TNO report

TNO 2021 R10121

Dutch In-service emissions testing programme for heavy-duty vehicles 2019-2020

Traffic & Transport
Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

Date	22 January 2021
Author(s)	Robin Vermeulen, Norbert Ligterink, René van Gijlswijk, Peter van der Mark Edo Buskermolen Vincent Verhagen
Copy no	2021-STL-REP-100337486
Number of pages	38 (incl. appendices)
Sponsor	Ministry of Infrastructure and Water Management
Project name	IenW – HD Steekproef 2019
Project number	060.40636

Samenvatting

In opdracht van het Ministerie van Infrastructuur en Waterstaat voert TNO het emissiemeetprogramma voor vrachtwagens en bussen uit. In dit programma meet en monitort TNO, op regelmatige basis, de uitlaatgasemissies van deze voertuigen om te onderzoeken hoe schoon ze in de praktijk zijn en wordt onderzocht via een zogenaamde screening of voertuigen aan de Europese emissienormen voldoen.

De gegevens die worden verzameld in deze programma's vormen de basis voor een bijstelling van de officiële getallen voor praktijkemissies – de zogenaamde emissiefactoren – die TNO jaarlijks oplevert. Emissiefactoren worden gebruikt op landelijke, regionaal en gemeentelijk niveau als input voor rekenmodellen voor luchtkwaliteit, emissieverspreiding en stikstofdepositie, en voor de beoordeling van huidig en voorgenomen beleid. Deze getallen vormen tevens de basis voor de nationale en internationale rapportages over de emissies van verkeer.
Ook wordt de opgedane kennis gebruikt als basis voor de Nederlandse inbreng in de internationale onderhandelingen over aanscherpingen van de emissienormen in Brussel en Genève.

De testvoertuigen voor het meetprogramma worden geselecteerd uit vloten van Nederlandse transporteurs aan de hand van de ranking van de registratie-aantallen in Nederland. 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 bedrijfswagens met een dieselmotor die aan deze norm voldoen en ligt de aandacht vooral bij de uitstoot van NO_x en deeltjes (ultra fijnstof PM0.1; deeltjes tot ongeveer 0.1 micrometer doorsnede). De NO_x uitstoot wordt bepaald met SEMS (Smart Emissions Monitoring System). Dit is een instrument dat de emissie van NO_x continu meet tijdens praktijkinzet van het voertuig. De werking van het roetfilter wordt gecontroleerd door meting van het aantal roetdeeltjes in de uitlaat bij onbelast, laag stationair toerental. Dit is de methode die wordt voorzien voor de algemeen periodieke keuring (APK) in Nederland voor de controle van de werking en aanwezigheid van een roetfilter.

In dit rapport wordt verslag gedaan van de resultaten van het emissiemeetprogramma vrachtwagens van de jaren 2019 en 2020. Het gaat om:
- Praktijkemissiemetingen en emissiescreeningstesten die zijn verricht aan een drietal vrachtwagens die voldoen aan de Europese eisen die in september 2019 van kracht zijn geworden (Euro VI, step D).
- Praktijkemissiemetingen en emissiescreeningstesten die zijn verricht aan een vrachtwagen met een tweebrandstoffenmotor (LNG-diesel).
- Resultaten van afgerond onderzoek naar een tweetal casussen met afwijkende emissies.
- Een overzicht van alle NO_x screeningstesten die in de afgelopen jaren zijn uitgevoerd met een veertigtal voertuigen met een Euro VI step A, B, C en D motor.
- Resultaten van een langlopende meting van de emissies voor het monitoren van het NO_x en NH_3 emissieniveau over de levensduur van een vrachtwagen met een Euro VI gecertificeerde motor.

Beknopte samenvatting van resultaten

Resultaat van het onderzoek is dat de drie geteste trucks van de nieuwste Euro VI generatie (Euro VI step D) gemiddeld genomen als schoon kunnen worden aangemerkt in de dagelijkse inzet waarin ze zijn getest. De NO_x-uitstoot per km ligt gemiddeld op ongeveer 60% van de officiële norm en door toepassing van roetfilters was er sprake van een zeer lage uitstoot van roetdeeltjes uit de uitlaat. Deze testresultaten geven een indicatie dat deze voertuigen iets schoner zijn dan de voorgaande generatie (met Euro VI step A tot C emissienorm). Of dit daadwerkelijk het geval is, kan worden bepaald door meer voertuigen te testen. Het grootste deel van de NO_x emissies wordt net als bij voorgaande generaties bij lage snelheden uitgestoten, zoals bij rijden in de stad. Dit komt doordat het SCR systeem, dat de NO_x uitstoot van een dieselmotor moet reduceren, niet of deels op werktemperatuur komt onder deze rijomstandigheden. Ook de vrachtwagen met een tweebrandstoffenmotor (dual fuel LNG-Diesel, met LNG als hoofdbrandstof en diesel pilot injectie) bleek schoon.

Met het emissiescreening en monitoringsinstrument SEMS (Smart Emissions Monitoring System) zijn testen gedaan waarmee een indicatie wordt verkregen of voertuigen voldoen aan de Europese norm voor de conformiteit van in gebruik zijnde voertuigen. De meeste van de inmiddels veertig geteste voertuigen met een Euro VI motor hadden een screeningsuitslag die lager lag dan de daarvoor vastgestelde limietwaarde wanneer een formele testroute werd gereden.
Van de veertig geteste trucks bleken bij vier voertuigen problemen op te treden. Drie verschillende trucks met hetzelfde motortype hadden verschillende problemen. Het eerste en het tweede voertuig hadden respectievelijk een hoge ammoniakuitstoot en een hoge NO_x screeningsuitslag. Bij het derde voertuig en een voertuig van een ander merk en type bleek het boorddiagnosesysteem niet effectief storingen van het emissiebeheerssysteem aan het licht te brengen, waardoor deze twee voertuigen langdurig met een sterk verhoogde NO_x uitstoot rond reden.

De truck die voor lange tijd werd gevolgd en doorgemeten, liet een geleidelijke toename van de NO_x emissies en een afnemende NH_3 emissie zien bij oplopende kilometerstand.

De huidige Euro VI eisen garanderen dus nog geen lage NO_x emissies in de stad of in sommige gevallen wanneer storingen optreden. Ook zijn de levensduureisen beperkt tot ongeveer de helft van de normale levensduur en worden er geen eisen gesteld aan de praktijkuitstoot van NH_3. Een verdere aanscherping van de Europese eisen na Euro VI is nodig om dit beter te reguleren.

Uitgebreide samenvatting van de resultaten

De drie trucks van de nieuwste Euro VI generatie (Euro-VI step D) zijn gemiddeld schoon tijdens hun dagelijkse inzet
De drie geteste vrachtwagens met een Euro VI step D gecertificeerde motor met nog een lage kilometerstand zijn elk gemiddeld genomen schoon tijdens de dagelijkse praktijkinzet. Twee van de geteste voertuigen waren zware trekker-opleggers, het andere voertuig was een lichtere distributietruck. De NO_x uitstoot lag met waarden van gemiddeld 370 tot 400 mg/kWh in de dagelijkse inzet onder de limietwaarde van de officiële praktijktest (690 mg/kWh)[1]. Op basis van deze testen kan, echter, niet worden geconcludeerd dat de voertuigen aan de Europese eisen voldoen. Hiervoor moet ook de officiële praktijktest worden uitgevoerd aan een minimum van drie verschillende vrachtwagens van hetzelfde type.
Een vrachtwagen met een tweebrandstoffenmotor, met als hoofdbrandstof LNG, (dual fuel LNG -diesel pilotinjectie) had in de praktijkinzet gemiddeld een lage NO_x uitstoot van 280 mg/kWh.

Het niveau van de NO_x uitstoot hangt nog af van hoe het voertuig wordt gebruikt. Omdat het gebruik van voertuig tot voertuig kan verschillen, kunnen de resultaten van voertuigen die in hun dagelijkse inzet zijn getest niet onderling worden vergeleken.

Het grootste deel van de NO_x uitstoot wordt bij lage snelheden uitgestoten
Ondanks de lage gemiddelde uitstoot zijn er specifieke omstandigheden met hogere uitstoot. De praktijk NO_x uitstoot lag ook bij de nu geteste nieuwste generatie trucks bij lage snelheden tot 50 km/h met waarden van 1050 tot 1780 mg/kWh nog hoger dan de limietwaarde. Dat komt voornamelijk door de koude start en het rijden bij een gemiddelde lage motorlast. Dit zijn namelijk beide situaties waarbij het SCR systeem, dat de NO_x uitstoot van een dieselmotor sterk moet verlagen, nog niet of maar deels op werktemperatuur is. De NO_x uitstoot bij lage snelheden tot 50 km/h, zoals die optreedt bij het rijden in de stad, maakte voor de drie geteste voertuigen 45 tot 60% uit van de totale uitstoot, ondanks het lage aandeel gereden kilometers in de stad (5% en 7% voor de lange afstand trucks en 20% voor de distributietruck). Bij hoge snelheden, zoals rijden op de snelweg is de NO_x uitstoot laag met waarden van 130 tot 170 mg/kWh.

De drie voertuigen met een Euro VI step D motor lijken qua NO_x wat schoner dan de eerdere Euro VI generaties (Step A tot C). De lichte truck met een Euro VI D motor had over het hele snelheidsbereik een lagere NO_x emissie dan twee vergelijkbare lichte trucks (Step A tot C) die eerder zijn gemeten in het kader van het Nederlandse steekproefcontroleprogramma. De twee trekkers met een Euro VI step D motor hadden met name lagere NO_x emissies bij hogere snelheden (>50 km/u). Omdat de testomstandigheden verschillend waren en omdat slechts drie voertuigen zijn getest kan niet worden geconcludeerd dat trucks met een Euro VI step D motor significant schoner zijn dan de eerdere Euro VI generaties. Om met zekerheid een conclusie te kunnen trekken, zouden meer voertuigen met een Euro D motor moeten worden getest.

