaust gas of a diesel engine into harmless substances with efficiencies over 90%. However, when the system is below a specific operating temperature, the efficiency of the SCR decreases rapidly and the NO_x emissions increase as a result. The heat needed for the SCR catalyst to reach and maintain its operating temperature needs to come from the hot exhaust gas of the engine. At high engine loads the exhaust gas contains enough heat to keep the SCR warm, but at low engine loads the exhaust gas is cooler and at a certain point may not contain enough heat to keep the SCR at its working temperature. Hence, low load, low speed operation of modern Euro VI diesel engines with SCR may lead to an increase of NO_x emissions. This effect is widely reported.

Because of the nature of this problem, the risk mainly exists for applications and situations were operations at low average speeds and low engine loads are common, such as for urban driving with lots of stop-and-go driving, traffic jams as happens for city buses, distribution vehicles, and also for refuse collection vehicles. Given this risk, questions rose about the emission levels of NO_x of Euro VI refuse collection vehicles (RCVs) in real-world operation. In the Netherlands 3941[7] refuse collection vehicles are registered of which 1017 (26%) have Euro VI certified engines.

In addition, the emission database needs to be updated with data of Euro VI diesel refuse collection vehicles so that new emission factors can be determined from a reliable set of real-world emissions data. Among the heavy-duty vehicles driving in cities busses and trucks, are important categories. There are 3941 RCVs compared the total number of 200,000 heavy-duty vehicles in the Netherlands.

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[7] RDW open database February 2018, count of vehicles marked as ‘vuilniswagen’ and GVW >3.5t (refuse collection vehicle).

Goal of the real-world emissions testing programme on refuse collection vehicles
The goal of the measurements is to determine the real-world NO_x emission levels of Euro VI heavy-duty refuse collection vehicles. This information is used to get insight in the behaviour of the NO_x emissions in relation to real-world operation and conditions and to monitor the effectiveness of the EU. The information is also used to update the Dutch emissions factors for those vehicles.

Approach
To determine the real-world NO_x emissions of refuse collection vehicles, eight of these vehicles were equipped with a Smart Emission Measurement System (SEMS). SEMS measured the emission level of the exhaust gas NO_x and a number of other parameters from the vehicle autonomously, over the daily routines of the refuse collection vehicles.

2 Emissions measurement programme

The emissions measurement programme aimed at determining the real-world NO_x emission levels of refuse collection vehicles. SEMS, a sensor-based emission method developed by TNO, was used to measure the tail-pipe NO_x emissions and a range of vehicle/engine parameters to be able to characterize the typical operation of RCVs. In this way, for the group of vehicles, days or weeks of data per vehicle could be collected. The vehicle sample consists of seven vehicles with Euro VI diesel engines and one Euro VI LNG engine.

2.1 Smart Emissions Measurement System

The emission measurements on the road were performed using a sensor-based Smart Emission Measurement System (SEMS) [TNO 2016a]. This system uses an automotive NO_x sensor, GPS and a data-acquisition system to record the sensor data and CAN data from the vehicle and engine at a sample rate of 1Hz.
The system can operate autonomously and wakes up at ignition/key-on of the vehicle. The system can be stowed away so that normal operation is not hindered by the measurement. The recorded data is send hourly to a central data server.

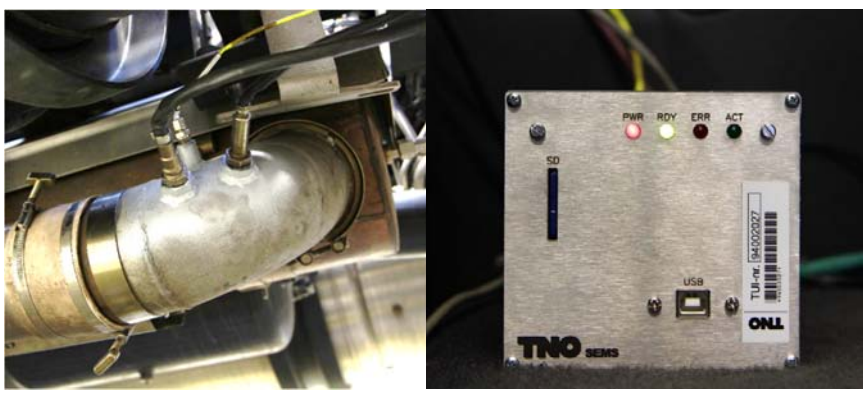

Figure 1: SEMS. Left, calibrated NO_x-O_2 sensor, NH_3 sensor and temperature sensor mounted in the tail-pipe. Right, autonomously running data recording unit with hourly data transmission to a central server via GPRS.

The raw data on the central server is post-processed automatically to filter and check the data. Mass-emissions are calculated combining sensor data and CAN data such as manifold-air flow, fuel rate, engine torque, and sensor O_2 concentration were possible. Testing routines contain the calibration of the NO_x and O_2 signal of the sensors. All raw measured concentrations of the sensor are corrected on the basis of these calibrations. For the vehicles for which no sufficient engine data was available to calculate the work specific emissions, an estimation of the average brake specific fuel consumption and CO_2 emission of a diesel engine was used to estimate the vehicle's emissions in g/kWh.

[TNO 2016a]: "…Since this method is not certified, and relies on signals of (in principle) unknown accuracy and origin, the results and sensors are continuously calibrated and compared with results of laboratory testing in cross-validation experiments. The accuracy and reproducibility of measurements with our current generation of SEMS equipment is in most cases within a bandwidth of 10%, and in many cases even within a much smaller bandwidth of a few percent..”.

Further information on the measurement method used by TNO and the accuracy can be found in [TNO 2016a].

2.2 Vehicle selection

Fleet of refuse collection vehicles in the Netherlands.
In the Netherlands 3941[8] refuse collection vehicles are registered of which 1017 (26%) have Euro VI certified engines. With 94% by far the largest share of vehicles has a diesel engine, followed by a 5% share of vehicles with a natural gas engine. DAF is the brand with the highest share of vehicles in the fleet of RCV’s.

Table 1: Fuel. Vehicles marked as ‘vuilniswagen’ (RCV). Source RDW opendata February 2018.

Fuel	Count	Percentage
Benzine	10	0%
CNG	199	5%
Diesel	3709	94%
Electricity	8	0%
LNG	14	0%
LPG	1	0%
Total	**3941**	

Table 2: ‘Euro class’. Vehicles marked as ‘vuilniswagen’ (RCV). Source RDW opendata February 2018.

Euro class	Count	Percentage
Euro 0	65	2%
Euro I	26	1%
Euro II	212	5%
Euro III	619	16%
Euro IV	96	2%
Euro V	840	21%
EEV	887	23%
Euro VI	1017	26%
(blank)	179	5%
Total	**3941**	

[8] RDW open database February 2018, count of vehicles marked as ‘vuilniswagen’ and GVW >3.5t (refuse collection vehicle).

