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TNO report

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Dutch In-service emissions testing programme 2015 - 2018 for heavy-duty vehicles: status quo Euro VI NO_x emissions

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Samenvatting

In opdracht van het Ministerie van Infrastructuur en Waterstaat voert TNO het steekproefcontroleprogramma voor vrachtwagens en bussen uit. In dit programma meet TNO, op regelmatige basis, de uitlaatgasemissies van deze voertuigen om te onderzoeken hoe schoon ze in de praktijk zijn en of ze aan de Europese normen voldoen. Euro-VI voertuigen vertegenwoordigen inmiddels een groot en snel groeiend aandeel in de Nederlandse vloot. Sinds de inwerkingtreding van Euro VI op 1 januari 2014, richt het meetprogramma zich dan ook voornamelijk op het meten en monitoren van de praktijkemissies van hoofdzakelijk dieselvoertuigen die aan deze norm voldoen. In dit rapport wordt verslag gedaan van de resultaten van het emissiemeetprogramma vrachtwagens 2015 - 2018 waarbij een overzicht wordt gegeven van alle tot dusver gemeten voertuigen met een Euro VI gecertificeerde motor, waaronder vrachtwagens, bussen, vuilniswagens en een enkel speciaal voertuig.

Resultaat van het onderzoek is dat bij meting van de NO_x-emissies van 32 zware dieselvoertuigen over de officiële wegtest, of over vergelijkbare testcondities, geen overschrijdingen van de norm werd gevonden. Echter voor gebruiksprofielen volgens de dagelijkse inzet van de onderzochte voertuigen werd gevonden dat in 17 van de 32 situaties de NO_x-uitstoot van de zware bedrijfswagens met een eerste generatie Euro VI dieselmotor gemiddeld hoger lag dan de normwaarde[1] die geldt voor de officiële Europese praktijkemissietest voor motoren van zware bedrijfswagens. Kanttekening is dat deze normwaarde alleen geldt voor de condities van de officiële Europese wegtest voor schadelijke uitlaatemissies van zware bedrijfswagens.

Het is gebleken dat het niveau van de gemiddelde en tijdelijke NO_x uitstoot van een Euro-VI voertuig sterk afhangt van de inzet. De hoogste NO_x emissies in de praktijk werden geconstateerd wanneer de gemiddelde snelheid van de voertuigen laag was. Met name bij rijden in de stad neemt de kans op tijdelijk en gemiddeld hoge NO_x emissies toe. Dit komt veel voor bij vuilniswagens, maar ook bij distributiewagens, bussen en bij zware trekker-opleggers die in de stad rijden. Een constructievoertuig liet ook hoge NO_x emissies zien. Voor de meeste voertuigen en toepassingen was de NO_x emissie zeer laag bij hogere gemiddelde snelheden, zoals op een buitenweg of snelweg.

De oorzaak van de verhoogde NO_x emissies bij lage gemiddelde snelheden is tweeledig; enerzijds kan het emissiebeheerssysteem onder deze condities vaak niet goed op werktemperatuur komen, anderzijds vallen dergelijke condities vaak buiten de grenzen van de geldende officiële wegtest. De Euro VI norm leidt voor de eerste generatie voertuigen (Euro VI Step A tot en met C) dus niet in alle praktijksituaties tot NO_x emissies van een vergelijkbaar of lager niveau.

Opvallend is dat de NO_x-uitstoot van Euro-VI bussen bij rijomstandigheden in de stad op een lager niveau ligt dat van distributietrucks onder vergelijkbare rijomstandigheden.

[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 voor de typegoedkeuring van 0,46 g/kWh: 1,5 x 0,46 = 0,69 g/kWh.

Voor stadsbussen moeten de emissies als onderdeel van de Europese typekeuring worden gemeten bij rijomstandigheden onder stadscondities. Voor distributietrucks is dit niet het geval en wordt deze officiële wegtest uitgevoerd voor gemiddelde rijomstandigheden van een vrachtwagen, dus op de snelweg, buitenweg en maar voor een bepekt deel in de stad.

Om de situatie te verbeteren, zijn onlangs de eisen van de officiële wegtest aangescherpt. De test wordt zwaarder voor alle zware bedrijfswagens met Euro VI motoren die vanaf september 2019 op de weg komen (‘step D’). Het gaat er hierbij om dat rijomstandigheden met een motorvermogen van minimaal gemiddeld 10% moeten worden meegenomen in de officiële wegtest. Ook wordt voor vrachtwagens de evaluatie van rijden in de stad een verplicht deel van de wegtest.
Voor stadsbussen was al sprake van flink aandeel stadsverkeer in de wegtest. Mogelijk zijn de emissies van stadsbussen daardoor wat lager dan bijvoorbeeld vuilniswagens waarvoor de eis nog niet geldt. De aanscherping is onder meer het resultaat van Nederlandse inbreng in de besprekingen in Brussel. Een Nederlands voorstel om alle zware voertuigen die in de stad worden gebruikt voor de typekeuring te testen volgens het gebruiksprofiel van stadsbussen heeft het binnen de EU overigens niet gehaald.

Een laatste verbetering van Euro VI, ‘Step E’, wordt in 2020 verwacht. Voor deze aanscherping van de regelgeving moeten in de officiële wegtest de emissie bij een start met niet bedrijfswarme motor worden meegenomen in de testevaluatie.
Ook de emissie van deeltjesaantallen moet worden meegenomen in de testevaluatie. Emissietesten zullen moeten uitwijzen wat het effect van beide stappen (D en E) is op het emissieniveau tijdens dagelijkse inzet. Monitoring van de emissies van zware bedrijfswagens over de levensduur geeft inzicht in trends van de emissies over de levensduur van voertuigen en inzicht in de effectiviteit van de Europese emissiewetgeving.