---

[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

De meeste voertuigen halen de NO_x screeningtest die indicatief is voor de formele Europese conformiteitstest
In het doorlopende meetprogramma werden alle Euro VI vrachtwagens onderworpen aan een screeningstest die indicatief is voor de Europese controle van de conformiteit van in gebruik zijnde voertuigen. Een emissiescreeningstool (SEMS) analyseert de NO_x uitstoot tijdens praktijkinzet. Wanneer de uitslag hoger ligt dan een vastgestelde drempelwaarde wordt door TNO besloten om het voertuig de officiële vastgestelde route te laten rijden die wordt voorgeschreven voor het controleren van de Europese conformiteit met een officiële wegtest.

De initiële screening voor de NO_x uitstoot leidde bij 29 van de 41 gescreende trucks met een Euro VI motor tot een uitslag die in de praktijkinzet lager lag dan de vastgestelde limietwaarde voor de screening.

Bij zeven voertuigen werd na een initiële uitslag die hoger lag dan de vastgestelde limietwaarde, bij een nadere test een goede uitslag gehaald wanneer de officiële route van de Europese wegtest werd gereden. Dit geeft aan dat de officiële testroute waarschijnlijk niet representatief is voor de praktijkinzet van het geteste voertuig.

Bij één voertuig voldeed de testroute achteraf niet aan de eisen.

Bij de conformiteitsscreening van drie verschillende trucks met hetzelfde motortype werden verschillende problemen gevonden: een hoge NH_3 emissie wat de reden was voor het testen van een tweede truck en een hoog NO_x emissiescreenings-testresultaat bij de tweede truck. De derde truck had witte aanslag in de uitlaat, wat een indicatie is van een niet goed functionerend SCR systeem.

Bij één voertuig trad een eenvoudige storing op waardoor het SCR systeem niet meer functioneerde met als gevolg sterk verhoogde NO_x emissies.

Het boorddiagnosesysteem bleek bij twee voertuigen niet effectief in het bewaken van de werking van de NO_x reductiesystemen
Moderne vrachtwagens zijn verplicht uitgerust met een boorddiagnosesysteem (OBD, On-Board Diagnostics) om onder meer de werking van het emissie-beheerssysteem te controleren en bij een defect een voor de chauffeur zichtbare storingsmelding te geven of, bij ernstige storingen, zelfs het vermogen van de motor terug te schroeven. Bij twee geteste voertuigen traden storingen op waardoor het emissiebeheerssysteem niet goed functioneerde. Bij één voertuig was er geen melding, bij het andere voertuig was er geen duidelijke melding van de storing.
In beide gevallen werden in het geheugen van het boorddiagnosesysteem geen zogenaamde foutcodes geregistreerd, nog was er sprake van een terugname van het motorkoppel. Hierdoor konden de voertuigen met niet of slechts deels werkende SCR systemen, en sterk verhoogde NO_x emissies, rond blijven rijden. In één geval heeft de fabrikant inmiddels een duidelijkere storingsmelding ingevoerd.

De NO_x uitstoot neemt toe over de levensduur
Metingen die zijn gedaan op verschillende momenten tijdens de levensduur van een trekker met een Euro VI gecertificeerde motor laten zien dat de NO_x uitstoot bij hogere kilometerstanden geleidelijk toeneemt.

Een beperkt aantal praktijktesten in het buitenland en gericht onderzoek [CLOVE, 2019] lieten al zien dat SCR systemen verouderen, met als gevolg een over de levensduur toenemend niveau van de NO_x uitstoot. Het boorddiagnosesysteem moet bewaken dat de uitstoot niet toeneemt tot boven een limiet van 1500 mg/kWh (Step A en B) en 1200 mg/kWh (Step C, D en E).

Een laatste aanscherping van Euro VI, ‘Step E’, wordt 1 januari 2022 van kracht. Voor deze aanscherping van de regelgeving moeten in de officiële wegtest de emissies na een koude start 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 hun totale levensduur geeft inzicht in trends van de emissies over de levensduur van deze voertuigen en inzicht in de effectiviteit van de Europese Euro VI emissiewetgeving.

De Euro VI eisen zijn niet afdoende om levenslang lage NO_x emissies te garanderen. Zo sluit een formele ISC test nog data uit van de test. Daarom is onlangs 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 is dat Euro-VII er op moet focussen dat lage NO_x-uitstootwaarden in alle voorkomende praktijkomstandigheden en gedurende de werkelijke voertuiglevensduur worden gewaarborgd. Voor de officiële wegtest voor de emissies zouden alle zware voertuigen die vooral 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 van de OBD-controle en het beter beveiligen van het emissiebeheerssysteem (voorkomen van AdBlue Manipulatie). 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 de kans op hoge schadelijke emissies die optreden tijdens de levensduur van een voertuig, bijvoorbeeld door manipulatie of veroudering van systemen, worden verlaagd.

Summary

On behalf of the Ministry of Infrastructure and Water Management, TNO is carrying out the emission measurement program for trucks and buses. In this program, TNO measures and monitors the exhaust gas emissions of these vehicles on a regular basis to investigate how clean they are in practice and it is investigated by means of a so-called screening whether vehicles meet the European emission standards.

The data collected in these programs form the basis for an adjustment of the official figures for real-world emissions - the so-called emission factors - that TNO provides annually. Emission factors are used at national, regional and municipal level as input for calculation models for air quality, emission distribution and nitrogen deposition, and for the assessment of current and proposed policy. These numbers also form the basis for national and international reports on traffic emissions.
The knowledge gained is also used as a basis for Dutch input in the international negotiations on tightening the emission standards in Brussels and Geneva.

The test vehicles for the measurement program are selected from fleets of Dutch transporters on the basis of the ranking of the registration numbers in the Netherlands. Euro VI vehicles now represent a large and rapidly growing share in the Dutch fleet. Since the entry into force of Euro VI on January 1, 2014, the measurement program focuses mainly on measuring and monitoring the practical emissions of mainly commercial vehicles with a diesel engine that meet this standard, and the focus is mainly on NO_x and particulate emissions (ultra-fine particles PM0.1; particles up to approximately 0.1 micrometre diameter).
The NO_x emissions are determined with SEMS (Smart Emissions Monitoring System). This is an instrument that continuously measures NO_x emissions during normal use of the vehicle. The functioning of the particulate filter is checked by measuring the number of soot particles in the exhaust at no-load, low idle speed. This is the method that is provided for the general periodic inspection (APK) in the Netherlands for checking the operation and presence of a soot filter.

This report reports on the results of the emission measurement program for trucks for the years 2019 and 2020. It concerns:

- Field emission measurements and emission screening tests carried out on three trucks that meet the European requirements that came into effect in September 2019 (Euro VI, step D).
- Field emission measurements and emission screening tests performed on a truck with a two-fuel engine (LNG diesel).
- Results of completed research into two cases with abnormal emissions.
- An overview of the NO_x screening tests that have been carried out in recent years with some forty vehicles with a Euro VI certified engine.
- Results of a long-term measurement of the emissions for monitoring the NO_x and NH_3 emission levels over the life of a truck with a Euro VI certified engine.

Brief summary of results

The result of the research is that the three tested trucks of the latest Euro VI generation (Euro VI D) can on average be regarded as clean in the daily use in which they have been tested. The NO_x emissions per km are on average about 60% of the official standard and the use of particulate filters resulted in very low emissions of soot particles from the exhaust. These test results give an indication that these vehicles are slightly cleaner than the previous generation (with Euro VI A to C emission standard). Whether this is actually the case can be determined by testing more vehicles. As with previous generations, most of the NO_x emissions are emitted at low speeds, such as when driving in the city. This is because the SCR system, which is supposed to reduce the NO_x emissions of a diesel engine, does not or partly reaches operating temperature under these driving conditions.
The dual fuel truck (LNG with diesel pilot injection) also turned out to be clean.

The emission screening and monitoring instrument SEMS (Smart Emissions Monitoring System) has been used to provide an indication of whether vehicles meet the European standard for the conformity of vehicles in use. Most of the 40 vehicles tested with a Euro VI engine had a screening result that was lower than the specified limit value when a formal test route was driven. Of the forty trucks tested four vehicles showed problems. Three different trucks with the same engine type were found to have different problems. The first and second vehicles had a high ammonia emission and a high NO_x screening result, respectively. In the third vehicle and a vehicle of a different make and type, the on-board diagnosis system was found to be ineffective in detecting malfunctions of the emission control system, causing these two vehicles to drive around for a long time with greatly increased NO_x emissions.

The truck, which was monitored and measured for a long time, showed a gradual increase in NO_x emissions and a decreasing NH_3 emission with increasing mileage.

The current Euro VI requirements therefore do not yet guarantee low NO_x emissions in the city or in some cases when malfunctions occur. The life-time requirements are also limited to approximately half of the normal life and no requirements are imposed on the real-world emissions of NH_3. Further tightening of the European requirements after Euro VI is necessary to regulate this better.

Extensive summary of the results

The three trucks of the latest Euro VI generation (Euro-VI D) are on average clean during their daily use
The three trucks tested with a Euro VI D certified engine with a low mileage are each on average clean during daily operation. Two of the vehicles tested are heavy tractor semi-trailers, the other vehicle was a lighter distribution truck. With values of an average of 370 to 400 mg / kWh in daily use, NO_x emissions were below the limit value of the official practical test (690 mg / kWh). However, it cannot be concluded on the basis of these tests whether the vehicles meet the European requirements. For this, the official PEMS test must also be carried out on a minimum of three different trucks of the same type.

The level of NO_x emissions still depends on how the vehicle is used. Because the use can differ from vehicle to vehicle, the results of vehicles tested in their daily use cannot be compared with each other.