Table 3: Brand. All vehicles and Euro VI. Vehicles marked as 'vuilniswagen' (RCV). Source RDW opendata February 2018.

	All		Euro VI	
Brand	**Count**	**Percentage**	**Count**	**Percentage**
DAF	2422	61%	536	53%
SCANIA	465	12%	160	16%
VOLVO	404	10%	176	17%
MERCEDES-BENZ	270	7%	56	6%
IVECO	157	4%	54	5%
MAN	67	2%	9	1%
GINAF	64	2%	8	1%
Rest	92	2%	18	2%
Total	**3941**	**100%**	**1017**	**100%**

Refuse collection vehicles come in various types. The construction of an RCV depends amongst other things on how the refuse is collected, and what type of refuse is to be collected. For regular household refuse in the Netherlands, roughly three types are in use: a rear loader for garbage bags, a rear or side container loader that lifts small containers and a container loader that lifts large containers which are emptied on top of the vehicle. The large containers are from central refuse collection points in cities. Other special types exist, such as a simple open container that is used to collect bulky household waste. Besides RCVs special service vehicles are used as well, such as container cleaners.

The data set contains five small container side or rear loaders, one large container top loader, one regular garbage bag rear loader, a container cleaner, and one vehicle that simulated an open container truck. The latter vehicle (vehicle code IV161) was a normal rigid truck, which underwent a use pattern and load to simulate bulky household waste collection. This was done by following an RCV in normal service. The tested vehicle had an engine, gearbox and empty mass equal to that of the RCV that was followed. Because no crane was present to hoist heavy pieces of garbage into an open container, the test results cannot be regarded as fully representative for the given operations as occasional crane operation is missing in the test.

Test vehicles
Eight of the vehicles run on diesel. Most brands are covered with the exception of Volvo. One of the test vehicle has a Euro VI natural gas (LNG: Liquefied Natural Gas) engine. The engines are certified as Euro VI step A, which means the engines are first generation Euro VI engines.

The test vehicles are a good representation of the Dutch fleet of refuse collection vehicles with a Euro VI diesel engine. Based on the results of this single vehicle with a gas engine no general conclusions can be drawn about the real-world emissions level of Euro VI engines running on natural gas.

For all tested vehicles the malfunction indicator light was off at the general vehicle check that is performed before and after the test period.

The vehicles ran during normal operation and were fuelled according to the operators with regular diesel fuel (EN590 diesel) and LNG. The exact compositions of the fuels are not known.

Table 4: Vehicle specifications. All vehicles are Euro VI step A of B certified. Eight run on diesel, one on LNG (Liquefied Natural Gas).

TNO vehicle code	Vehicle	Fuel, EU emission norm	Type	Mass empty in running order GVW Test mass [kg]	Max. Engine power [kW]	Emission control	Axle config.
SC125	Scania	Diesel Euro VI-A	Small container rear loader	15790 26500 Varying	206	EGR, SCR	6x2
DA141	DAF	Diesel Euro VI-A	Small container rear loader	16390 27000 Varying	210	EGR, SCR	6x2
SC149	Scania	LNG Euro VI-A	Small container side loader	14480 27500 Varying	206	TWC	6x2
IV153	Iveco	Diesel Euro VI-A	Small container rear loader	15306 27500 varying	228	SCR	6x2
MB156	Mercedes-Benz	Diesel Euro VI-A	Hook loader/cleaner	11655 35000 varying	290	EGR, SCR	8x4
DA157	DAF	Diesel Euro VI-A	Rear loader	16290 27000 varying	210	EGR, SCR	6x2
IV161[1]	Iveco	Diesel Euro VI-A	Rigid + box	7110 14000 9810	185	SCR	4x2
GI172	Ginaf	Diesel Euro VI-A	Hook loader / Large container top loader	17840 29500 varying	235	SCR	6x2
DA173	DAF	Diesel Euro VI-A	Small container rear loader Plugin-electric garbage processing unit	16550 27000 varying	210	EGR, SCR	6x2

EGR: Exhaust Gas Recirculation, SCR: Selective Catalytic Reduction, TWC: Three-Way Catalyst.
[1]Vehicle ‘chased’ an RCV during normal service. Due to the fact that the vehicle had no crane to add load during the trip, the results are not representative.

Figure 2: Pictures of five refuse collection vehicles and a container cleaner (middle right) that were tested.

3 Results

3.1 Data set with real-world RCV operation

The data set contains data of real-world operation of 6 refuse collection vehicles, one rigid truck and one container cleaner. Table 5 shows the test trip characteristics per vehicle. A graphical representation of the speeds driven is included for the first 5.5 hours in Figure 3. As can be seen, the speed profiles are vastly different among the vehicles.

Average speeds range from 6.4 to 26.5 km/h. Shares of idling are generally large from 30 to 60%. The engine load, here expressed as a percentage of maximum engine power, ranges from 7%, which is very low, up to about 21%.

> Given the wide spread in operational conditions of the tested refuse collection vehicles in daily operation, the emissions levels of individual vehicles cannot be compared.

Table 5: Overview of trip data.

TNO vehicle code	Time [h]	Distance [km]	Average speed [km/h]	Average engine power [%]	% time speed = 0, engine running [%]	% cold engine T coolant <70C [%]	Type of operations
SC125	69.4	685	11.1	n.a.	54	n.a.	Domestic refuse, urban
DA141	84.8	1160	13.6	12	50	7	Domestic refuse, urban
SC149	72.2	1054	14.6	19	48	7	Domestic refuse, urban
IV153	57.5	1353	23.4	21	30	5	Domestic refuse, urban and rural
MB156	21.1	559	26.5	11	53	10	Container cleaning, urban and rural
DA157	107	1509	18.5	17	45	3	Domestic refuse, urban
IV161	7.5	48	6.4	7	60	n.a.	Domestic coarse refuse, urban
GI172	66.5	730	10.1	15	48	5	Domestic refuse, urban, underground container
DA173	291	4469	15.4	15	40	9	Domestic refuse, urban