Onlangs is binnen de EU een inventarisatie gestart naar de noodzaak en de mogelijkheden voor aanscherping van de normstelling voor vrachtauto’s na Euro-VI. Inzicht uit de uitgevoerde metingen heeft opgeleverd dat het er bij Euro-VII vooral om moet gaan dat lage NO_x-uitstootwaarden ook in veeleisende praktijkomstandigheden zoals met een lage motorbelasting worden gewaarborgd. Voor de officiële wegtest voor de emissies zouden alle zware voertuigen die in de stad worden ingezet, moeten worden getest met een representatief inzetprofiel, waarbij rijden in de stad het grootste deel van de test uitmaakt, zoals dat ook bij stadsbussen het geval is. Ook moet bij normstelling volgens Euro VII aandacht zijn voor het robuuster maken en het beter beveiligen van het emissiebeheerssysteem. Monitoring van de emissies met hulp van de sensoren aan boord van het voertuig over de levensduur van het voertuig kan de reikwijdte van de controle vergroten. Hierdoor kan het risico op hoge schadelijke emissies die optreden tijdens de levensduur van een voertuig, bijvoorbeeld door manipulatie of veroudering van systemen, worden verlaagd.

Summary

Contracted by the Ministry of Infrastructure and Water management TNO conducts the in-service emissions testing programme for trucks and buses. In this programme, TNO measures on a regular basis the tail-pipe emissions of these vehicles to determine how clean they are in the real world and if the vehicles comply with the EU standard. Euro VI vehicles with a diesel engine currently represent a large share in the Dutch fleet of heavy duty vehicles. Since 2014, the programme therefore mainly aims at testing this group of vehicles. This report elaborates on the results of tests that have been performed in the period 2015 to 2018 on trucks, buses, city and regional buses, refuse collection vehicles and one construction vehicle.

The result of the investigation is that with 32 heavy duty vehicles with a certified Euro VI engine, over the formal PEMS test on the public road or under comparable conditions, no exceedance of the applicable limit value was observed. In daily operation, however, for 17 out 32 situations the NO_x emission of heavy duty vehicles with a Euro VI certified engine was on average higher than the limit value that accounts for the formal PEMS test for these vehicles on the public road. It must be noted that the limit value is only applicable for the conditions that are prescribed for the formal European test with PEMS (Portable Emissions Measurement System)[2].

The level of the average and temporary NO_x emissions still strongly depends on the operation of the Euro VI vehicles. The highest NO_x emissions were observed for situations where the average speed was low. The probability that NO_x emissions increase is highest when vehicles drive in the city. This happens a lot for refuse collection vehicles, but also for distribution trucks, city buses and even for long haulage vehicles. For most vehicles and applications, the NO_x emission was lower than the limit value for the Euro VI standard when vehicles drive at higher average speeds such as often is the case at rural roads and motorways.

The cause of the high NO_x emissions at low speeds and engine loads is twofold: on the one hand the emission control system may not get at working temperature under those conditions, on the other hand such conditions often fall outside the boundary conditions of the formal PEMS test on the public road. For the first generation of Euro VI vehicles (Euro VI step A to C) the standard does not lead in all real world conditions to NO_x emissions at the level of the standard.

It is noted that the NO_x emissions of Euro-VI buses under driving conditions in the city are at a lower level than those of distribution trucks under comparable driving conditions. For city buses, emissions must be measured as part of the European type test under driving conditions under city conditions. For distribution trucks this is not the case and this official road test is carried out for average driving conditions of a truck, i.e. on the highway, on the road and only for a specific part in the city.

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[2] 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.

To improve the situation the PEMS test was adapted. The test will be more stringent for heavy duty vehicles with Euro VI engines that enter the market on September 2019 (Euro VI Step D). The test is extended to low load operation and urban driving will be an explicit part of the test evaluation for heavy trucks.
For city buses urban driving was already part of the test and the test evaluation. The emission of city buses are therefore probably lower than for instance refuse collection vehicles for which no representative test is required. The improvements are, amongst others, the result of the Dutch position in Brussels. The Dutch proposal to test vocational vehicles that often drive in cities over the PEMS test for buses was not adopted.

A last improvement of Euro VI, step E, is expected around 2020. This will include the cold start in the evaluation of the formal road test with PEMS as well as a test of the particle number emissions. Emission tests will show the impact of these improvements (Step D and E) on the real world emissions. Monitoring of the emissions of heavy duty vehicles reveals trends over the lifetime of this group of vehicles and in the effectiveness of the EU emission regulation.

Recently, the EU started an evaluation of the needs and possibilities for further tightening of the standard. The emissions tests have revealed that Euro VII should mainly address the issue with high NO_x emissions under demanding driving conditions. All vehicles driving in cities should be tested in the city with a representative driving profile, such as currently happens for city buses. Euro VII should also aim at making the emission control system more robust and secure. Monitoring with sensors on board of the vehicle could extend the emissions control to the fleet level and could decrease risks on high noxious emissions, as for instance caused by manipulation.

Contents

1 Introduction

Reduction of the tail pipe NO_x emissions from vehicles is desirable from an air quality point of view. In the last two decades, EU emissions regulations tried to command a reduction of the NO_x emissions from vehicles with a diesel engine, but for heavy duty vehicles only managed to establish substantial reductions as of the introduction of Euro VI (Vermeulen et al., 2016). The substantial reduction of the NO_x emissions from diesel engines is mainly achieved by the application of an exhaust gas aftertreatment system that uses Selective Catalytic Reduction (SCR). The SCR system is often complemented by Exhaust Gas Recirculation that reduces the NO_x load entering the SCR.

For vehicles with the first generation of Euro VI engines it was reported (Vermeulen et al., 2016) that NO_x emissions of vehicles with Euro VI certified engines have on average decreased substantially compared to the NO_x emissions of previous generations of engines. This is partly due to a more stringent limit for the NO_x emissions, but also due the introduction of a new emission test that has to be conducted on the public road. As of Euro VI (31 December 2013), this test with a Portable Emission Measurement System (PEMS) became a mandatory part of the EU type approval process in the form of an in-service conformity test.