Most of the NO_x emissions are emitted at low speeds
Despite the low average emissions, there are specific conditions with higher emissions. In practice, NO_x emissions were even higher than the limit value for the now tested latest generation trucks at low speeds of up to 50 km / h with values from 1050 to 1780 mg / kWh. This is mainly due to the cold start and the driving at an average low engine load. These are both situations in which the SCR system, which must significantly reduce the NO_x emissions of a diesel engine, is not yet or only partially at operating temperature. The total NO_x emissions at low speeds of up to 50 km / h, as occurs when driving in the city, accounted for 45 to 60% of the total emissions for the three tested vehicles, despite the low share of kilometers driven in the city (5 and 7% for the long-haul trucks and 20% for the distribution truck).
At high speeds, such as driving on the motorway, NO_x emissions are low with values from 130 to 170 mg / kWh.

The three vehicles with a Euro VI D engine seem somewhat cleaner in terms of NO_x than the previous Euro VI generations (A to C). The light truck with a Euro VI D engine had a lower NO_x emission over the speed range than two comparable light trucks that were measured earlier. The two tractors with a Euro VI D engine had notably lower NO_x emissions at higher speeds (> 50 km/h). Because the test conditions were different and because only three vehicles were tested, it cannot be concluded that trucks with a Euro VI D engine are significantly cleaner than the previous Euro VI generations. To investigate this, more vehicles with a Euro VI D engine should be tested.

Most vehicles pass the NO_x screening test, which is indicative of the formal European conformity test
In the continuous measurement program, all Euro VI trucks were subjected to a screening test that is indicative of the European verification of the conformity of vehicles in use. An emissions screening tool (SEMS) analyzes the NO_x emissions during normal use. If the result is higher than a predetermined threshold value, TNO will decide to let the vehicle drive the officially established route that is prescribed for checking European conformity with an official road test.

The initial screening for NO_x emissions resulted in 29 of the 41 trucks screened with a Euro VI engine with a result that was lower than the set limit value for the screening.

In seven vehicles, after an initial result that was higher than the set limit value, a good result lower than the set limit value was achieved during a further test when the official route of the European road test was driven. This indicates that the official test route is probably not representative of the field use of the tested vehicle.

For one vehicle, the test route subsequently failed to meet the requirements.

During the compliance screening of three different trucks with the same engine type, several problems were found: a high NH_3 emission, which was the reason for testing a second truck.

A high NO_x screening result on the second truck was the reason to test a third truck. The third truck had white deposits in the exhaust, which is an indication of a malfunctioning SCR system.

In another vehicle, a simple malfunction occurred, causing the SCR system to stop functioning, resulting in greatly increased NO_x emissions.

The on-board diagnostic system was found to be ineffective in monitoring the NO_x reduction systems in two vehicles
Modern trucks are required to be equipped with an on-board diagnostic system (OBD, On-Board Diagnostics) to, among other things, check the operation of the emission control system and, in the event of a defect, to give a fault message visible to the driver or, in the case of serious faults, even reduce the power of the engine. Faults occurred in two tested vehicles, causing the emission control system to malfunction. In one vehicle there was no report, in the other vehicle there was no clear report of the malfunction. In both cases, no so-called error codes were registered in the memory of the on-board diagnostic system, and there was no reduction of the engine power. This allowed the vehicles to drive with non-functioning or only partially functioning SCR systems and greatly increased NO_x emissions. In one case, the manufacturer has introduced a clearer malfunction indication.

NO_x emissions increase over the lifespan
Measurements taken at various times during the life of a tractor with a Euro VI certified engine show that NO_x emissions gradually increase at higher mileage. A limited number of practical tests abroad and targeted research [CLOVE, 2019] have already shown that SCR systems age, resulting in an increasing level of NO_x emissions over the lifetime. The on-board diagnostic system must monitor that emissions do not increase above a limit of 1500 mg / kWh (Euro VI A and B) and 1200 mg / kWh (Euro VI C, D and E).

A final tightening of Euro VI, "E", will take effect January 1, 2022. For this tightening of the regulations, the emissions after a cold start must be included in the test evaluation in the official road test. The emission of particle numbers must also be included in the test evaluation.

Emission tests will have to show what the effect of both steps (D and E) is on the emission level during daily use. Monitoring the emissions of heavy commercial vehicles over their entire lifespan provides insight into trends in emissions over the lifespan of these vehicles and insight into the effectiveness of European Euro VI emission legislation.

The Euro VI requirements are not sufficient to guarantee low NO_x emissions for a whole vehicle life. For example, a formal in-service conformity test excludes data from the test. That is why an inventory was recently started within the EU into the necessity and the possibilities for tightening the standards for trucks after Euro-VI. Insight from the measurements carried out is that Euro-VII must focus on ensuring that low NO_x emission values are guaranteed in all common real-world conditions and during the actual vehicle life. For the official road emissions test, all heavy-duty vehicles primarily used in urban areas should be tested with a representative deployment profile, with urban driving being the major part of the test, as is the case with city buses.

When setting standards in accordance with Euro VII, attention must also be paid to making the OBD control more robust and better securing the emission control system (preventing AdBlue manipulation). Monitoring the emissions with the help of the on-board sensors over the life of the vehicle can extend the scope of the monitoring. This can reduce the risk of high harmful emissions occurring during the life of a vehicle, for example from manipulation or aging of systems.

Contents

1 Introduction

Reduction of the tail pipe NO_x emissions from vehicles is desirable from an air quality point of view and for the reduction of nitrogen deposition, and eutrophication, in nature reserves. In the last two decades, the EU emissions regulation aimed to reduce the NO_x emissions from vehicles. For heavy duty vehicles with a diesel engine the regulation only managed to establish substantial reductions as of the introduction of Euro VI (Vermeulen et al., 2016) at the end of 2013. This substantial reduction of the NO_x emissions from diesel engines of heavy-duty vehicles is mainly achieved by the application of Selective Catalytic Reduction (SCR). The SCR system is often complemented by Exhaust Gas Recirculation that reduces the NO_x load from the diesel engine entering the SCR.

For vehicles with the first generation of Euro VI engines it was reported (TNO 2014 and TNO 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 with a vehicle on the public road instead of only testing an engine in a laboratory test bench. As of Euro VI (31 December 2013), this road 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 2019) and (Söderena, P., Nylund, N., 2018) showed that for certain heavy-duty vehicle applications despite the more stringent Euro VI requirements, the NO_x emissions may be higher than expected, especially at lower speeds as occur in urban driving. On motorways NO_x emissions levels were mostly on average comfortably below the level of the Euro VI limit.
The shortfall of the PEMS road test to control NO_x emissions at low speeds was recognized and addressed by changing the test requirements and the evaluation of the test for Euro VI certified engines. Changes in the requirements are marked as different ‘steps’. With step D, which was entered into force by September 2019, substantial improvements were introduced, aiming at a better control of NO_x emissions under low load, low speed driving conditions.

The general objectives of the Dutch in-service emissions testing programme are to:
- Determine the Dutch emission factors for the Dutch fleet of heavy commercial vehicles.
- Determine trends over the different EU standards and steps: Are the vehicles getting sufficiently cleaner with each generation/step in the real world?
- Use the data and insights in Brussels in discussions about the improvement of the test procedures and EU standards.
- 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.

On behalf of the Ministry of Infrastructure and Water Management, TNO measures the real-world emissions of a selection of heavy-duty vehicles representative for the Dutch fleet.

This report documents the results of the measurements that were conducted in the period 2019 to 2020 with the addition of new data of three of the latest generation vehicles with Euro VI step D certified engines, a vehicle with a heavy-duty dual fuel engine, two concluded cases and long term durability testing of one vehicle. The report also contains an update on NO_x emissions screening throughout the programme in the period 2015 to 2020. For now in total 40 vehicles with Euro VI certified engines were screened.

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

For the general objectives of the programme the goal of the emissions measurement programme is to:
- determine 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 to an alternative screening method. PEMS is used for testing the in-service conformity according to formal requirements or to accurately determine emissions levels over defined on-road test trips. Both systems and the test methodology are described in [Heijne et al., TNO 2016a].

2.1 SEMS, Smart Emissions Measurement System

SEMS is a sensor-based system developed by TNO [Heijne et al., TNO 2016a] 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.

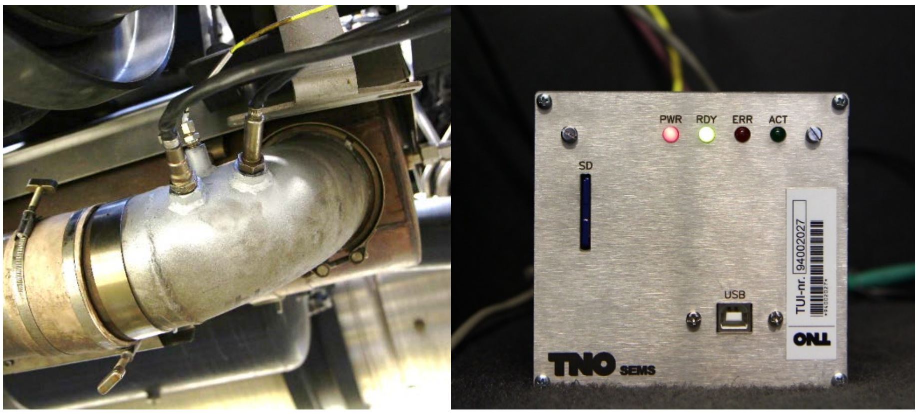

Figure 1: SEMS. *Left*: calibrated NO_x-O_2 sensor, NH_3 sensor and temperature sensor mounted in the tail-pipe. *Right*: autonomously running data recording unit with hourly data transmission to a central server via GPRS.

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 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[2].