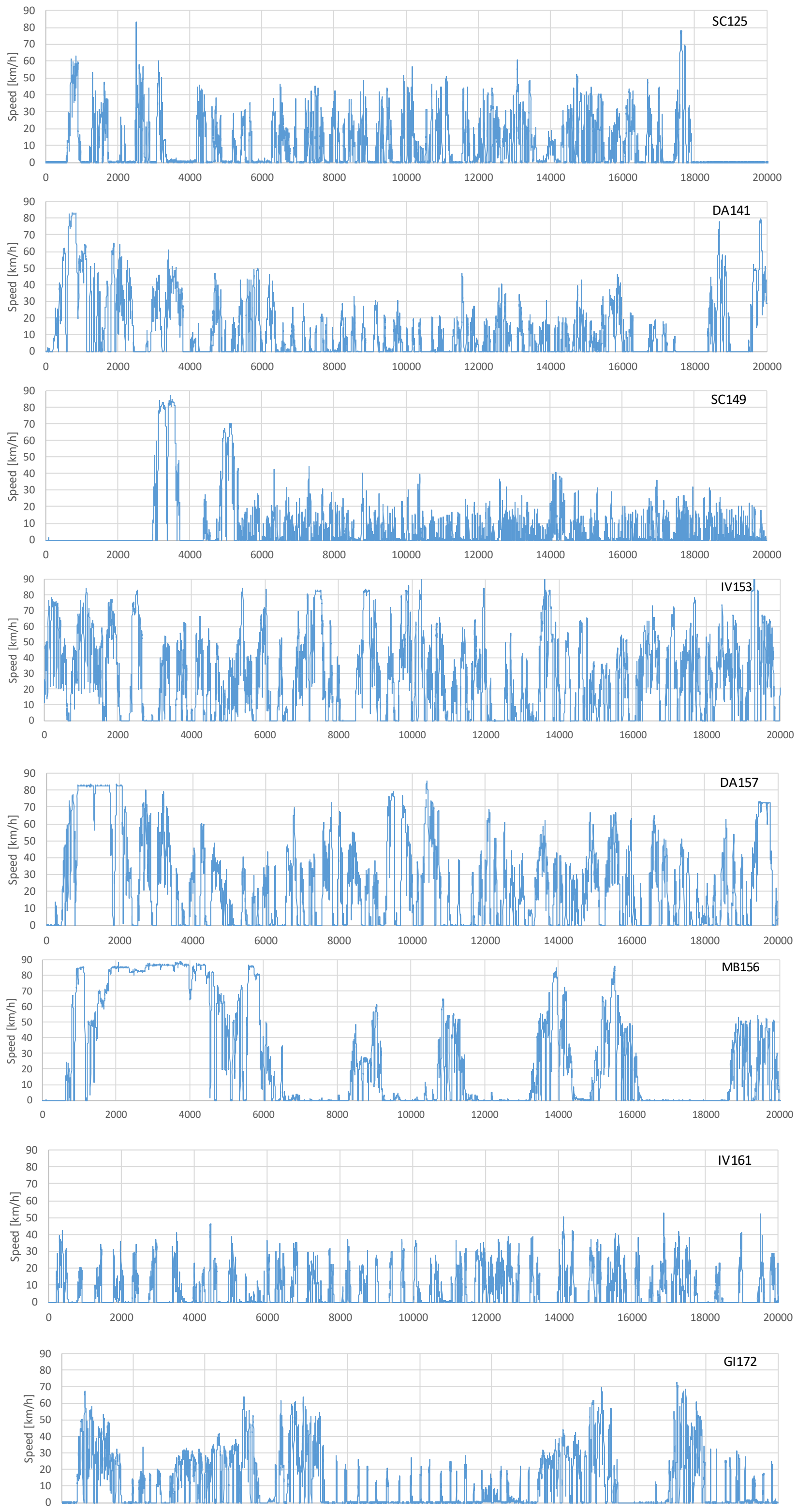

Figure 3: Examples of the speed profiles of the first 5.5 hours of real-world operation showing very different speed profiles for each of the nine vehicles tested.

3.2 Case vehicle DA173

When the measurement instruments of vehicle DA173 were dismounted, a white deposit has been observed covering parts of the inner tail-pipe and the sensors of the SEMS system.

The white deposit probably has caused false NO_x sensor readings, especially at higher exhaustgas temperatures above 200 °C. A sensor check with calibration gas at ambient and the sensor at operating temperature showed a good sensor response comparable to that of a fresh NO_x sensor. However, when hot air (200-400°C) was blown onto the sensor nose, the sensor showed high NO_x readings up to 2700 ppm until all white deposit finally disappeared. The values obtained during the emissions test on the vehicle are probably influenced by the deposit, especially when the exhaust gas was above 200 °C when the deposit starts to decompose. Although the measurement with the NO_x sensor has been influenced by the deposit, the results indicate that these emissions are higher than the level of 0.69 g/kWh that accounts as a limit for the formal real-world test with PEMS.

The white deposits in the tail-pipe of the vehicle may have been formed from urea that is not completely decomposed to ammonia but to crystal-like by-products of incomplete thermolysis and hydrolyses of the urea. No lit MIL has been observed nor any error codes have been reported by OBD that relate to the exhaust aftertreatment system.

Figure 4: White deposit was observed in the tail-pipe of vehicle DA173.

3.3 Trip average NO_x emissions

The average NO_x emissions were calculated in g/kWh and g/km for all data and for data where the engine was warm. A warm engine is defined here as an engine with a coolant temperature higher than 70°C.

The NO_x emissions vary a lot. Average NO_x emissions of driving with a warm engine vary from 0.3 to 2.3 g/kWh and 0.3 to 4.2 g/km and go up to respectively 9 g/kWh and 10 g/km for one operation-vehicle combination. The latter result is not regarded as fully representative, see paragraph 2.2.

At lower average speeds the NO_x emissions tend to increase, but not for all vehicles/operations. Table 6 shows the NO_x emissions and the average speed for each vehicle tested. The relation between the two is also demonstrated in Figure 7 and Figure 8.

Table 6: NO_x emissions in g/kWh and g/km for all daily operations, including cold start and operation with a warm engine only (coolant temperature higher than 70 °C).

TNO vehicle code	Fuel, EU emission norm	Average Speed [km/h]	NO_x All [g/kWh]	NO_x Warm [g/kWh]	NO_x All [g/km]	NO_x Warm [g/km]
SC125[1]	Diesel, Euro VI	11.1	0.3	n.a.	0.6	n.a.
DA141	Diesel, Euro VI	13.6	2.3	2.3	4.3	4.2
SC149	LNG, Euro VI	14.6	0.7	0.5	1.5	1.2
IV153	Diesel, Euro VI	23.4	0.7	0.5	1.3	1.1
MB156	Diesel, Euro VI	26.5	0.3	0.3	0.4	0.3
DA157	Diesel, Euro VI	18.5	1.2	1.2	2.3	2.1
IV161[2]	Diesel, Euro VI	6.4	n.a.	8.9	n.a.	10.2
GI172	Diesel, Euro VI	10.1	0.9	0.8	3.0	2.8
DA173[3]	Diesel, Euro VI	15.4	Test error			

[1] No CAN data available. Brake specific emissions are estimated based on an assumed brake specific fuel consumption of 230 g/kWh.

[2] This vehicle was tested under worst case conditions which can't be regarded as fully representative. The data set also contains no cold engine operations.

[3] The SEMS emission sensors were fouled. The measured concentrations of NO_x and NH_3 have been affected by the fouling.