Studies by (Vermeulen et al., 2016) and (Söderena, P., Nylund, N., 2018) showed that for certain heavy-duty vehicle applications despite the more stringent requirements, the NO_x emissions may be higher than expected, based on the limits for the engine test and the in-service conformity (ISC) test on the public road. In (Vermeulen, Ligterink, 2018) it was demonstrated that substantial parts of normal driving, such as driving at a low engine load and driving in the city, may fall outside of the boundaries of the ISC test on the public road. Together, this leads to the situation that NO_x emissions levels of vehicles with a Euro VI certified engine still depend on actual driving conditions and exceed the Euro VI limit values. Therefore, within the Dutch in-service emissions testing programme, TNO is conducting for the Ministry of Infrastructure and Water management, it was decided to test a number of different representative HDV vehicles of different types of applications in normal daily operation, to determine actual NO_x emissions levels.

The general objectives of the Dutch in-service emissions testing programme are to:

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

This report presents NO_x emissions data that was gathered throughout the programme in the period 2015 to 2018 for 46 vehicles with Euro VI certified engines and gives an overview of the data, with a focus on the determination of NO_x emissions of heavy-duty vehicles with Euro VI-step A and a few C (as of Sept. 2016) certified engines, under a range of normal representative driving conditions which are considered normal use in the Netherlands.

2 Method: Real-world emission monitoring using SEMS and PEMS

The emissions measurement programme aimed at determining the real-world NO_x emission levels of heavy-duty vehicles and to screen the in-service conformity of the vehicles. In the programme, both the Smart Emissions Measurement System (SEMS) and the Portable Emissions Measurement System (PEMS) are used. SEMS is used for measuring NO_x emissions during daily operation and the screening of in-service conformity according an alternative screening method and PEMS for testing the in-service conformity according formal requirements or to accurately determine emissions levels over defined on-road test trips.

2.1 SEMS, Smart Emissions Measurement System

SEMS is a sensor-based system developed by TNO [Heijne et al. 2016] and is used in the programme to measure and analyse the tail-pipe NO_x emissions during daily operation and a range of vehicle/engine parameters to be able to characterize the typical operation of the vehicles. In this way, for the group of vehicles, weeks up to months of data was collected per vehicle. The SEMS uses an automotive NO_x sensor, an ammonia 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 sent hourly to a central data server.

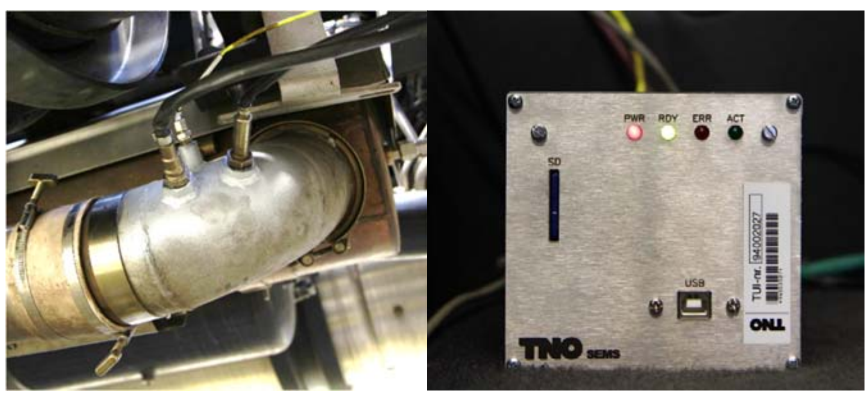

Figure 1: SEMS. Left, calibrated NO_x-O_2 sensor, NH_3 sensor and temperature sensor mounted in the tail-pipe. Right, autonomously running data recording unit with hourly data transmission to a central server via GPRS.

The raw data on the central server is post-processed automatically to filter and check the data. Sensor output is corrected using sensor specific calibration values. Mass-emissions and instantaneous engine power are calculated combining sensor data and CAN data such as manifold-air flow, fuel rate, engine torque, and sensor O_2 concentration where possible. For the vehicles for which no sufficient engine data were available to calculate the work specific emissions, an estimation of the average brake specific fuel consumption and CO_2 emission of the engine was used to estimate the vehicle’s emissions in g/kWh.

2.2 PEMS, Portable Emissions measurement System

For more accurate technology assessment and in-service conformity checking in a Portable Emissions Measurement System (PEMS) has been used to measure the NO_x emissions on the public road. A limitation is that the tests are bound to well-defined test routes and represent only a few hours of vehicle operation while a merit is the more accurate measurement and the fact that it is the formally prescribed instrument for in-service conformity testing[3].

2.3 NPET, Nanoparticle Emission Tester

Stationary measurements of the tail pipe particle number concentrations have been introduced in the program in 2018. The results are used to obtain an indication of the diesel particle filters (DPF) filtration performance. The measurements are conducted before the SEMS measurement at the same occasion when SEMS is installed on the vehicle. For the measurements, the particle number (PN) concentration in the tail pipe is measured at idle (500-600 rpm) and at a high engine speed (1500-2000rpm). Additionally, the ambient PN concentration is measured before and after the exhaust measurements. The instrument used is an NPET model 3795 of the manufacturer TSI. The instrument is meant to measure the solid particle number concentration in post DPF diesel exhaust and uses a volatile particle remover to reduce semi-volatile and nucleation mode particles.

Table 1: Specifications of the Nanoparticle Emission Tester, NPET

Instrument	**NPET**
Model	3795
Range	1,000-5,000,000 P/cm^3
Mode	Semi volatiles and nucleation mode particles are evaporated and oxidized and therefore not counted
Detection efficiency	23nm: <50% 41nm: >50% 80nm: 70-130% 200nm: <200% 30nm C40 droplets: <5%
Response time	
10-90%-10%	<5s
0-90%	<10s

2.4 In-service conformity screening

The Dutch in-service emissions testing programme aims to screen the in-service conformity. This means that firstly indicative tests are performed to determine whether or not there is an increased probability that an Euro VI certified engine in a vehicle fails the formal in-service conformity (ISC) test. The process contains a number of steps:

1 *SEMS screening test*: When SEMS is mounted, the vehicle is also checked (MI and display error codes) and the owner is asked to provide information about

[3] EC regulation 582/2011

the history of the vehicle. The SEMS data from the vehicle in daily operation is used to determine the SEMS Factor [Heijne, 2016] applying the pass-fail evaluation rules of a formal PEMS test, using the SEMS data instead. In the case the SEMS Factor is higher than 1.5 step 2 will be taken, else step 4.