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 during installation of SEMS 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 manufactured by 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% 0-90%	 <5s <10s

[2] EC regulation 582/2011

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 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*. Overall results are reported in an annual report. And a summary of the result of each vehicle is send 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 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.

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 2019a].

Report [TNO 2019a] reported the status quo of NO_x emissions of heavy-duty vehicles with an engine certified Euro VI step A to C.

This report discusses results of three newer vehicles with engines with Euro VI step D certified engines and results of investigations that were still running but weren't concluded before the previous report [2019b] was published.

This concerns:
- two cases where problems were found with the emissions control system,
- one case for which emissions tests have been performed since 2013 to determine a possible effect of aging on the level of the NO_x emissions over the life time of the vehicle and
- one case for which extensive PEMS test have been performed and reported but the SEMS tests during normal operation were still running (heavy-duty dual fuel engine (LNG-Diesel)).

Table 2 summarizes the most important requirements for the different steps under Euro VI.

Table 2: 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	0,40 / 0,46 g/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	(A to D) 10% highest MAW, power threshold (see below), (E) 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 one full urban MAW	PEMS payload	Implementation date all vehicles
A	1.5	N	20	N	N		50-60%	31-12-2013
B	1.5	N	20	N	N		50-60%	01-09-2015
C	1.2	Y	20	N	N		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%	01-01-2022[1]

[1]derogation for PI and HDDF engines.

Table 3: Overview of the test sample. All vehicles have a Euro VI certified engine. The number with a ‘+’ sign is for vehicles reported for the first time in this report. These are SEMS measurements with the vehicles with a step D certified engine and the SEMS measurements with a vehicle with a Heavy-Duty Dual Fuel (HDDF) engine.

		PEMS	**SEMS**
Tractor (semi) trailer	CI*(Diesel) N3 step A to C	6	10
	CI*(Diesel) N3 step D		+2
	SI** (LNG) N3 step A to C	2	
	HDDF*** LNG - diesel N3,1A step A to C	1	+1
Rigid	CI (Diesel) N2 step A to C	1	4
	CI (Diesel) N2 step D		+1
	CI (Diesel) N3 step A to C		4
Refuse Collection Vehicle	CI (Diesel) N3 step A to C		8
	SI (LNG) N3 step A to C		1
	SI (CNG) N3 step A to C		1
Buses	CI (Diesel) 12m step A to C	2	2
	CI (Diesel) 18m step A to C		3
Tipper	CI (Diesel) N3 step A to C		1

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

Table 4: Specifications of the heavy-duty vehicles selected for the 2020 programme, the focus for vehicles for the 2020 programme was on testing vehicles with a Euro VI step-D certified engine, and vehiclesfor which testing has started in 2018 or 2019 and which are concluded in 2020 and reported in this report.

TNO vehicle code	Make/ model	Euro class, step	Engine, EU vehicle category	Odometer [km]	Vehicle configuration	Application	Tests	Remarks
Tests already running before 2020 and reported in this report								
DA122	DAF XF	VI, A	CI, N3	29.900-843.573	Tractor + semi-trailer	National + international distribution	PEMS N3, SEMS N3	MIL during testing programme
DA173	DAF CF	VI, A	CI, N3	38.741-43.271	Refuse collection vehicle with e-PTO	Collection of refuse	SEMS normal use, SEMS N3	Short MIL during normal use and test, not noted by test engineers
VO180	Volvo FH	VI, C	HDDF/1A, N3	19.990-158.694	Tractor + semi-trailer	National distribution	PEMS N3, SEMS normal use	No MIL
MA181	MAN TGX	VI, B	CI, N3	90.000-424.406	Tractor + semi-trailer	National distribution	SEMS normal use	No MIL
New tests 2020								
VO182	Volvo FH	VI, D	CI, N3	26.841-34.067	Tractor + semi-tanker trailer	National + international distribution	SEMS normal use	No MIL
DA183	DAF XF	VI, D	CI, N3	65.463-66.735	Tractor + semi-trailer	National + international distribution	SEMS normal use	No MIL
DA184	DAF LF	VI, D	CI, N2	32 763-41.422	Rigid	Local/National distribution	SEMS normal use	No MIL

[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.

Figure 2: Tested vehicles with Euro VI step A to C certified diesel engines and one heavy-duty dual fuel engine (below left).

Figure 3: The three test vehicles with Euro VI step D certified diesel engine. The tests on the vehicle on the right were ordered by AECC (Association for Emissions Control by Catalyst).

3 Results

3.1 In-service conformity screening

The majority of vehicles with a Euro VI certified engine 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 has led 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. There seems to be an optimization of the emission control towards the ISC test, where not all parts of normal operations are covered. Even converting data of normal use to the ISC data using the pass-fail evaluation does not close this gap [AECC 2020]. Also there is a difference between the routes driven. The PEMS ISC test route has to fulfil various requirements, is limited in time (engine work) and does not contain the large variations that occur in normal operation, such as manoeuvring, docking, short trips, semi-warm starts etc. Also the PEMS trips can still be optimized to achieve low emissions over the test. In the case of one PEMS test, the test proved not fully compliant with the formal ISC requirements.

For two vehicles the initial SEMS screening test result lead to the decision to further investigate the concerning vehicle. See paragraphs 3.1.1 and 3.1.2.

Table 5: Overview of ISC screening test results of vehicles with Euro VI certified engines.

EU vehicle category, engine		PEMS test (# of vehicles)
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) (and SF <1.5)
M3, CI		CF<1.5 (2)
	Step 1 SEMS screening test normal daily operation (# of vehicles)	**Step 2, when SF step 1 > 1.5 SEMS screening over applicable ISC test route (N2, N3, …) (# of vehicles)**
N3, CI	SF<1.5 (8)	
	SF>1.5 (4)	SF<1.5 (4)
	SF>1.5 (1) high ambient temperature no MI	SF=1.5 Additional investigation completed, see par. 3.1.1 (1)
	Vehicle 1. SF<1.5 high ammonia (1) Vehicle 2. SF>1.5 (1) Vehicle 3. test error SCR deposits (1)	Additional investigation completed, see par. 3.1.2 (1)
N2, CI	SF<1.5 (5)	
	SF>1.5 (2)	SF <1.5 (2)
M3, CI	SF<1.5 (4)	
	SF>1.5 (1)	SF<1.5 (1)

3.1.1 *Case MA181*

An emission test was performed with a Smart Emission Measurement System (SEMS) on a MAN TGX with a Euro VI step B certified engine. NO_x and NH_3 emissions were measured with SEMS during daily operation of the vehicle. Initially, the real-world NO_x emissions were on average 5.3 g/km and 5.8 g/kWh in daily use. The SEMS Factor was 8.8. The average ammonia concentration was very low. The owner said that the vehicle consumed hardly any Adblue, compared to other vehicles. During the installation of the SEMS it was noted that the ambient temperature on the display was 62 °C which was about 40 °C above the actual temperature.

Figure 4: Photo of the display in the dashboard showing a value for the ambient temperature which deviates about 40 °C from the actual ambient temperature.

A diagnostic check was performed with the MANcats diagnostic tool at the service workshop, to check for the presence of diagnostic trouble codes (DTC). No DTC related to the sensor nor the emissions control system were found and there was no Malfunction Indication. The ambient temperature sensor was replaced. After the repair the real-world NO_x emissions were on average 1.5 g/km and 1.4 g/kWh, the SEMS Factor was 1.5 and the average ammonia concentration was 26 ppm. After discussion with the OEM it was concluded that probably the temperature sensor had a malfunction. This was not detected because the sensors specification was still in range of the diagnostic tolerances as the sensor has a working range up to 80 °C. At the given high sensor values around 62 °C, however, the Adblue dosage is stopped by the motor management system because at such real ambient temperatures problems could arise because of possible changes of Adblue properties at those temperatures.

The conclusion is that the broken ambient temperature sensor has very probably caused the high NO_x emissions and the low Adblue consumption in the test period before the temperature sensor was replaced. A SEMS screening test lead to a SEMS Factor >>1.5 while no Malfunction Indication was present, nor a dtc (diagnostic trouble code) was stored. The vehicle could perform its normal operation with high NO_x emissions while the malfunction remained undetected by the OBD.

3.1.2 *Case DA173*

Emission tests were performed with a Smart Emission Measurement System (SEMS) on a DAF Euro VI N3 refuse collection vehicle of Breda city council with a step A certified engine (MX11). The vehicle has an electric PTO (Power Take-Off) with plug-in facility to power the hydraulic system.

NO_x and NH_3 emissions were measured with SEMS during daily operation of the vehicle. Due to a high SEMS Factor of 4.5 observed for this test, it was decided to perform an in-service conformity N3 trip on 19 January 2018. For this test the SEMS Factor was 3.0. On 5 April 2018 when the de-installation of the test equipment took place, it was observed that the inside of the tail pipe, and also the emissions sensors, had white deposits on them. After examination it was concluded that the white deposits could have influenced the emission test results because the deposits interfere with the measurement and can cause very high positive deviations from the real value. Because of this, all previous test results are considered invalid. The test engineers reported that the Malfunction Indicator was not lit. An diagnostic test (DAVIE 4) was performed on 5 April 2018 to check for diagnostic trouble codes. Despite the high NO_x emissions, no recent nor any older diagnostic trouble codes (dtc's) that could be related to a possible problem with the SCR system, were found.

The manufacturer was contacted and the test data was examined.
The manufacturer decided to investigate the vehicle. The following is based on information communicated by the manufacturer: the manufacturer concluded after examination that an error was present and the MI was lit (November 2018). DAF reported that the cause would be a problem with the HC-purger, a component necessary for active regeneration of the diesel particulate filter (DPF) and SCR. The engine ran in protection mode without active regeneration. As a result, deposits on the SCR could not be regenerated which caused accumulation of deposits in the SCR. The MI indicator possibly was not noted by the test engineers because it only lights up for 15 seconds after key on.