Several mechanisms affect NO_x emissions levels:

SCR catalyst temperature

All Euro VI diesel engines use either EGR combined with SCR or only SCR to reduce the engines NO_x emissions. An SCR catalyst needs to have a certain operating temperature before it can actively reduce NO_x using the reagent ureum or AdBlue. The catalyst heats up by the exhaust gas of the engine. A vehicle driving at a higher engine load has higher exhaust gas temperatures and can heat up a catalyst quicker and to a higher temperature. Vice versa, a diesel engine that is idling, has a low exhaust temperature (80-100 °C) which may cool down an SCR catalyst below the needed working temperature. This can also happen at low loads when driving. Depending on the type of catalyst, the catalyst temperatures need to be at least around 170-200 °C before it can reduce NO_x. From further analysis of the data it appears that for most of the tested vehicles a high enough temperature is reached around average speeds of about 15-20 km/h.
A large share of RCV operate at average speeds in this speed range, some below this speed range and some at higher speeds (see Figure 9).

One diesel vehicle was operated at winter time, the ambient temperature was around 0-2 °C, which are almost worst-case conditions. Additionally, this vehicle (IV161) has a very low average speed due to its typical operation of bulky refuse collection (the vehicle is stationary for a long time during loading). All in all, the conditions resulted in very high NO_x emissions of about 10 g/km, indicating an inactive SCR system.

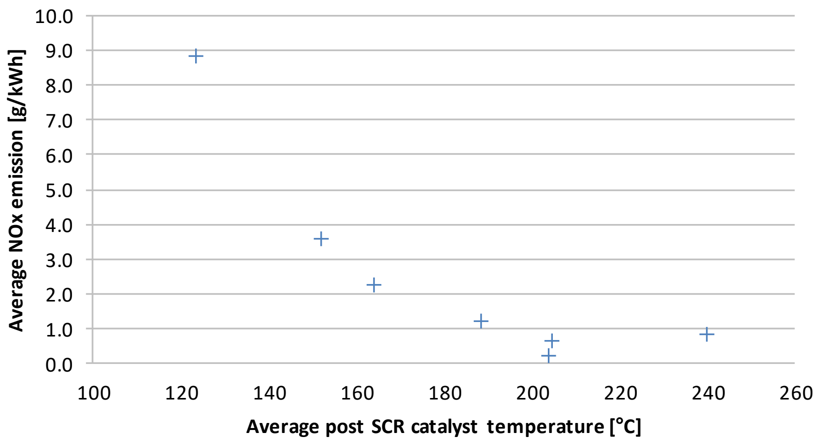

Figure 5: Average tail-pipe NO_x emissions and post SCR catalyst temperature of seven of the tested diesel vehicles. Clearly, NO_x emissions increase when the catalyst temperature decreases.

SCR thermal inertia
Catalysts have a thermal inertia which means that it takes time to warm up and it also takes time to cool down when the engine does not produce much exhaust heat, for instance when the vehicle is idling. How much NO_x is actually reduced at a certain moment therefore also depends on the history: what happened before that moment. For an effective SCR catalyst operation it is beneficial that periods of low speed and low load be preceded by periods with higher speeds and loads. Frequent higher load operation may help to keep the SCR catalyst warm enough. Additionally, catalysts can buffer urea and NH_3. Urea which has been dosed to the catalyst at temperatures above about 200°C, can take care of NO_x conversion in the temperature range of 150-200°C (even when there is no urea injection in this period). Some vehicles clearly showed low average NO_x emissions due to intermittently driving low loads and speeds and higher loads and speeds.
Such conditions occurred where a vehicle serviced a few streets in small village after which it drove via rural roads to the next village.

Power take-off
Engine load and thus exhaust temperature also depends on the use of auxiliaries. RCVs often use auxiliary power from the power take-off (PTO) of the engine to drive a hydraulic system that is needed to operate the garbage press, a crane or lifting system that hoists the containers and a tipper system. For the tested loaders the average power for the PTO during PTO operation was about 4-10% of the maximum engine power.

The exhaust temperature is then sufficiently high, due to a relatively high torque (at low engine speed). In one case the average vehicle speed of the operation was very low but a relative high power demand from the PTO made that the engine ran at a sufficiently high load on average to keep the SCR catalyst warm during long periods with lots of stops for garbage intake.

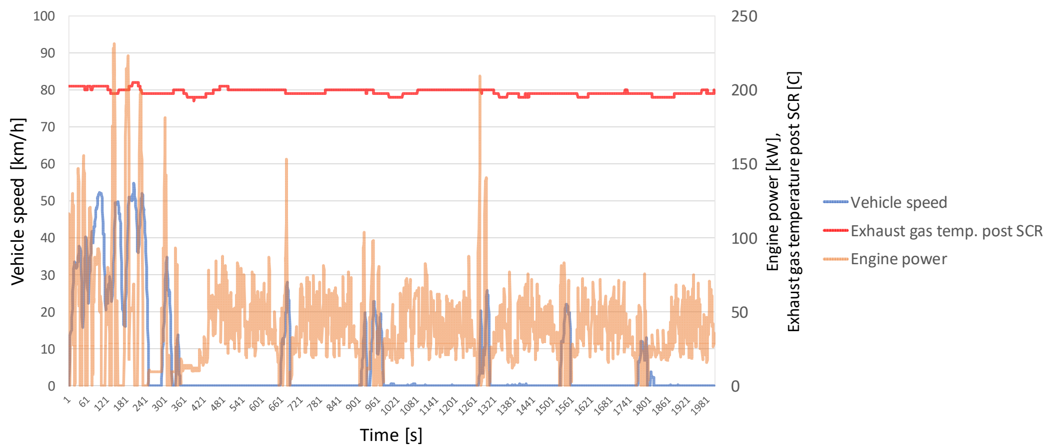

Figure 6: A period of real-world operation of one of the vehicles. This vehicle uses a high level of engine power in its operation required for the power-take-off. Despite the low average speed, the SCR catalyst does not cool down due to this additional load.

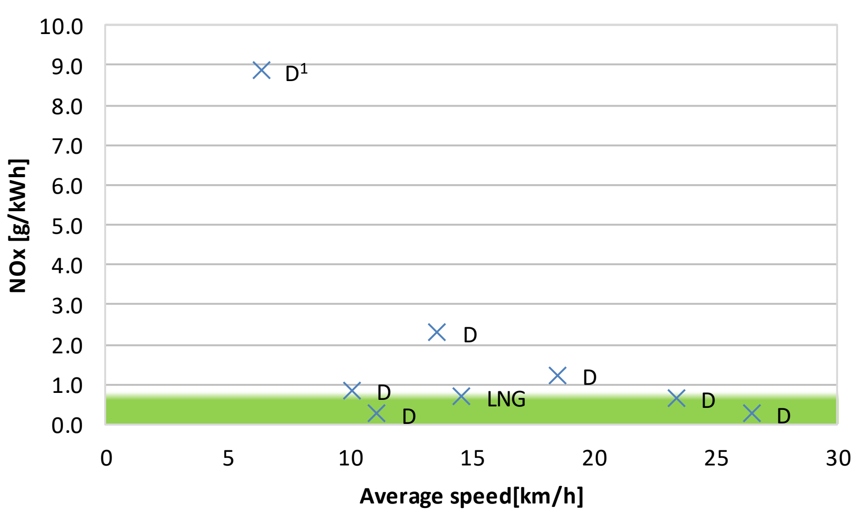

Figure 7: Average NO_x emissions in g/kWh over all test data, per vehicle. The top of the green area represents a NO_x emission level of 0.69 g/kWh, which is the same level as the limit that accounts for a PEMS test (real-world type-approval and in-service conformity test) for heavy-duty engines and vehicles. The limit for in-service conformity is composed of the limit for a WHTC engine test (0.46 g/kWh) and a conformity factor of 1.5 applied to this limit (0.69 = 1.5 x 0.46). Vehicle D[1] is tested under worst case conditions which can't be regarded as representative, see paragraph2.2.