2 *SEMS screening ISC route*: Perform additional checks on the vehicle. Read OBD for error codes, check Malfunction Indicator and display for possible error signs. Run an in-service conformity test route using the SEMS that is already mounted on the vehicle. The SEMS Factor is calculated for this trip applying the pass-fail evaluation rules of a formal PEMS test. In the case the SEMS Factor is higher than 1.5 the result is communicated to the national Type Approval Authority and it can be decided to run a PEMS test. If the SEMS Factor is lower than 1.5 step 4 is taken.
3 *PEMS ISC test*: Optionally, it can be decided to perform an additional test according the formal test requirements with PEMS.
4 *Reporting and archiving test data in the database*. Report overall results in an annual report. Send a summary of the result of each vehicle to the national TAA.

After each step of the process the OEM is invited to discuss the results.

2.5 Vehicle selection: heavy-duty vehicles with Euro VI certified engines

Since the introduction of Euro VI on the market in 2013, the focus of the Dutch programme changed to testing the new generation of engines and emissions abatement in heavy-duty vehicles. Each year a ranking for each vehicle class (city bus, medium truck, heavy truck, RCV) was made, based on the number of registrations of each Euro VI engine type/family. This has led to a total test sample of Euro VI vehicles containing 46 individual heavy-duty vehicles, mostly with a diesel engine. The second group were ‘specialties’. Vehicles in this group were selected not only by their engine type/family, but also by the special purpose of the vehicle or by an ad hoc request, for instance to evaluate the emission performance of a given new or alternative technology.

Refuse collection trucks and city buses were selected because initial measurements on a few vehicles showed high NO_x emissions of the vehicles when operating in urban driving conditions. The results were reported in [TNO 2018a] and [TNO 2018b] respectively. For an assessment of environmental technology, vehicles on alternative fuels two conventional LNG fuelled trucks and a dual fuel, LNG-diesel trucks have been tested as well [TNO 2017a], [TNO 2019]. A number of vehicles have not been reported extensively yet, and on a number of vehicles the testing and investigation is still running, see appendix A.

See Table 2 for the categories of vehicles that have been tested and the tests performed with those vehicles. A limitation of the dataset is that the vehicle mileages, as read from the odometers at the start of the tests, are still relatively low. Odometer readings range from 20.000 km to about 400.000 km for one N3 class tractor in a single case, while for instance for the latter lifetime mileage expectance would be 1.2 to 1.5 million kilometres. It means that there are no old vehicles in the dataset.

Table 2: Overview of the test sample with vehicle categories tested, types of vehicles tests and number of vehicles of each type tested.

		PEMS	SEMS
Tractor (semi) trailer	CI*(Diesel) N3	6	8
	SI** (LNG) N3	2	
	HDDF*** LNG -diesel N3,1A	1	1
Rigid	CI (Diesel) N2	1	4
	CI (Diesel) N3		4
Refuse Collection Vehicle	CI (Diesel) N3		8
	SI (LNG) N3		1
	SI (CNG) N3		1
Buses	CI (Diesel) 12m	2	2
	CI (Diesel) 18m		3
Tipper	CI (Diesel) N3		1

*CI: Compression Ignition engine. **SI: Spark Ignition engine. ***HDDF: Heavy-Duty Dual Fuel engine.

3 Results

3.1 In-service conformity screening

The majority of vehicles has been put to a screening test with SEMS and/or PEMS. Result for the tested vehicles is that in all cases the initial SEMS screening test lead to false positives; I.e. where the SEMS screening Factor was higher than 1.5 in normal operation, when eventually the applicable SEMS ISC route was driven the SEMS screening Factor was lower than 1.5.
In the case of one PEMS test, the test proved not fully compliant with the formal ISC requirements. For one vehicle, an N3 class, diesel Refuse Collection Vehicles (RCV) white deposits were found in the tail-pipe rendering the SEMS measurement invalid. The white deposits gave cause for further investigation of the vehicle by the OEMS which is not yet finished. This vehicle was the second vehicle after an earlier tested vehicle with the same engine type had a SEMS Factor higher than 1.5 but no conclusions can be drawn as the investigations for this type are not yet finished. One other vehicle that has high average emissions is currently under investigation and four vehicles are currently being tested with SEMS during daily operation.

Table 3: Overview of ISC screening test results.

EU vehicle category, engine		**PEMS Test**
N3, CI		CF<1.5 (6)
N2, CI		CF>1.5 (1, trip not compliant)
N3, SI (LNG)		CF<1.5 (2)
N3 HDDF (LNG -diesel)		CF<1.5 (1)
M3, CI		CF<1.5 (2)
	SEMS screening test	**SEMS screening ISC route**
N3, CI	CF<1.5 (6)	
	CF>1.5 (6)	CF<1.5 (4)
		Investigation running (2)
	CF=? (1) SCR deposits	Investigation running (1)
	Test running (4)	
N2, CI	CF<1.5 (4)	
	CF>1.5 (2)	CF <1.5 (2)
M3, CI	CF<1.5 (4)	
	CF>1.5 (1)	CF<1.5 (1)

3.2 Results: Real world NO_x emissions levels for the different vehicle categories

Total average NO_x emissions were determined for all vehicles. There is a large spread in average speed and NO_x emissions between all vehicles.