The deposits were removed manually by DAF and regeneration was triggered to clean the exhaust. A PEMS test was performed by DAF afterwards and DAF declared a CF well below 1.5. This value proved unreliable and the test was rendered 'invalid' due to a PEMS measurement error caused by the PEMS supplier during PEMS maintenance. Resultingly, definite conclusions could not be drawn. Another PEMS test has been performed, the result is that according to DAF the Conformity Factor over the valid test lies below 1.5.

It was remarked that the MI possibly was not noted by the test engineers of TNO due to the short period of 15s during which it is lit after key-on. DAF analysed the MI notification to drivers and decided to modify the system, i.e., the orange 'engine check' and the MI remain lit. This modification is taken in production in April 2019.

In the heavy-duty emissions testing programme this vehicle was the third vehicle tested in a row with the same engine type. Two other vehicles with the same engine type were tested before. The first vehicle had a high level of ammonia concentration in the exhaust. The second vehicle showed a SEMS Factor for NO_x higher than 1.5.

3.2 Results: real-world NO_x emissions of the tested vehicles

Total average NO_x emissions were determined for all vehicles. For the tested vehicles with a step D certified engine, these are N2 rigid lorries and N3 tractor semi-trailers. Also the results of the tested vehicle with a heavy-duty dual fuel engine (LNG- diesel) are presented.

There is a large spread in average speed mainly for the N2 rigid trucks. The N2 rigid trucks with a step A certified engine had a low average speed compared to the truck with a step D certified engine. The tractor semi-trailers have higher average speeds with still some, but less spread.

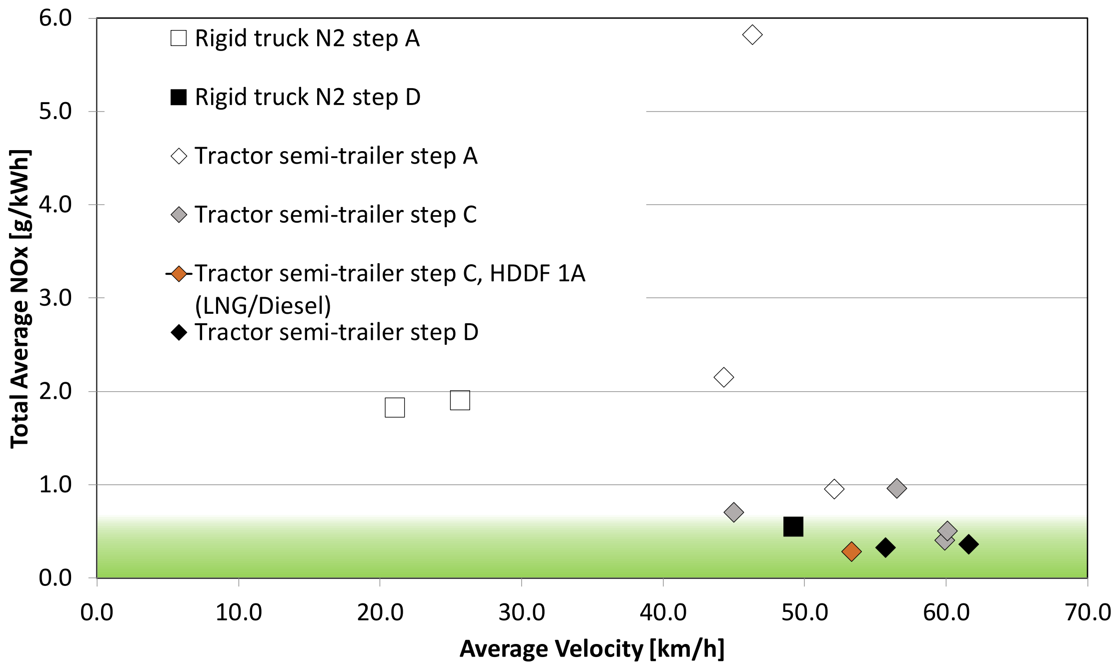

Figure 5: Total average NO_x emissions versus average speed for all vehicles tested with SEMS in normal daily operation. The upper side of the green area represent a NO_x emissions level of 0.69 g/kWh, which is the limit of the conformity factor of 1.5 expressed in gNO_x/kWh (1.5x0.46=0.69 g/kWh) for the formal ISC test. Individual vehicles can't be compared as operation differs from vehicle to vehicle.

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 all of the vehicles are higher. This is for a large share caused by the high emissions after a cold start when the Selective Catalytic Reduction system to reduce the NO_x emissions of the engine is not at it's working temperature and by driving at low speeds which can cause the SCR to stay below or to get below it's working temperature. This means that the share of cold starts and the amount and duration of driving at low speeds and loads largely determines the emissions level of NO_x. This makes it hard to compare different vehicles at these circumstances as operation probably did differ from vehicle to vehicle. At higher speeds, when the SCR is warm and more stable, the two vehicles with step D certified engines seem to have lower NOx emissions than comparable vehicles with step A certified engines, but the sample size of step D certified is still too low to draw firm conclusions for the impact on the emissions performance of the more stringent step D requirements. The vehicle with the heavy-duty dual fuel engine has generally low NOx emissions in its tested operation.

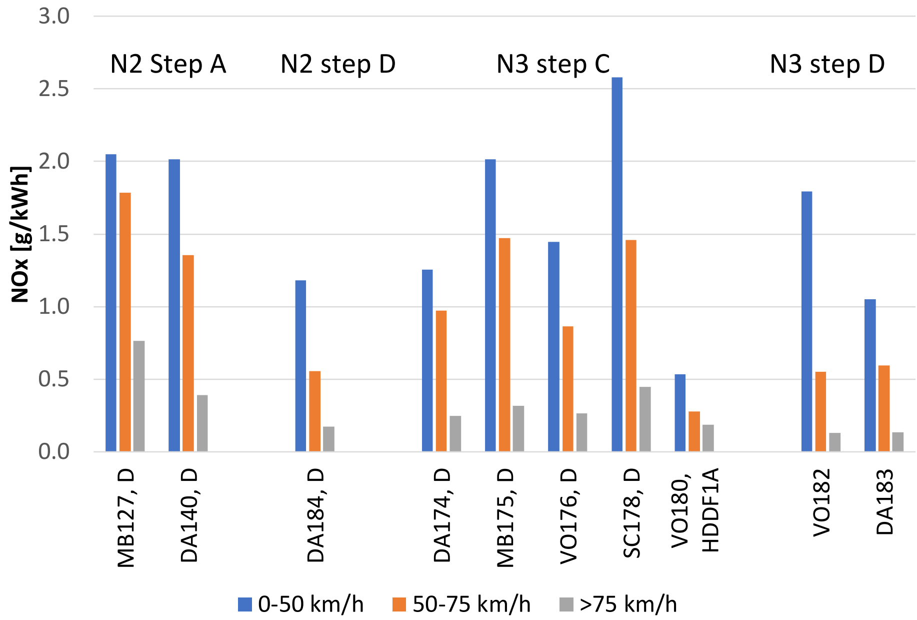

Figure 6: Overview of real-world NO_x emissions as measured with SEMS during daily operation for medium lorries and tractor semi-trailers, all with Euro VI certified engines (D=Diesel, HDDF = Heavy Duty Dual Fuel Engine). The vehicles with engines certified according different sub-class (Step A, C as tested in 2018-2019 and D) are shown together. Three speed ranges are distinguished. Individual vehicles can't be compared as operation differs from vehicle to vehicle.

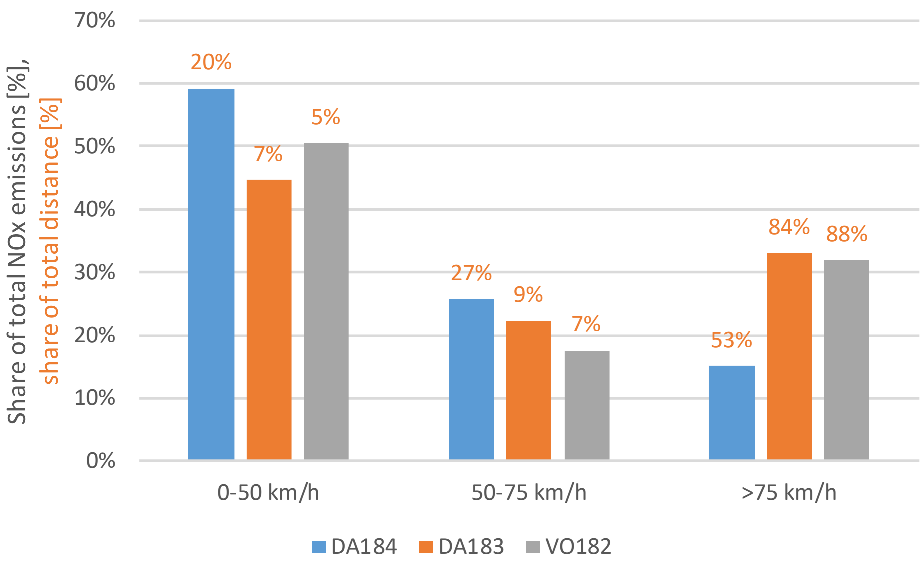

Figure 7: The share of the NO_x emissions of the total emissions per speed interval of the tested vehicles with a step D certified engine. A large share of the total NO_x (45 to 59%) is emitted at the low speed range whereas the most of the kilometres (53 to 88%) are driven in the higher speed range.