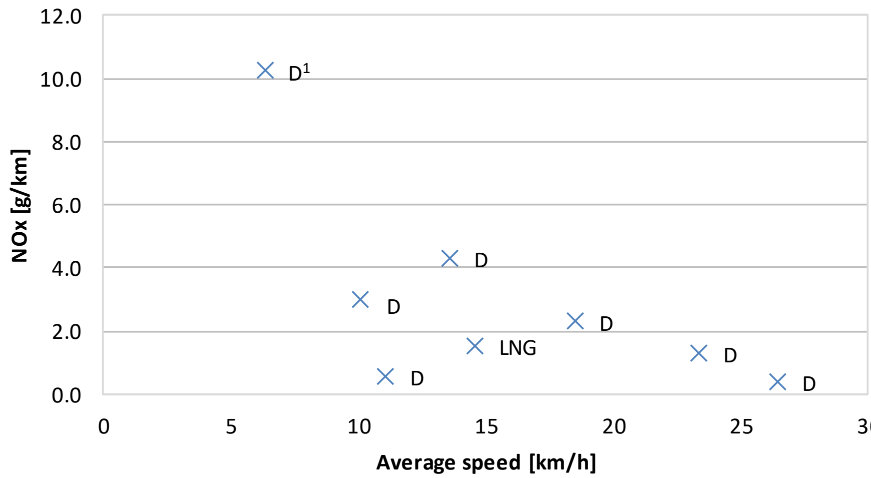

Figure 8: Average NO_x emissions in g/km over all test data, per vehicle. Vehicle D[1] is tested under worst case conditions which can't be regarded as representative, see paragraph 2.2.

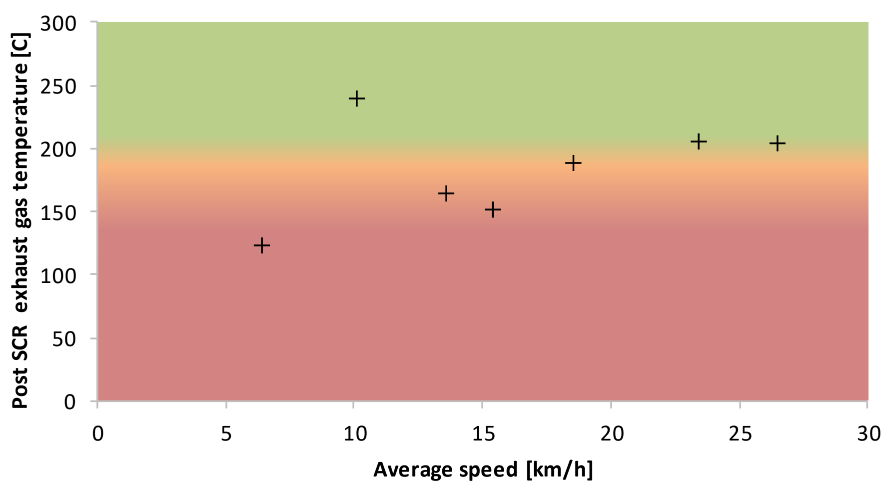

Figure 9: Post SCR exhaust gas temperature for all diesel vehicles. The average temperature decreases towards lower operational speeds with exception of one vehicle (#2 from the left). The engine of this vehicle uses a very high power for the power take-off when the vehicle is loading garbage. For Euro VI engines SCR activity becomes critical below 180-200 °C. Below 160-180, °C SCR is generally inactive.

3.4 Average NO_x emissions over the speed range

The NO_x emissions were averaged in intervals of vehicle speed to reveal possible dependency on speed and engine load. It should be noted that the largest portion of driving, due to the typical operation of most refuse collection vehicle, is in the lower speed range of 0-50 km/h.

Higher speeds occur in the case small villages are to be served from garbage depot or when a vehicle that serves a large city drives via large main routes through the city to the depot, which is often located at the outskirts of the city.

Regarding the NO_x emissions over the speed range, a very mixed picture arises, see Figure 10. Some vehicles have higher emissions at lower speeds, while for others this trend is opposite.

The diesel-powered vehicle with the lowest NO_x emissions at the low speeds (GI172) showed a very high engine load at garbage loading situations. The engine probably needed to deliver substantial amounts of power to (take in and) compress garbage. The additional power proved to be enough to keep the SCR system at a sufficiently high working temperature. The vehicle with LNG engine (SC149) showed more or less the same trend. For this engine, some NO_x peaks were measured at accelerations starting from speeds over 50km/h, but the share of driving at those speeds was low for this vehicle.
Another vehicle that has low emissions only served small villages (MB156). Between short periods with low speed garbage collection where a few streets were served, the vehicle drove substantial portions at high speeds to get to the next village. Sufficient heat was stored in the SCR during those periods and during garbage compression, all together leading to an SCR warm enough to reduce the engine's NO_x emission with high efficiency.

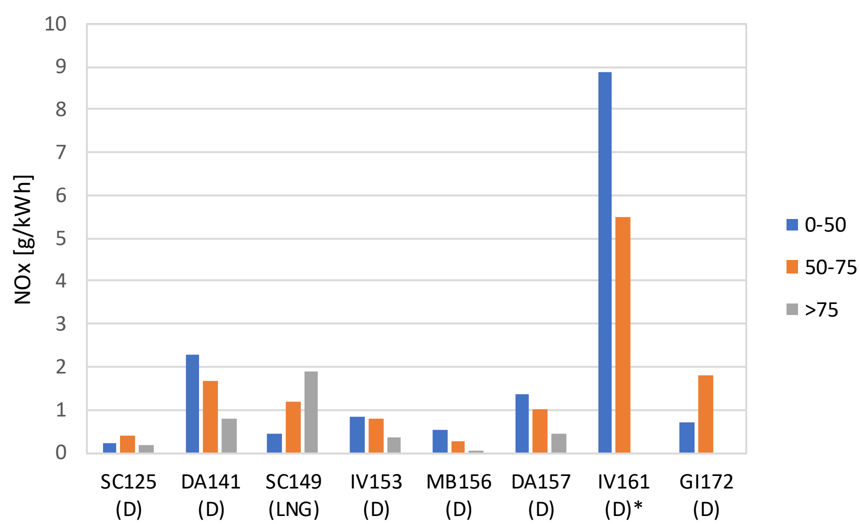

Figure 10: Average NO_x emissions in g/kWh per speed range (in km/h). *Vehicle IV161 is tested under worst case conditions which can't be regarded as full representative, see paragraph 2.2.