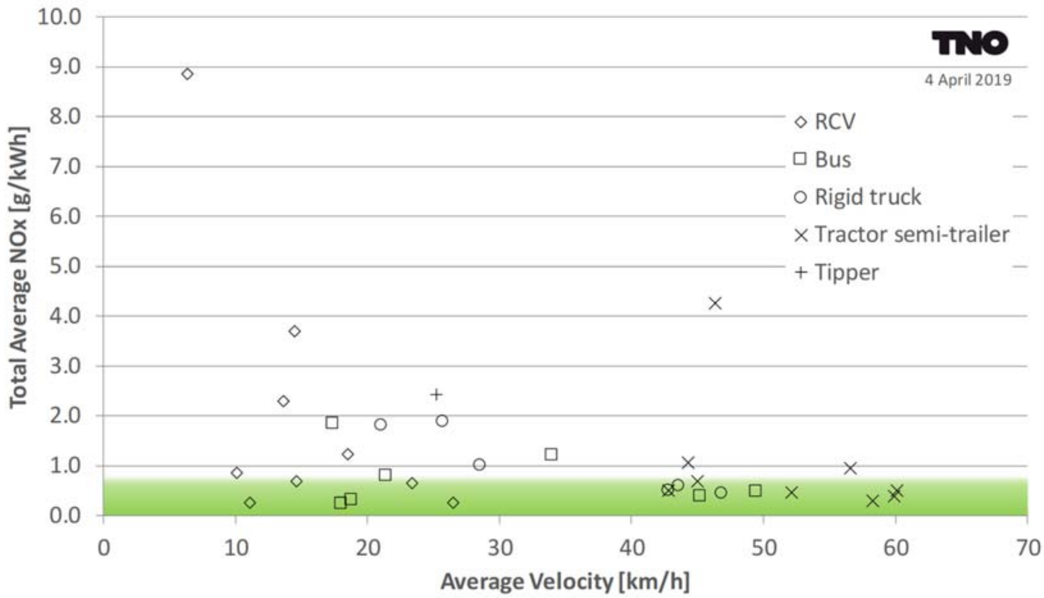

Figure 2: Total average NO_x emissions versus average speed for all vehicles tested with SEMS in normal daily operation. The upper side of the green area represent a NO_x emissions level of 0.69 g/kWh, which is the limit of the conformity factor of 1.5 expressed in gNO_x/kWh (1.5x0.46=0.69 g/kWh) for the formal ISC test. Individual vehicles can't be compared as operation differs from vehicle to vehicle.

Refuse collection vehicles [TNO 2018a] have the lowest average speeds. From 6 to about 26 km/h and this results in a large spread of average NO_x emissions, from 0.3 to 9 g/kWh. RCV operation is characterized by stops for refuse collection. Stop times depend on type of refuse collected (small containers, large containers, garbage bags, coarse refuse) and driving speeds depend on the area that is serviced. In cities speeds are lower as opposed to rural areas and small villages. The highest NO_x emission was measured in a case of coarse refuse collection with long stops for manual loading of the refuse and short driving intervals. Measurements for this vehicle were executed in winter time and the emission abatement concept was 'SCR only', meaning there is no additional Exhaust Gas Recirculation to reduce diesel engine NO_x emissions. For another vehicle, NO_x emission were low despite a low average speed. This vehicle used a high amount of power from the power take off to lift large under floor containers. Another vehicle has a throttle valve which can control diesel engine lambda (air to fuel ratio) so that exhaust temperatures remain higher at low speeds and NO_x remains low, even at low speeds.

Buses [TNO 2018b] have higher average speeds, from 17 to 49 km/h. However, from the dataset over individual city bus lines average speeds are noted as low as 13 km/h. The higher speeds are for buses that service rural areas and villages from a larger city. Usually, these buses stop at less bus stops in a city and often exit and re-enter the city centre straight away. This means that average driving speeds will be higher in urban areas and on average higher because driving contains rural roads and sometimes a motorway. Average NO_x emissions remain below 2 g/kWh for the buses measured.

It is noted that the NO_x emissions of Euro-VI buses under driving conditions in the city are at a lower level than those of distribution trucks under comparable driving conditions. For city buses, emissions must be measured as part of the European type test under driving conditions under city conditions. For distribution trucks this is not the case and this official road test is carried out for average driving conditions of a truck, i.e. on the highway, on the road and only for a specific part in the city.

Average speeds of *rigid trucks* spread a lot as well, but are not as low as for buses and refuse collection vehicles. Rigid trucks include the lighter versions around 10t that are used for city distribution (delivery of goods and parcels) and which typically show the lowest average speeds. In those cases NO_x emissions are generally the highest, on average up to 2 g/kWh down to 0.5 g/kWh for the operations with higher average speeds. Some of the trucks distribute through the country and drive a lot of motorway to enter a city and deliver goods throughout a city which brings average speed downward.

The *long haulage trucks or tractor semi-trailers* have the highest average speeds up to about 60 km/h. Not all these vehicles run mainly motorways. Three of the vehicles are used to service supermarkets and shops from distribution centres. These vehicles tend to have a lot of starts and semi-warm operation because the vehicle is moved around at distribution centres and near shops. One vehicle distributes flowers to France but despite a lot of motorway time also spends a lot of time (about 30% of total operational time) in northern French cities to distribute flowers to the shops. Average NO_x emissions for all tested vehicles vary from as low as 0.3 g/kWh to about 1 g/kWh. One vehicle is currently under investigation because preliminary test results show high NO_x emission of on average about 4.3 g/kWh. The vehicle hardly uses reagent (AdBlue), the consumable which is needed for an SCR to work. This vehicle is currently under investigation so no conclusions can be drawn about the cause of the high measured NO_x emissions for this individual case.

The 4x10 *tipper* hauls sand to construction sites. It drives from a depot to the site where work consists of a lot of idling, low speed sand dumping and manoeuvring at the site. Hence, the vehicle has a relatively low average speed. The operation has periods of high engine load when the vehicle is fully loaded with sand versus low engine loads for running empty. The prolonged periods at the construction sites and low payload afterwards together lead to average NO_x emissions being higher and around 2.5 g/kWh on average.