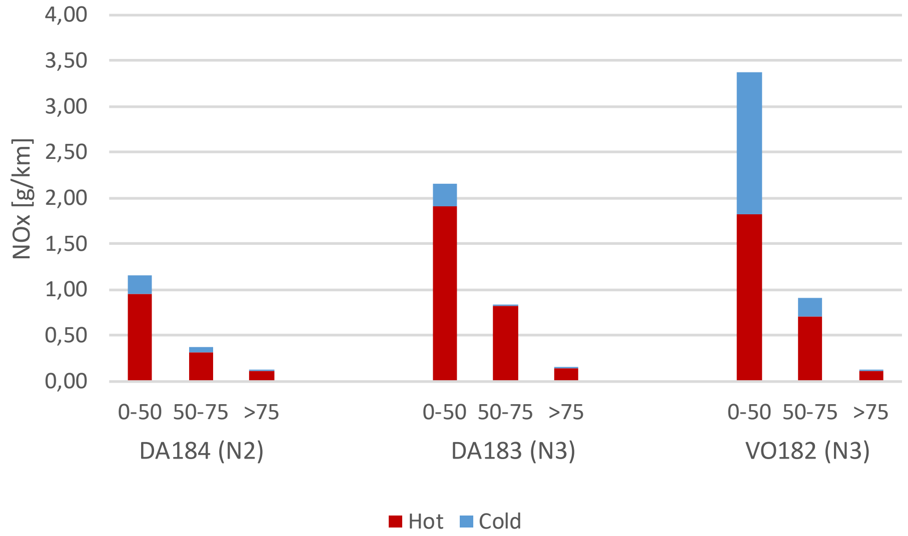

Figure 8: Contribution of cold starts in total emissions per speed interval: NO_x emissions when the engine has a coolant temperature <70 ºC (Cold) and >= 70 ºC (Hot).

3.3 Long term NO_x monitoring of a tractor semi-trailer.

From December 2013 until May 2020 several emissions tests were conducted on a DAF XF tractor semi-trailer (TNO test code DA122) to monitor the NO_x emissions over a large part of the normal lifetime of the vehicle. The first emissions tests were conducted when the vehicle had an odometer reading of 29.900 km. The tests ran until the odometer reading of 843.573 km which is beyond the ‘useful life’ of 700.000 km as determined in EU Regulation (EC) 595/2009, article 4(2) (For category N3 vehicles: 700.000 km or 7 years, whichever is the sooner).

Table 6: Overview of tests conducted over a part of the lifetime of the vehicle.

Odometer [km]	Date [dd-mm-yyyy]	Activity	Remarks
29.900	9-12-2013	PEMS tests, 2 N3 trips	No MIL
271.700	26-8-2015	PEMS tests, N3 trip	No MIL
380.392	8-3-2016	PEMS tests, N3 trip	No MIL
564.082	4-1-2018	Installation SEMS	
650.052	28-8-2018	SEMS test, N3 trip	MIL activated during test. The US NO_x sensor was defect. The owner had the sensor replaced.
n.a.	September 2019		MI ‘Adblue malfunction’ NO_x sensor US and DS and Adblue dosing unit were replaced
827.093	11-3-2020	SEMS test, 2 N3 trips	No MIL 1^{st} test invalid (DPF regeneration)
843.573	4-5-2020	De-installation SEMS	No MIL

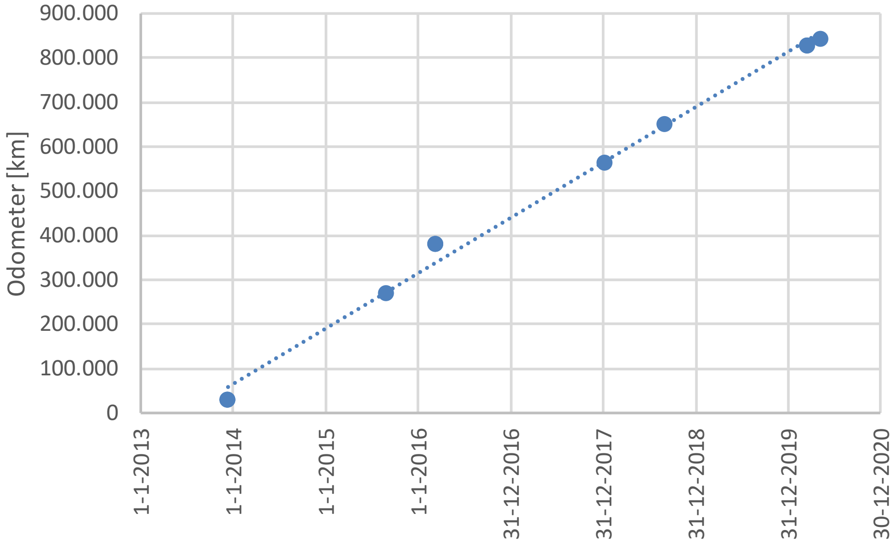

Figure 9: Odometer reading at various moment in time.

The vehicle drove on average 127.000 km per year. The on-board computer registered the consumption of 25678 liters of fuel which means a fuel consumption of 30,4 l/100km.

Conformity screening
PEMS tests, and later on SEMS tests, were executed at different mileages to determine the NO_x conformity factors. The tests were done according to the applicable rules for driving an N3 test route for vehicles with a Gross Vehicle Weight higher than 12t and for evaluation of the emissions data over the test.

Figure 10 shows the conformity factors over the N3 in-service conformity test routes at different mileages. The tests show CF's well below 1,5 at the lower mileages. At 650.052 km the SF (unofficial CF as determined with SEMS) is 2,0 but the MIL went on during the test. The upstream NO_x sensor had to be replaced and subsequently the vehicle owner has had a repair carried out where the sensor has been replaced. Due to planning issues of the vehicle no retest was possible at that time.

Starting with the test at 380.392km, the test results show a trend where the CF (or SF) increases at the higher odometer readings. The tests at an odometer reading of 827.093 km, where the useful life period is exceeded, show a SF of 1.6, after the first test appeared invalid because of a DPF regeneration.
At motorway speeds under fully warmed up conditions, the increase of the NO_x emission at a higher odometer reading is visible as well, see Figure 11.

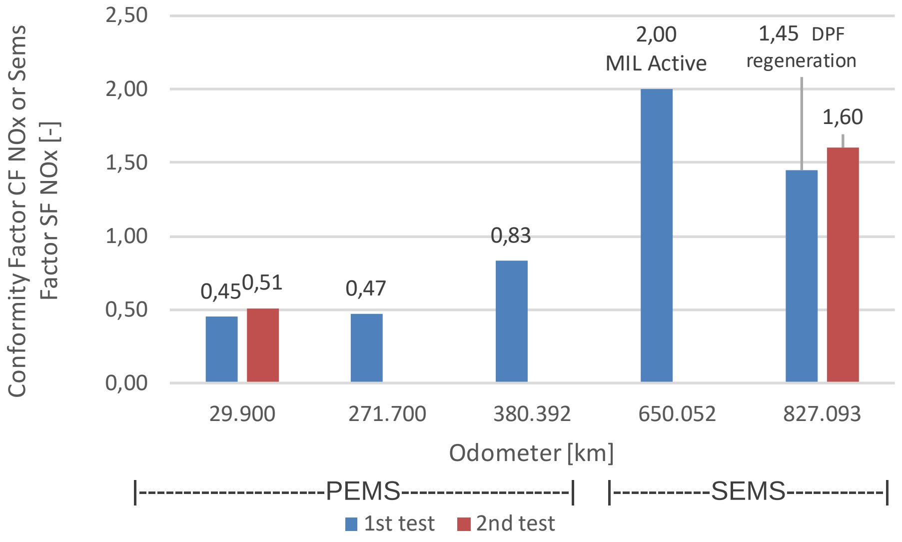

Figure 10: NO_x conformity factors (PEMS) and SEMS Factors (SEMS) over N3 in-service conformity test routes at different mileages.

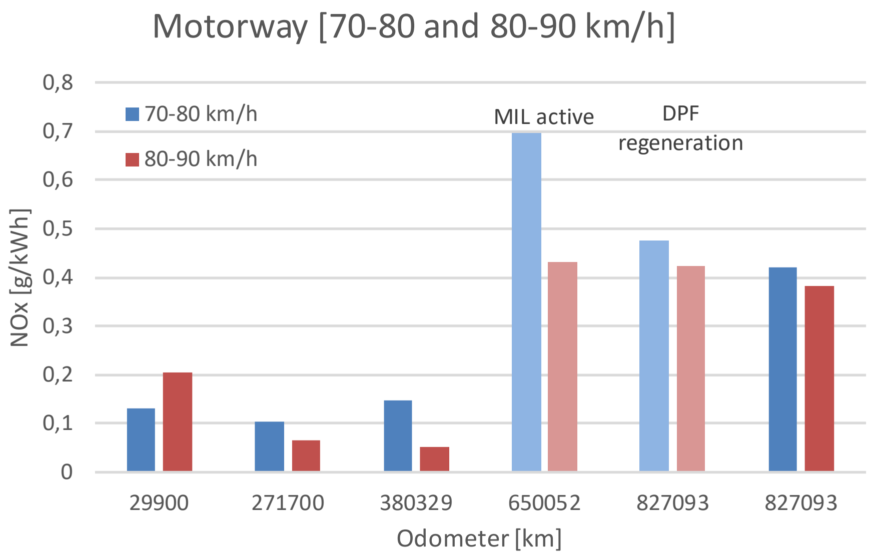

Figure 11: NO_x in speed bins at motorway speeds. The trips have comparable motorway driving with a fully warmed up drive train and aftertreatment. Trips are driven with the same total vehicle weight (tractor, semi-trailer and payload).

Long term monitoring of the NO_x emissions with SEMS
As of January 2018 a SEMS system was installed to monitor the NO_x and NH_3 emissions continuously over a long period of time until May 2020. Data was averaged to show possible trends of the emissions over time.