3.5 Contribution of cold starts

The cold start and the period just after it are relevant for emissions. The reason is that usually a cold engine produces higher emissions, while the emission control system is not yet at operating temperature and thus does not effectively reduce those emissions. For this investigation, the cold and warm operation have been identified based on the engine coolant temperature.

An engine coolant temperature of above 70°C is considered as warm engine operation and operation below this temperature is considered 'cold engine operation'. This includes the cold start itself.

Among the tested RCVs, cold engine operation makes up about 3 to 7% of the total operation time (see Table 7). There is one exception of a vehicle that has a 10% share of cold engine operation.

Table 7: Fraction of time with cold engine operation of total operation. Cold is defined as coolant temperature <= 70 °C.

	Fraction coolant temperature <=70 °C
DA141 (D)	7%
SC149 (LNG)	7%
IV153 (D)	5%
MB156 (D)	10%
DA157 (D)	3%
GI172 (D)	5%
DA173 (D)	9%

The contribution of the emissions under cold engine conditions to the total emissions is 120 to 310 mg/km for the tested vehicles. This equals 5 to 23% of total NO_x emissions, dependent on the vehicle. The percentage also depends to a large extent on the emission level under warm engine emissions.

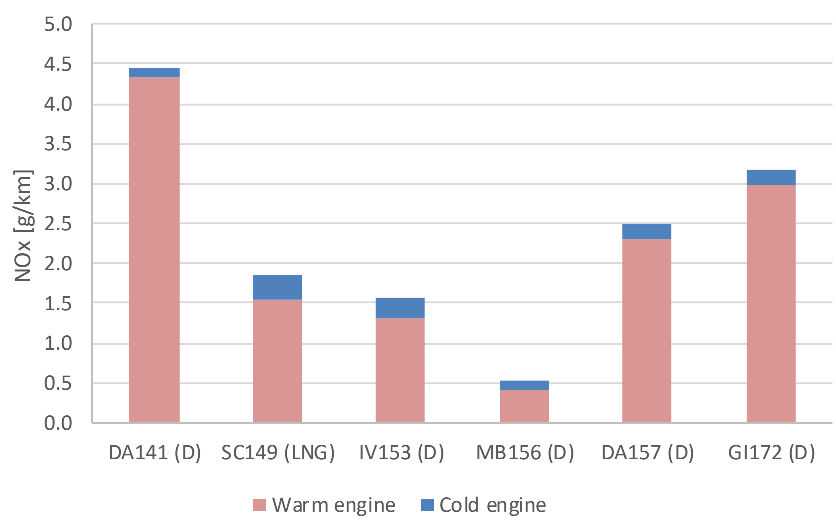

Figure 11: NO_x emissions under cold and warm engine operation.
Cold: engine coolant temperature <=70C.
Warm: engine coolant temperature >70C.

3.6 Half-hour average NO_x emissions

The emissions of NO_x were also determined over short periods of time. This is relevant in addition to the average urban emissions, because temporary emission excursions may contribute a lot to local ambient concentrations, e.g. at the street level. The average NO_x emissions were calculated for a moving time window of 30 minutes.

The results were binned: 0-1 g NO_x/kg CO_2, 1-2 g NO_x/kg CO_2, and so on. Figure 12 shows the frequency distribution of the bins for each vehicle. The graph can be interpreted as follows: e.g. for the diesel-powered vehicle MB156, in 80% of the 30-min windows the average NO_x emission was between 0 and 1 gram per kilogram of CO_2.

Just as observed for the average emissions, the vehicles show different behaviour. However, the half-hour average emissions vary even more, also within the operation of a vehicle.

The analyses show that, depending on the vehicle, 20% up to over 95% of the 30-minute windows have higher emissions than 1 g NO_x/kg CO_2[9], a value which is comparable to an emission level of 1.5 times the type-approval limit over an engine test. The DA141 and DA157 vehicles run spend a lot of time in the 2 - 5 g NO_x/kg CO_2 range, while the MB156, the IV153, the GI172 and the LNG-powered SC149 spend most time in the 0-1 g/kg range.

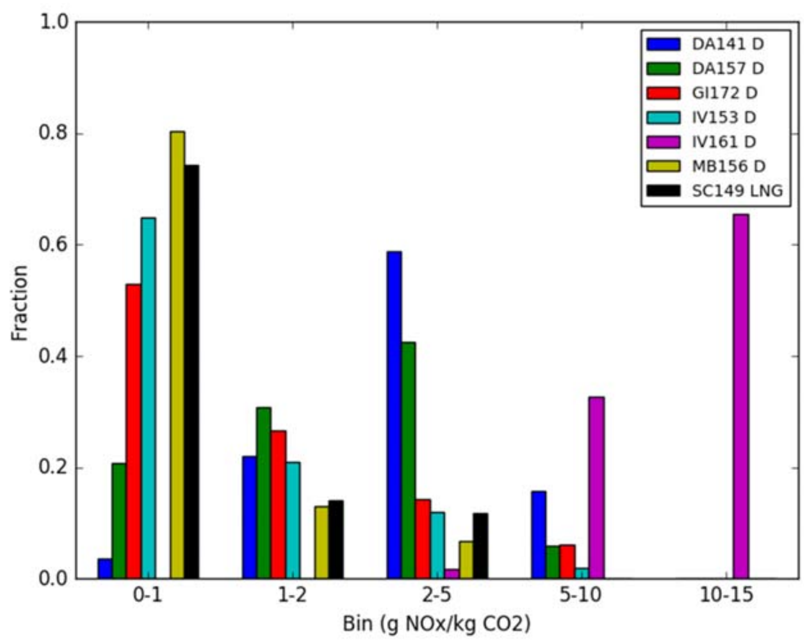

Figure 12: Frequency distribution of 30-min window average emissions of NO_x for all vehicles. 1 gNO_x/kgCO_2 is comparable to 0.69 gNO_x/kWh. Vehicle IV161 is tested under worst case conditions which can't be regarded as fully representative, see paragraph 2.2.

The frequency distribution for all vehicles together is displayed in Figure 13. The red line represents the sum of all windows of all vehicles.

[9] 0.46 g NO_x/kWh x 1.5 = 0.69 g NO_x/kWh. For 1 kWh, approximately 200-230 g of fuel is required (dependent on the use of the vehicle and the engine). 1 kg of fuel leads to the emission of 3.17 kg of CO_2. 0.69 / 0.215 / 3.17 = 1.0 g NO_x/kg CO_2.

Clearly visible is the 10 to 20% time share where no or very low average emissions occur. Across all vehicles, 40% of the 30-min windows have an average emission level over 1 g NO_x per kg CO_2.