When the data of all vehicles is divided over speed bins for low, medium and high speed it becomes apparent that at low speeds NO_x emissions for most of the vehicles are higher.

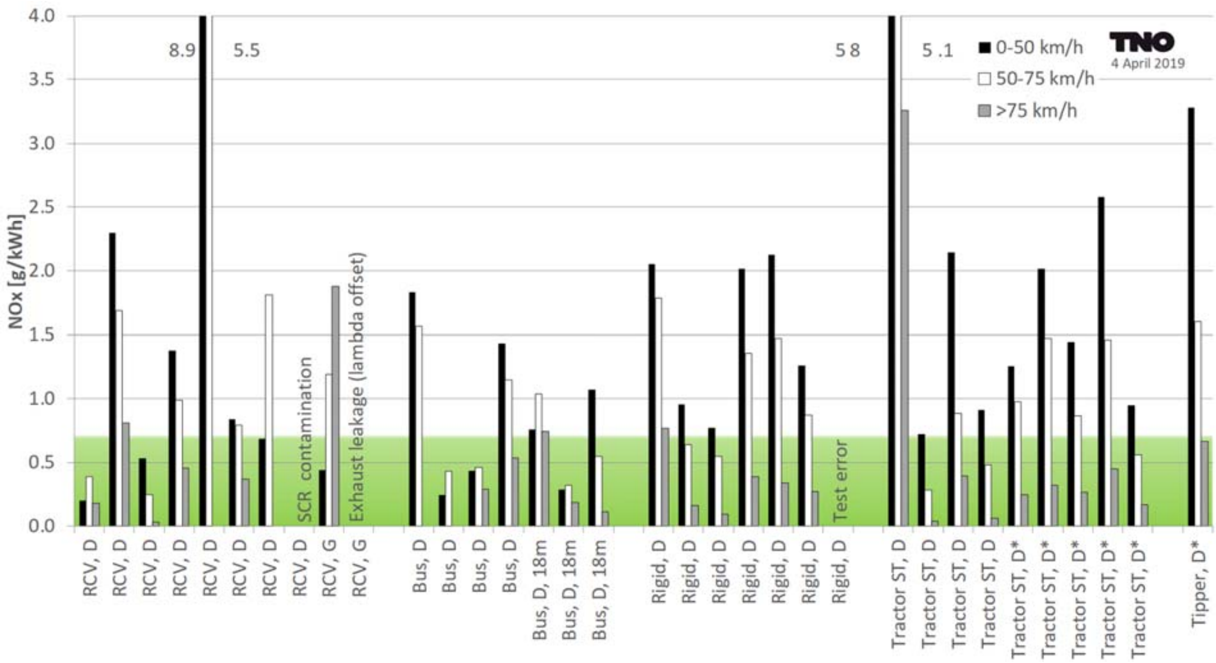

Figure 3: Overview of real world NO_x emissions as measured with SEMS during daily operation for a number of different vehicle types, all with Euro VI certified engines. Three speed ranges are distinguished. * represents Euro VI step C, all others Euro VI step A. D=Diesel, G=Gas (CNG or LNG). The upper side of the green area represent a NO_x emissions level of 0.69 g/kWh, which is the limit of the conformity factor of 1.5 expressed in gNO_x/kWh (1.5x0.46=0.69 g/kWh) for the formal ISC test. Individual vehicles can't be compared as operation differs from vehicle to vehicle.

For a certain share of total emissions this is caused by cold engine operation. Warming up of a heavy duty engine is most often done by idling or running at low speeds. Elevated emissions produced during this period, because emission abatement is not yet active, contribute to the higher emissions. Cold engine operation (Coolant temperature is below 70° C) is for most vehicles 3 to 10% of the total time, but individual cases show cold operation up to 32% when vehicles idle a lot. Cold emissions shares in total emissions depend a lot on how much is emitted when the engine is warm. For example emissions after cold starts can contribute 30% to total emissions when the overall emissions are low (0.5 g/kWh).

A large share of the higher NO_x emissions at low speeds is caused during warm engine operation when SCR temperatures drop below working temperatures.

3.3 Monitoring particulate matter emissions

As of entry into force of 'Euro VI', the emission limits for particle number emissions type approval are set at a level which for diesel engines requires the application of a so-called 'closed' diesel particulate filter. This type of filter is able to reduce particulate matter emissions to a very low level [Giechaskiel, 2015].
To screen the selected vehicles, recently a test is added to the Dutch in-service emissions testing programme which uses a particle counter to measure the particle concentration at a stationary test in the exhaust tail pipe at two engines speeds; idle (500-600 rpm) and 'high' speed (1500-2000 rpm).

Additionally, the local ambient particle concentration is measured.
The measurements are conducted when the vehicle is prepared for the SEMS test. For the measurement the NPET instrument of TSI is used. Measurements conducted on five heavy duty vehicles show particle number concentrations at given engine speeds under no load conditions below concentration found in the ambient air. This indicates that very probably tested vehicles have properly functioning particle filters.

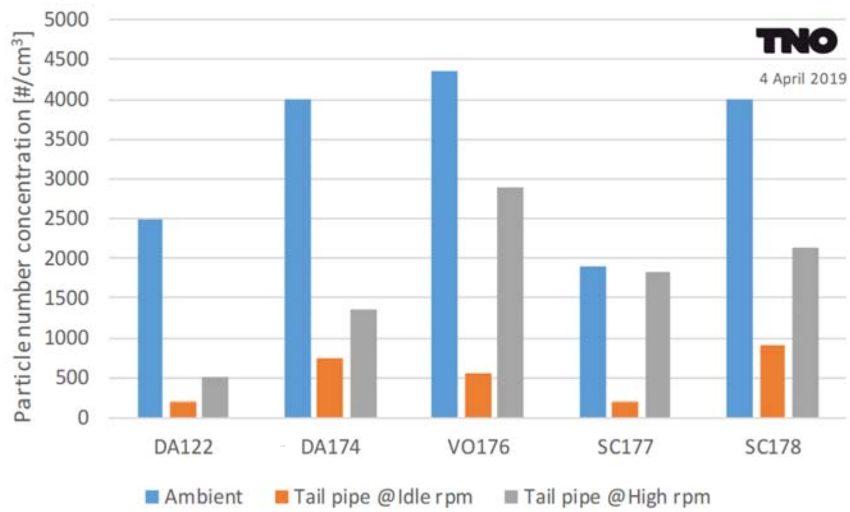

Figure 4: Particle number concentration measured at a stationary test in the ambient air and in the tail pipe at idle and high engine rpm settings. This test is used to screen for possible problems with diesel particle filters. The test is introduced at a later stage as part of the SEMS test procedure. The test is conducted when SEMS is mounted to the vehicle.