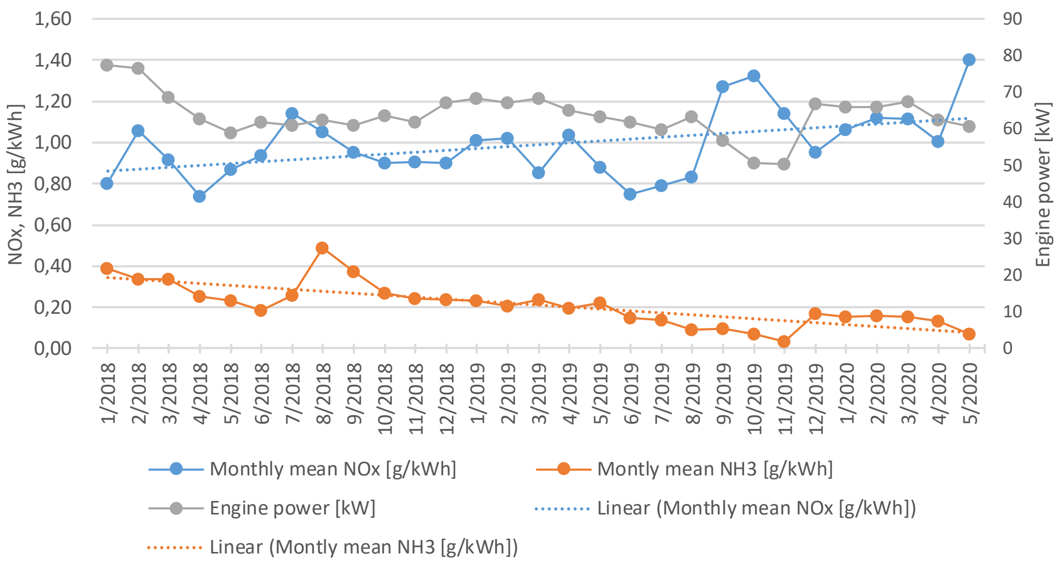

Figure 12: Monthly averages of NO_x and NH_3 emissions over almost 2,5 years, from 564.082 km in January 2018 to 843.573 km in May 2020. Linear trend lines show an increase of the NO_x emission and a decrease of the NH_3 emission over time starting at a very high level of NH_3 slip in 2018. The highest NH_3 emission in August 2018 coincides with the month in which an US NOx sensor had to be replaced after a Malfunction Indication. In September and October 2019 the NO_x emissions increased which may be partly caused by an decrease in average power. The owner mentioned an indication at the dashboard of an Adblue error that occurred in September 2019. The Adblue dosing unit and two NO_x sensors were replaced. A further detailed analyses showed a step in NO_x emissions though. See Figure 13. NH_3emissions level is indicative as the sensor used for the measurement is inaccurate at higher NH_3 concentrations.

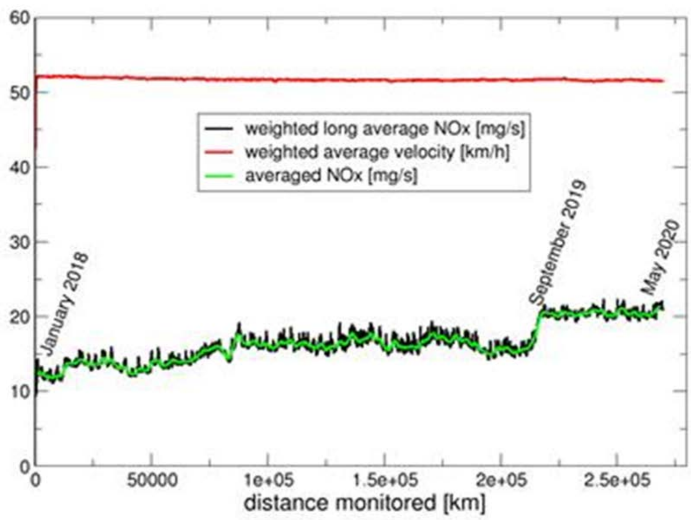

Figure 13: A statistical approach weighing influences of cold starts, velocity, engines speed and CO_2 emissions give the corrected NO_x emissions in mg/s over time. This reveals a step in NO_x emissions from about 15 to 20 mg/s around September 2019. The owner mentioned an indication at the dashboard of an Adblue error that occurred in September 2019. The Adblue dosing unit and two NO_x sensors were replaced.

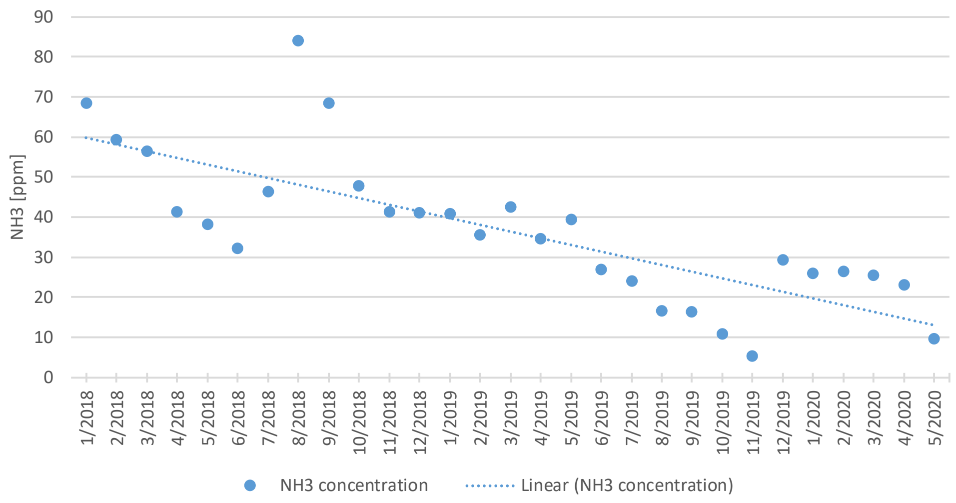

Figure 14: Monthly mean NH_3 concentration from 564.082 km in January 2018 to 843.573 km in May 2020.

3.4 Monitoring particulate matter number emissions

As of entry into force of 'Euro VI', compulsory from 2014 onward, 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].

Some heavy-duty vehicles have active regeneration of DPF, which may lead to additional PM emissions in normal use. Other use a slight increase in exhaust gas temperature to increase soot removal from the DPF. However, there are also Euro-VI trucks that do not seem to have any active control for the DPF, but continuous operation.

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 rpm). Additionally, the local ambient particle concentration is measured. The measurements are conducted when the vehicle is prepared for the SEMS test or when the SEMS equipment is removed. For the measurement, the NPET instrument of TSI is used.

Measurements conducted on seven heavy duty vehicles show particle number concentrations at given engine speeds under no load conditions below concentration found in the ambient air. The eighth vehicle has slightly higher particle number emissions. With a warm engine and when idling a well-functioning DPF of a passenger car has a PN emission below 5.000 #/cm^3 [TNO 2020] . With a cold engine PN concentrations can be higher, up to 250.000 #/cm^3. For the future periodic inspection test of passenger cars with a DPF the PN concentration of 250.000 #/cm^3 is set as a limit value. The results with PN concentrations at idling well below 5.000 for all tested seven vehicles and just above 5.000 #/cm^{3}for one vehicle indicate that the tested vehicles have properly functioning diesel particle filters.

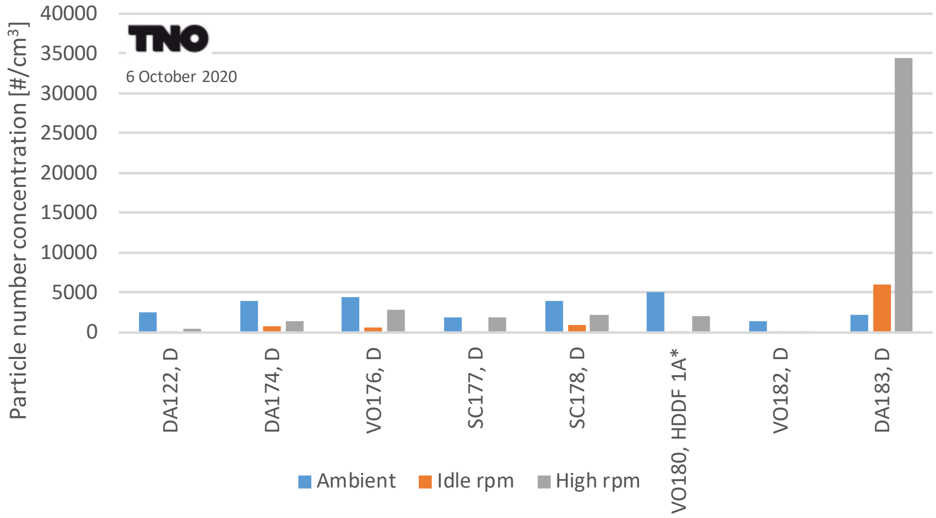

Figure 15: Particle number concentration measured at a stationary test in the ambient air and in the tail pipe at idle and high engine rpm settings. This test is used to screen for possible problems with diesel particle filters. The test is introduced at a later stage as part of the SEMS test procedure. The test is conducted when SEMS is mounted to the vehicle. *The VO180 with HDDF (heavy-duty dual fuel) engine is measured with the TSI APET (Automotive Particle Emission Tester) whereas the other vehicles were measured with the TSI NPET (Nano Particle Emissions Tester).

4 Conclusions

In the Dutch in-service emissions testing programme for heavy-duty vehicles three representative vehicles with Euro VI step D certified engines of different categories were tested and tests and investigations of three other vehicles that were still running since 2019 were concluded. The tail-pipe emissions levels of the vehicles 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.