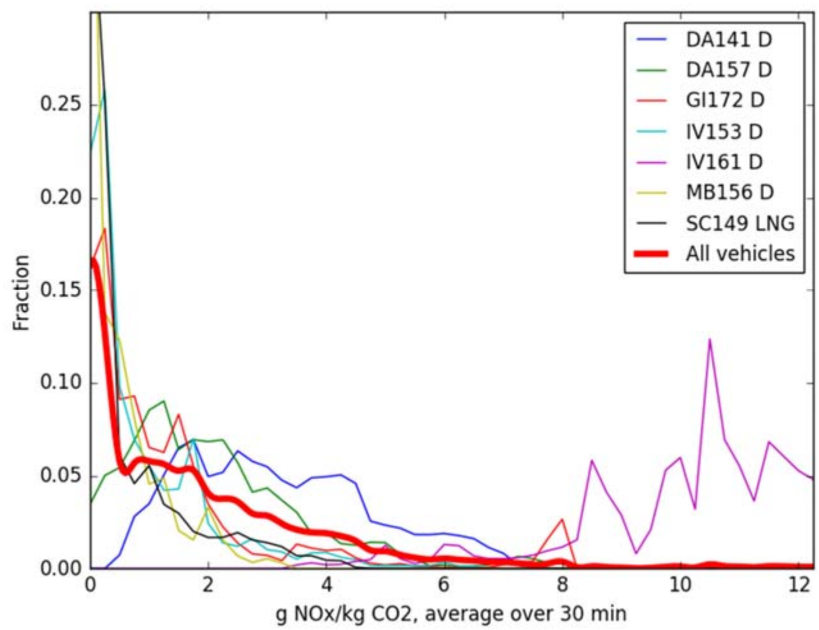

Figure 13: Frequency distribution of 30-min window average emissions of NO_x for all test data combined. Vehicle IV161 is tested under worst case conditions which can't be regarded as representative, see paragraph 2.2.

The previous graphs show that the actual emission levels vary over time.

One of the possible parameters that influence the actual emission levels is the speed. Higher average speeds imply higher average engine loads.
The instantaneous (per-second) emissions of NO_x per kg CO_2 were binned as a function of the average speed driven. Figure 14 shows the results.

It can be observed that in the speed range that refuse collection vehicles operate most of the time (0-30 km/h), the emission levels vary a lot among the vehicles. Some of the vehicles have higher emission levels at low speeds. At higher speeds the emission levels per kg CO_2 decrease. The GI172 has gradually increasing emission levels over the speed range, peaking at over 11 gNO_x/kg CO_2 for highway speeds.

Note that because of physical and chemical processes, history effects occur in the emission behaviour of especially the diesel-powered vehicles with an SCR catalyst. Therefore, the window emissions are dependent on what happened before the start of the window, and can vary to a large extent as a result.

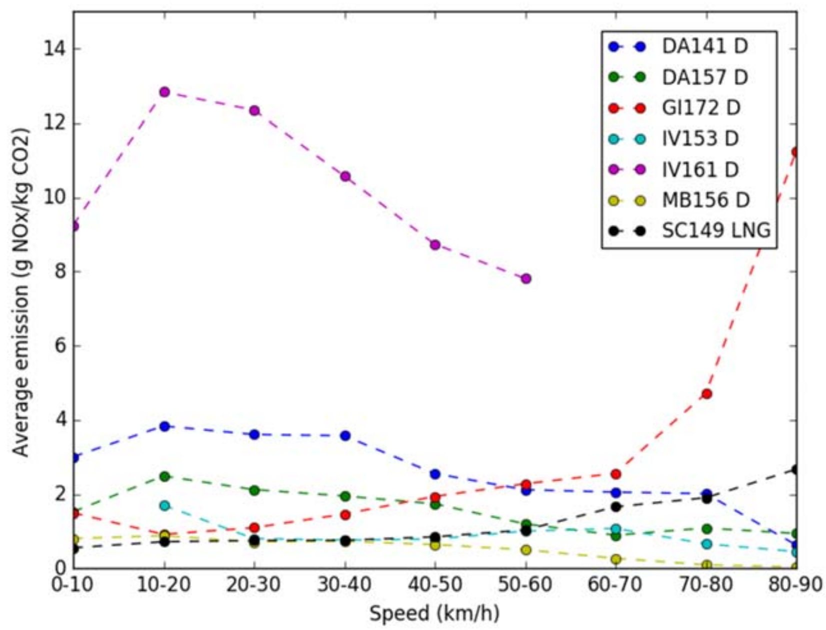

Figure 14: Speed binned emission data of NO_x per kilogram of CO_2. Vehicle IV161 is tested under worst case conditions which can't be regarded as fully representative, see paragraph 2.2.

3.7 Power levels and coverage by the EU real-world emission test for type-approval and in-service conformity

The average engine power has a large effect on exhaust gas temperature and thereby on the SCR system's ability to reduce NO_x emissions. In the EU emission legislation for heavy-duty vehicles and engines, and more specific for the real-world PEMS test for type-approval and in-service conformity, the scope for evaluation is limited. For the current requirements (582/2011/EC, until 'step C') there is a threshold for engine power which is 20% of the maximum engine power with an extension to 15%. This means that so-called Moving Averaging Windows of the PEMS test with average engine power in these windows below this power threshold are to be excluded from the test evaluation. In this way periods with a low average power are not part of the scope of the test evaluation. An amendment to this regulation called 'step D' contains a revision of the threshold for engine power from the 20 to 15% range to a fixed threshold of 10%. This requirement enters into force as of 1 September 2019 and applies for new vehicles.

Using the data of the RCVs it was investigated how much of the operational time falls outside the scope of the requirements for in-service conformity when average power is concerned. To approximate the EU pass-fail evaluation method that uses moving averaging windows with a fixed reference quantity (work or CO_2), windows with a fixed time of 30 minutes were used instead.

For all the vehicle-operation combinations different distributions of average engine power emerge from the data, which can be observed from Table 8.

This exercise demonstrates that for refuse collection vehicles under real-world operation substantial amounts of this operation are not in the scope of current evaluation of the real-world PEMS test: For most of the tested refuse collection vehicles this condition happens more than half of the time of normal operation. But also for reduced power threshold to be used in the future for 'step D' (10%), still substantial shares of real-world driving is excluded from evaluation.
On average during 29% of the time, the 30 min windows were below 10% power for the trucks tested. Excluding IV161 that would be 18% of the time. A simple calculation exercise shows that when one would assume no SCR conversion for these windows, while for the remaining windows the 0.69 g/kWh requirement would be met, then about 84% of the NO_x would be emitted during the windows which are exempted from the test.