3.4 Euro VI and PEMS test for in-service conformity: limited coverage of normal operation

For the regulation of NO_x emissions of engines of heavy-duty vehicles a number of measures are implemented in the type approval framework. The basis is a type approval emissions test of the engine that demonstrates the emission performance with regard to the regulated gaseous pollutant emissions of the given engine type. This is amongst others complemented by additional requirements to check the conformity of production, on-board diagnostics (functionality of emissions critical components), the NO_x measures (e.g. AdBlue consumption) and in-service conformity. The latter is an important test that as of Euro VI (31 December 2013) needs to be conducted with the engine in a representative vehicle, on the public road. Engines have to comply to a so called maximum conformity factor standard of 1.5 that relates to the emissions limit of the engine test, for NO_x 1.5 x 0.46 g/kW = 0.69 g/kWh. Vehicles in-service need to comply over the useful life. The duration of this period depends on the legislative category (e.g. 700.00km for N3, GVW>12t trucks). For an in-service conformity test vehicles shall have no malfunctions (all malfunctions repaired). Malfunctions are to be detected by the on-board diagnostics system, with a threshold limit for the NO_x emissions. In certain cases drivers/owners are forced to make necessary repairs because a torque inducement may render normal operation of the vehicle impossible until the repair is done.

The whole package of tests and requirements should guarantee sustainably low emissions over the useful life of a heavy-duty vehicle. Previous tests on heavy-duty vehicles reported in (Vermeulen et al., 2016) showed higher NO_x emissions than expected based on in-service conformity test limits, which indicates a limited coverage of normal operations by the in-service conformity PEMS test. This has led to the decision for the Dutch test programme to extend the testing to vehicle categories that operate in cities (RCV, buses, distribution trucks).

Table 4: Overview of most important NO_x requirements in EC Regulation numbers 595/2009, 582/2011 and subsequent amendments.

NO_x limit WHSC/WHTC engine test				400 / 460 mg/kWh				
PEMS test for OCE/TA and ISC				Yes				
PEMS Conformity Factor limit				1.5 (1.5 x 0.46 g/kWh)				
PEMS data exclusions				10% highest MAW, power threshold, cold start (see below)				
Euro VI step	NO_x OBD threshold limiet [g/kWh]	Additional OBD monitors	PEMS Power threshold	PEMS Cold start	PEMS PN	PEMS urban MAW	PEMS payload	Implementation date all vehicles
A	1.5	N	20	N	N	n.b.	50-60%	31-12-2013
B	1.5	N	20	N	N	n.b.	50-60%	01-09-2015
C	1.2	Y	20	N	N	n.b.	50-60%	31-12-2016
D	1.2	Y	10	N	N	Y	10-100%	01-09-2019
E	1.2	Y	10	Y	Y	Y	10-100%	t.b.d

For the first generations of Euro VI engines, step A to C, low load and low speed operations fall outside the boundaries of the PEMS test for in-service conformity[4]. Low power operation and high emissions events are excluded from the test evaluation (Vermeulen et al., 2018). Also for the heavy category of vehicles >12t (N3) urban operation is not, or partly in the test evaluation and the mentioned exclusions may delete the remainder of urban operation from the test evaluation. Up to step C, only medium payloads are prescribed for the test, while in normal use payloads from 0 to 100% are common. Vocational vehicles are tested according their GVW category over mostly either an N2 distribution trip (GVW 3.5-12t) or an N3 long haulage trip (GVW>12t). Refuse collection vehicles are often build on an N3 chassis and as such the engine is only tested in a long haul truck with the majority of the test being motorway operation while urban driving and low loads are being excluded. For city buses (M3, class 1) there is already a dedicated bus route, the M3 route which contains 70% of urban driving.

[4] EC regulation nr. 582/2011

Nevertheless, low loads had still to be excluded, according evaluation rules up to a maximum of 50% of the test windows (Moving Averaging Windows). High emissions events (10% of the test windows (MAW)) are also still excluded from the PEMS test. Initiated by the Netherlands, the observed higher and varying NO_x emissions, especially at low load low speed operation, has been debated in the Brussels EU PEMS expert working group in the recent years.

This has led to improved test procedure and new more stringent requirements as of step D (Implementation date 'All vehicles': 1 September 2019):

- Lower power threshold from 20 to 10%.
- Extension of payload range from 50-60% to 10-100%.
- Inclusion of mandatory urban moving averaging window, mainly relevant for N3 and possibly also for N2.
- Extension of the urban part of the N3 route from 20 to 30% of the test time. This is excluding the cold period.
- Better definitions for the trip sub parts and longer allowed total test time.

Further improvements are expected for step E (implementation date is not fixed yet) with inclusion of the cold start, a particle number test and additional requirements auxiliary emission strategies (AES). Monitoring the NO_x emissions by means of real world emissions testing would reveal the impact of these changes on the NO_x emissions levels for normal daily operation of heavy duty vehicles.