- Three vehicles, two tractor semi-trailers and a rigid distribution truck with step D certified engines have real-world average NO_x emissions ranging from 370 to 400 mg/kWh.
  - The average in-use NO_x emissions are lower than the limit of 690 mg/kWh (CF=1,5[3]) of the formal EU road test with Portable Emission Measurement System (PEMS). A side note is that this limit only accounts for the formal EU PEMS test procedures.
  - A large share of the NO_x emissions is emitted at low speeds from 0-50 km/h such as in urban areas. In this speed range, the NO_x emissions of the three vehicles range from 1050 tot 1780 mg/kWh. Due to these high levels, despite the lower mileages at low speeds, the share is 45 to 59% of total NO_x emissions.
  - A part of the higher NO_x emission at low speeds is caused by the cold start, when engine and aftertreatment are still cold or partly cooled down and cannot reduce the NO_x emissions from the diesel engine with a high efficiency. The cold start and driving after a cold start, until the engine coolant has reached 70 ºC, contribute 8 to 31% of total NO_x emissions of the three vehicles with Euro VI step-D certified engines.
  - Another part of the higher NO_x emissions at low speeds is still caused by operation at low loads and idling due to which the SCR system cools down or cannot reach its working temperature. At higher speeds >50 km/h the average NO_x emissions are clearly lower than the limit of the EU PEMS test, but at low speeds the warm engine emissions are 1000 to 1200 mg/kWh.
  - The NO_x emissions of the three vehicles driving typical motorway speeds are around 150 mg/kWh.
- The emissions are measured in the real world over normal operation by the transport companies. The conditions, such as routes, driving style and payload differ. This means that results of individual vehicles cannot be compared.
- The improved procedure for the PEMS test for step D, with lower engine load (10% vs. 20% power threshold) and a mandatory urban part to be part of the evaluation, aimed at reducing NO_x emissions at these low speed conditions with a warm engine, but did not succeed in reaching NO_x emissions lower than the formal engine test limit of 0.46 g/kWh under those conditions. For the light N2 truck with a step D engine the NO_x emissions are lower over the speed range than of two comparable vehicles.

---

[3] With a conformity Factor of 1,5 to be applied to the NO_x limit of the WHTC engine of 460 mg/kWh the maximum NO_x emissions in a Moving Averaging Window (MAW) after applying the data exclusion rules (excluding data of a cold engine, low engine power and 10% of the highest MAW) is 690 g/kWh.

For the two tractors with step D engine the NO_x emissions at low speeds including cold start are at a comparable level, at speeds higher than 50 km/h the NO_x emissions are lower than comparable vehicles. Due to the small sample size and the fact that test routes were different, the effects are not statistically significant, but the vehicles with step D engine seem to have somewhat lower NO_x emissions. Differences in driving conditions lead to higher differences between individual vehicles than the differences noted between vehicles with different certifications. It is therefore recommended to test more vehicles with a Euro VI step D engine.

- A tractor semi-trailer with a heavy-duty dual fuel engine with LNG as main fuel has a low average in-use NO_x emission of 280 mg/kWh.
- The conformity screening of the NO_x emission lead for twenty-nine out of forty screened trucks with a Euro VI certified engine to a good test result. For seven vehicles, after an initially bad result, a good test result was achieved when the formal EU ISC PEMS test route was driven. For one vehicle the test route didn’t meet the formal requirements rendering the result invalid. For three trucks with the same engine type different problems were found: a high NO_x emission screening test result in normal operation, high NH_3 emissions and a third had white deposits in the exhaust indicating a malfunctioning SCR system. For the latter truck and another one, the on-board diagnostics appeared not effective in clearly indicating the malfunctions, because of which the two vehicles could continue normal operation with high NO_x emissions, see the next lines for further elaboration of the issues found.
- The screening tests lead to false positives in most cases because the ISC test regime excludes critical data with high NO_x emission events and in addition in normal operation there a large variety of conditions occur which are not covered in an ISC test.
- An official in-service conformity test still excludes too much information. It is therefore recommended to monitor lifetime emissions of vehicles such that also the effectiveness of policy measures can be determined. Emission monitoring during normal operation is necessary to obtain a representative insight in real emissions.
- Two vehicles with a Euro VI certified engine had a problem with malfunctioning components:
  - In one case the malfunction of a simple sensor was not detected by the on-board diagnostics but lead to deactivation of the SCR system and consequently, high tail-pipe NO_x emissions. The vehicles could continue normal operation while having high NO_x emissions of about 5000 mg/kWh, high above the limit.
  - In the other case a malfunction of the regeneration system lead to white deposits in the exhaust system which caused the SCR system to not work properly. The malfunction was indicated briefly just after key-on but the vehicle could continue its normal operation. Due to the fouling of the measurement sensor no reliable emission value could be determined.
  - In both cases the vehicles could continue normal operation while the SCR system did not work or did not work properly. In the two cases, the on-board diagnostics therefore failed its intended function to make sure that malfunctions leading to high NO_x emissions are immediately repaired.
- OBD systems do not always detect emission related malfunctions. It is therefore recommended to include improvement of diagnostic and monitoring functionalities as part of the Dutch position in the emission legislation development.

- One tractor semi-trailer vehicle with a Euro VI step A certified engine was measured at different moments during its lifetime and the NO_x and NH_3 emissions were monitored continuously as of an odometer reading of 560.000 to 840.000 km:
  - The NO_x emissions at lower odometer readings were within the limit of the PEMS test (CF<1.5). At 840.000 km a single non-formal test indicated a higher Conformity Factor of 1.6.
  - The monitoring of NO_x emission over time showed a slight increase NO_x emissions over 2.5 years of time from around 900 mg/kWh at 560.000km to 1200 mg/kWh at 840,000km with a larger step-like increase around 750,000km.
  - The NH_3 emissions gradually decreased over this monitoring period from monthly mean concentrations of about 70 ppm to 20ppm.
  - Malfunctions with NO_x sensors and the Adblue dosing system were indicated at the dashboard and the errors have been repaired by the owner.
- Indicative particle number concentration measurements have been conducted on eight 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 functionality of the DPF of DPF equipped vehicles. For the eight vehicles tested, the tail-pipe particle number (PN) concentrations of seven were below ambient PN concentrations and one vehicle had slightly higher than ambient concentrations. For all eight vehicles this indicates a well-functioning DPF for those vehicles.

For the vehicles with Euro VI D certified engines that were monitored, high NO_x emissions still occur at low speeds and after a cold start. For Euro VI step E, additional requirements have been implemented (effective 2022) for the PEMS test that should further improve the situation and especially the higher NO_x emission at lower speeds and loads and after a cold start. However, the PEMS test will not cover the variety of conditions that occur in normal operation in the Netherlands. To deal with this, PEMS tests should be all-inclusive, i.e. all random normal driving conditions should be considered in the test. 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. It is therefore strongly recommended to prolong these monitoring activities and to bring the findings forward in the Dutch position in the further development of EU emissions legislation.

Acknowledgements
Acknowledgments go to all transport companies which provided their vehicles for testing in the Dutch in-service emission testing programme.

5 References

[AECC 2020] AECC presentation 4th AGVES meeting 9 July 2020.

[CLOVE 2019] CLOVE Consortium, *Study on post-EURO 6/VI emission standards in Europe*, Brussels, October 18, 2019.

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

[TNO 2014] Vermeulen, Spreen, Ligterink, Vonk, *The Netherlands In-Service Emissions Testing Programme for Heavy-Duty 2011-2013*, TNO 2014 R10641 | 226 May 2014

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

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

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

[TNO 2017b] Kadijk, G., Vermeulen, R., Buskermolen, E., Elsgeest, M., van Heesen, D., Heijne, V., Ligterink, N., van der Mark, P., *NO_x emissions of eighteen Light Commercial Vehicles: results of the Dutch Light-Duty road vehicle emissions testing programme 2017*, TNO report R11473, 6 December 2017

[TNO 2018a] Vermeulen, R.J., van Gijlswijk, R., van Heesen, D., Buskermolen, E., Verbeek, R., van Goethem, S., *Tail-pipe NO_x emissions of refuse collection vehicles with a Euro VI engine in daily operation in the Netherlands*, TNO report TNO R 2018 10313|2, 15 June 2018

[TNO 2018b] Vermeulen, R.J., van Gijlswijk, R., van Goethem, S., *Tail-pipe NO_x emissions of Euro VI buses in daily operation in the Netherlands*, TNO report TNO 2018 R11328|1, 15 November 2018

[TNO 2018c] Vermeulen, R.J., Ligterink, N.L.I., *Evaluation of the EU real-world PEMS test for heavy-duty vehicles*, TNO report TNO 2018 R10550, 15 November 2018

[TNO 2019a] Vermeulen, R.J., *Emissions testing of a Euro VI LNG-diesel dual fuel truck in the Netherlands*, TNO report TNO 2019 R10193, 5 April 2019

[TNO 2019b] Vermeulen, R.J. van Gijlswijk, R., van Heesen, D., Buskermolen, E., van Goethem, S., *Dutch In-service emissions testing programme 2015 - 2018 for heavy-duty vehicles: status quo Euro VI NO_x emissions*, TNO report TNO 2019 R10519, 10 April 2019

[TNO 2020] Gerrit Kadijk et al., *Follow-up research into the PN limit value and the measurement method for checking particulate filters with a particle number counter*, TNO report TNO 2020 R10006, 13 January 2020

[Merkiz 2016] Merkisz, Jerzy et al. (2016) *Actual emissions from urban buses powered with diesel and gas engines*, 6th Transport Research Arena April 18-21, 2016

[Söderena 2018] Söderena, P., Nylund, N., Pettinen, R., and Mäkinen, R. (2018) *Real Driving NO_x Emissions from Euro VI Diesel Buses*, SAE Technical Paper 2018-01-1815, 2018, https://doi.org/10.4271/2018-01-1815

6 Signature

The Hague, 22 January 2021 TNO

Peter van der Mark
Projectleader

Robin Vermeulen
Author