Table 8: Distribution of engine power. Engine power averaged over 30 minute windows. Vehicle IV161is tested under worst case conditions which can't be regarded as representative, see paragraph 2.2

Average engine power	DA141	SC149	IV153	MB156	DA157	IV161	GI172	DA173
[%]	Diesel N3	LNG N3	Diesel N3	Diesel N3	Diesel N3	Diesel N3	Diesel N3	Diesel N3
<10	10%	9%	2%	54%	24%	100%	15%	15%
<15	61%	21%	25%	67%	56%	100%	44%	63%
<20	86%	49%	45%	83%	76%	100%	84%	89%
>=20	14%	51%	55%	17%	24%	0%	16%	11%

Another issue is that refuse collection vehicles are tested as normal trucks, i.e. using a long-haul N3 trip instead of a trip with sufficient urban driving which is typical for most RCV's. The long-haul N3 trip contains 20-25-55% shares for respectively urban, rural and motorway driving The real-world M3 bus trip would be better suited because it contains 70% urban driving and 30% of rural driving which results in substantially longer testing at urban driving. This would probably better guarantee lower Also for the PEMS real world test there is no requirements to operate the truck as a RCV. The frequent stops, the operation of the PTO, all typical for RCV operation, are not required for the test.

3.8 Ammonia emissions

Besides the NO_x emissions, the ammonia emissions were measured as well. This was done with an automotive NH_3 sensor.

<u>The data can only be used to obtain indicative levels of average NH_3 emissions concentrations, because the sensor's accuracy is limited, especially when the concentrations exceed 20ppm</u>.

For each vehicle, overall average ammonia concentrations have been determined as well as moving averages over a period of half an hour. For the latter the maximum average concentration and the percentage of 30-minute windows that have ammonia concentrations above 10ppm were determined. The threshold of 10ppm is used, because for a type approval engine test of half an hour (the WHTC test cycle) the limit for the average ammonia concentration is 10ppm.

In this way, from the test data an indication can be obtained about if and whether emissions higher than this threshold of 10ppm occur in the real-world.

From the seven vehicles that were equipped with the NH_3 sensor only with one vehicle all half-hour windows were below 10 ppm. For all other vehicles the percentage of half-hour windows where NH_3 concentrations exceeded 10 ppm were in the sub 15%-range. Two vehicles occasionally showed very high half-hour average concentrations up to a maximum of about 170-180 ppm. It has yet to be determined what was the cause of this observed emission behaviour.

Table 9: Ammonia emissions: total average, highest 30 minute average, percentage of 30 minute averages higher than 10ppm. The data can only be used to obtain indicative levels of average NH_3 emissions concentrations, because the sensor's accuracy is limited, especially when the concentrations exceed 20ppm.

	DA141 Diesel N3	IV153 Diesel N3	MB156 Diesel N3	DA157 Diesel N3	IV161 Diesel N3	GI172 Diesel N3	DA173 Diesel N3
Average [ppm]	1	4	4	8	2	5	Test error
Max 30min [ppm]	8	24	14	180	15	30	Test error
% 30min > 10ppm	0	9	5	14	5	14	Test error

4 Conclusions

Tail-pipe emissions levels of eight refuse collection vehicles with a first generation Euro VI diesel engine and one Euro VI LNG engine were examined using a Smart Emissions Measurement System to determine the level of NO_x and NH_3 emissions when operated on their normal daily routes, i.e. under real-world conditions.

- Eight of the tested vehicles run on diesel and are a good representation of the Dutch fleet of refuse collection vehicles with a Euro VI diesel engine. One of the tested vehicle has a Euro VI LNG (Liquefied Natural Gas) engine. For this vehicle, due to the very small sample no general conclusions can be drawn about the real-world emissions level of Euro VI engines running on LNG.
- The average emissions levels of NO_x of the tested diesel vehicles during daily operation vary a lot. The average NO_x emissions range from about 0.4 to 4.3 g/km. One vehicle running on LNG had an average NO_x emissions of 1.5 g/km.
- The average work-specific NO_x emissions during daily operation of the tested vehicles are 0.3 to 2.3 g/kWh. This means that there are cases where the NO_x emissions are higher than one might expect based on the limit of the real-world in-service conformity test, which for NO_x is 0.69 g/kWh[10]
- For one of the eight diesel vehicles white deposits were observed in the tail pipe possibly caused by a problem with the SCR system.
- For trips with low average speeds (below ~15 km/h) and with low engine loads, NO_x emissions tend to be higher.
- Also during a trip NO_x emissions can vary a lot, partly as a result of variable load of the engine.
- The increase of NO_x emissions at low average speeds for diesel vehicles is caused by how the emission control with selective catalytic reduction (SCR) works. The catalyst of this type of emission control system needs to be warm to effectively reduce the NO_x emissions of the diesel engine. At low engine loads (power) the catalyst may cool down due to the cooler exhaust gas of the diesel engines at those conditions. Actual NO_x emission levels thus depend on if and how much during a trip the SCR catalyst cools down due to low load operation.
- For the tested vehicles the operation varied a lot, from worst case conditions with regard to NO_x emissions at very low average speeds of 6 km/h to operations with average speeds of 23 km/h and even 26 km/h for a service vehicle. In cases where refuse collection vehicles collect large underground containers high average power take-off loads were observed. Engine load thus depends on the power-take-off capacity and usage. Also the engine load varied depending on the payload of the vehicle, the speed profile, the amount of stops and whether the engine is shut off or not during stops. Engine power for the nine cases ranges from an average of 7% for worst case conditions up to 21%.
- Evaluation of the operation of the vehicles showed that the vehicles regularly drive with an average engine power lower than 15%.

[10] This limit value is composed of the limit for the NO_x emissions over a type-approval engine test of 0.46 g/kWh and a conformity factor of 1.5 that accounts for the real-world test on top of the type-approval limit (1.5x0.46 g/kWh=0.69 g/kWh).

Periods with an average engine power lower than the threshold of 15% are always excluded from the evaluation of the formal 'real-world' PEMS test for type-approval and in-service conformity. For most of the tested refuse collection vehicles this condition happens more than half of the time of normal operation. This means that substantial shares of normal operation of refuse collection vehicles fall outside the boundary of the conditions of the current[11] real-world test. NO_x emissions are not controlled under those conditions.
Even when the upcoming change of the power threshold to 10%[12] is regarded, refuse collection vehicles still operate a significant amount of time outside this boundary condition.

- The contribution to total NO_x emissions of increased NO_x emissions after a cold start is 5-23% for the tested diesel vehicles. These numbers take into account that refuse collection vehicles drive a relatively short period of the day with a cold engine.
- The ammonia emissions of the tested vehicles are 1 to 9 ppm on average over the entire test period. Average concentrations of ammonia over shorter periods of time, in this case 30-minute windows, are at maximum 8 to 180 ppm among the tested vehicles with their respective operation profiles. Higher results above 20 ppm are less accurate, due to the limitations of the ammonia sensor used. For the laboratory engine type-approval test of 30 minutes the limit for the ammonia concentration is 10 ppm.

[11] Euro VI Step A to C
[12] Euro VI Step D

5 References

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6 Signature

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