4 Conclusions

In the Dutch in-service emissions testing programme for heavy-duty vehicles a number of representative vehicles with Euro VI certified engines of different categories were tested. Tail-pipe emissions levels of vehicles with Euro VI engines were examined using a Smart Emissions Measurement System to determine the level of NO_x emissions when operated on their normal daily routes, i.e. under real-world conditions. A selected group of vehicles was tested with PEMS over specified test routes of a few hours long. When high NO_x emissions were observed, vehicles were also tested over specified in-service conformity routes to get an indication of the NO_x emission conformity of the vehicle in-service. The vehicles were selected based on ranking of registrations of engine type and are a good representation of the Dutch fleet of heavy-duty vehicles with a Euro VI certified engine.

- When a formal in-service conformity route was driven, all vehicles had an indicative in-service conformity factor below the limit of 1.5.
- For the Euro VI certified diesel engines the overall average NO_x emissions levels in normal daily operation still vary a lot from case to case, from about 0.3 g/kWh to 4 g/kWh and 9 g/kWh in a special case. Largest variations and high NO_x emissions were observed for the cases with higher shares of low speed and low engine load operations, for instance at urban driving combined with a lot of idling, where NO_x emissions tend to be clearly higher. Typical examples are city refuse collection, city bus lines, city distribution of goods, also by long haulage trucks and in one case construction services. For those cases, in local driving situations, but also for average operation, the limit value[5] that is set for the formal EU type in-service conformity test, a specific test to be conducted on the public road, are regularly exceeded.
- At motorway speeds NO_x emissions are consistently low, typically around 0.1-0.5 g/kWh.
- The increase of NO_x emissions at low average speeds for diesel vehicles is related to the way the emission abatement technology 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.
- The observed good results for NO_x emissions over indicative in-service conformity screening tests on the one hand and the large spread of NO_x emissions for the same vehicles in normal daily operation in the Netherlands on the other hand, show that not all representative and normal operations are well-covered by the EU emissions legislation. This accounts for the Euro VI certified engines of step A to C.

[5] the Conformity Factor of the EU in-service conformity test represents 1.5 times the limit value for the WHTC engine certification test (1.5 x 0.46 = 0.69 g/kWh)

- For Euro VI step D additional requirements are implemented that should improve the situation and especially the higher NO_x emission at lower speeds and loads. The impact has to be measured once step D certified vehicle enter the market as of September 2019.
- The NO_x emissions of Euro-VI buses under driving conditions in the city are at a lower level than those of distribution trucks under comparable driving conditions. For city buses, emissions must be measured as part of the European type test under driving conditions under city conditions. For distribution trucks this is not the case and this official road test is carried out for average driving conditions of a truck, i.e. on the highway, on the road and only for a specific part in the city.
- There are no provisions for testing vocational vehicles. Refuse collection vehicles for instance are tested as N3 vehicle over a long haulage test route. It is recommended to adapt the EU regulation so that engines of heavy-duty vehicles that usually operate in urban driving are always tested with sufficient urban driving and with representative driving cycles. For engines that are used in refuse collection vehicles the bus route could be used.
- Indicative particle number concentration measurements have been conducted on five vehicles at idle and high engine speed in a stationary test set-up. This test set-up is added to the programme to screen the emissions performance of DPF equipped vehicles. For the five vehicles tested, the tail-pip particle number (PN) concentrations were below ambient PN concentrations and indicate a well-functioning DPF for those vehicles.
- Continuation of monitoring the emissions of heavy-duty vehicles during the life time of the vehicles reveals trends of these emissions and the effectiveness of EU emissions legislation in achieving sustainably low emissions over the useful life of the category of heavy-duty vehicles.

Acknowledgements
Acknowledgments go to all transport companies which provided their vehicles for testing in the Dutch in-service emission testing programme and The Ministry of Water management which funds the testing programme.

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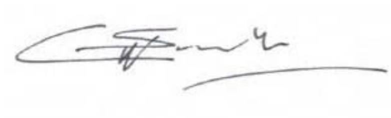
6 Signature

The Hague, 10 April 2019 TNO



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A Overview of vehicles not yet reported

Results of vehicles with Euro VI certified engines have been reported throughout the programme (2013-2018) in TNO 2016b, TNO 2017a, TNO 2017b, TNO 2018a (refuse collection vehicles) and TNO 2018b (buses). New tests, performed in 2018 and early 2019, that were not yet reported are mentioned in the table below.

TNO vehicle code	Make/ model	Euro class, step	EU vehicle category	Type	Application	Test	Average NO_x [g/kWh]	SF/CFNO_x[1]	Remarks
DA174	CF	VI, C	CI, N3	Tractor	National distribution	SEMS	0.40	SF<1.5	
MB175	Actros	VI, C	CI, N3	Tractor	National distribution	SEMS	0.70	SF<1.5	
VO176	FH	VI, C	CI, N3	Tractor	Foreign long haulage and distribution	SEMS	0.50	SF<1.5	
SC177	G450	VI, A	CI, N3	Tipper	Construction	SEMS	2.44	T.b.d	Preliminary result: Investigation running
SC178	P410	VI, C	CI, N3	Tractor	National distribution	SEMS	0.96	T.b.d	Preliminary result: Investigation running
VO179	FM	VI, B	CI, N3	Tractor	National distribution	SEMS	0.47	T.b.d	Preliminary result: Investigation running
VO180	FH	VI, C	HDDF, N3	Tractor	National distribution	PEMS	0.41	CF<1.5	CF average of 3 PEMS ISC tests
MA181	TGX	VI, A	CI, N3	Tractor	National distribution	SEMS	5.39	T.b.d	Preliminary result: Investigation running

[1]CF: Conformity Factor, a factor determined according the data-evaluation rules and over PEMS tests according EU Regulation nr. 582/2011. For both the limit is 1.5, which is 1.5 x the limit for the type approval WHTC engine test. For NO_x; 1.5 x 0.46g/kWh = 0.69 g/kWh. SF: SEMS Factor, for screening the in-service conformity. A factor calculated according data-evaluation rules comparable to the rules used for formal PEMS testing, using SEMS data of real-world tests or ISC routes instead.