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TNO report

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Tail-pipe NOx emissions of Euro VI buses in daily operation in the Netherlands

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Samenvatting

In het kader van het Nederlandse steekproefcontroleprogramma voor vrachtwagens en bussen, dat TNO uitvoert in opdracht van het Ministerie van Infrastructuur en Waterstaat, zijn de stikstofoxiden (NO_x) emissies van vijf Euro VI bussen voor het openbaar vervoer gemeten tijdens verschillende representatieve praktijksituaties met het Smart Emissions Measurement System 'SEMS' [TNO, 2016a].
Daarnaast zijn twee Euro VI bussen uitgebreid op de openbare weg doorgemeten met het meetsysteem 'PEMS' over de voor de typegoedkeuring en de conformiteitstest voorgeschreven busrit en ook over enkele representatieve buslijnen. Alle zeven bussen hebben een eerste generatie Euro VI dieselmotor met een SCR katalysator voor de reductie van de NO_x emissies en een roetfilter voor de reductie van de fijnstofuitstoot van de dieselmotoren. De motoren van de geteste bussen representeren 64% van de geregistreerde typen Euro VI motoren in OV bussen in Nederland.

Resultaat van het onderzoek is dat in de zeven verschillende situaties de gemiddelde NO_x-uitstoot varieert van 0.3 g/km tot 2.9 g/km (gram per kilometer) en van 0.2 tot 1.9 g/kWh (gram per kilowattuur geleverde motorarbeid). Voor drie van de zeven situaties liggen de gemiddelde praktijk NO_x emissies boven de normwaarde van 0,69 g/kWh[1] die geldt voor een formele praktijktest. Kanttekening is dat de normwaarde alleen geldt voor de condities van de officiële Europese wegtest voor schadelijke uitlaatemissies.

De twee bussen die met 'PEMS' over de Europese wegtest voor bussen zijn getest, hebben een conformiteitsfactor die lager is dan de geldende limietwaarde. Vier bussen zijn onderworpen aan een indicatieve screeningstest voor de conformiteit. Na een hoge uitkomst van één bus over de initiële screeningstest is een tweede bus getest over de voorgeschreven busrit. Over die test lag de screeningsuitkomst lager lag dan de limietwaarde. Uit de hogere gemeten gemiddelde NO_x emissies van een aantal bussen in de praktijk en de kans op tijdelijk verhoogde NO_x emissies in de praktijk, blijkt dat er nog een verschil is tussen de officiële Europese wegtest voor bussen en de praktijk. De Euro VI eisen leiden dus nog niet voor alle bussen en bijbehorende inzet tot NO_x emissies beneden het 'Euro VI' emissie niveau.

Sinds de invoering van de officiële Europese 'PEMS' test voor zware bedrijfswagens in 2013 is er al een testrit die speciaal bedoeld is voor motoren die in stadsbussen worden ingezet. De belangrijkste oorzaak voor het verschil tussen de praktijk en de officiële test ligt waarschijnlijk bij de aanvullende eisen van de officiële test [TNO, 2018a]. Die eisen zorgen er namelijk voor dat een substantieel deel van de testgegevens niet wordt meegenomen bij de testevaluatie. Onlangs zijn de aanvullende eisen van de officiele wegtest verbeterd en aangescherpt.
De test wordt daarmee zwaarder voor bedrijfswagens met Euro VI motoren die vanaf september 2019 op de weg komen ('step D') en dus ook voor bussen.
Dit is onder meer het resultaat van Nederlandse inbreng in de besprekingen in Brussel.

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

Een laatste verbetering van Euro VI, ‘Step E’, wordt in 2020 verwacht. Emissietesten zullen moeten uitwijzen wat het effect van beide stappen is op het emissieniveau tijdens dagelijkse inzet.

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

Fabrikanten moeten voor de Europese toelating van vrachtauto’s en bussen een formele test met mobiele meetapparatuur op de openbare weg uitvoeren, zowel bij de typegoedkeuring van op de markt te brengen voertuigen als bij de controle van de conformiteit van in gebruik zijnde voertuigen. Onder meer deze wegtest heeft ervoor gezorgd dat gewone Euro VI vrachtauto’s en ook bussen met dieselmotoren bij de dagelijkse inzet op de weg voor de uitstoot van stikstofoxiden flink schoner zijn geworden.

Uit het voorgaande onderzoek kwam ook naar voren dat in stedelijke toepassing enkele voertuigen niet zo schoon waren als je op basis van de normstelling zou mogen verwachten. Een aanbeveling was om extra voertuigen te testen die in stedelijk gebied worden ingezet omdat juist dan de emissie van stikstofoxiden een wisselend beeld liet zien. Met emissietesten aan voertuigen in stedelijke inzet kan worden getoetst of Euro VI effectief is voor de representatieve omstandigheden en of de stedelijke inzet van invloed is op het emissieniveau van stikstofoxiden.
Aan deze aanbeveling is gevolg gegeven door vuilnisauto’s en ov-bussen in de praktijk door te meten. De NO_x emissies van de vuilniswagens zijn inmiddels gerapporteerd en laten een zeer wisselend beeld zien [TNO, 2018b].
Ook zijn de emissies van vijf ov-bussen tijdens praktijkinzet gemeten. Eerder zijn al twee bussen doorgemeten met mobiele meetapparatuur op de openbare weg. De resultaten van de metingen aan de zeven bussen zijn samengevat in dit rapport.

NO_x uitstoot varieert in de praktijk
Het niveau van de NO_x uitstoot varieert tijdens dagelijkse inzet en hangt af van de manier waarop elke bus wordt ingezet en de omstandigheden. Bij de testen met mobiele meetapparatuur aan twee voertuigen bleek dat één voertuig onder vergelijkbare zware maar realistische testcondities, een stadsbuslijn met een lage gemiddelde snelheid, hoge NO_x emissies had terwijl het andere voertuig juist hele lage NO_x emissies had. Dit impliceert dat lage NO_x emissies onder relatief zware praktijkcondities technisch mogelijk zijn.

NO_2 fractie
Bij twee bussen zijn de NO_2 emissies gemeten. De fractie van de NO_2 emissie in de totale NO_x emissies lag voor een bus met een hoge NO_x emissie op ongeveer 30% en voor een bus met juist een lage NO_x emissie op ongeveer 50%.

Ammoniak emissies
De ammoniakconcentratie in de uitlaat is bij vijf bussen doorgemeten.
De gemiddelde ammoniakconcentratie in het uitlaatgas varieert van bus tot bus van 1 tot 5 ppm. Dit is lager dan de 10ppm limiet die geldt voor een motortest die voor de typegoedkeuring moet worden gedaan. Voor één bus zijn hogere tijdelijke emissies gemeten. In dat geval liep het halfuur gemiddelde enkele malen op tot 100ppm. De nauwkeurigheid van deze meting is in het bereik boven 20ppm beperkt en geeft daarom slechts een indicatie van verhoogde ammoniak concentraties.

EU wetgeving, monitoring en trends
Op 1 september 2019 wordt Step D van de Euro VI norm van kracht.
De aanscherping van de Euro VI norm omvat voornamelijk verbeterde testeisen waarbij ‘stad’ en ‘lage motorlast’ nadrukkelijker deel uitmaken van de officiële wegtest voor schadelijke uitlaatemissies. Het is nog onduidelijk hoe dit uitpakt voor het niveau van de praktijk NO_x emissies tijdens daadwerkelijke inzet. Ook oudere voertuigen zijn niet getest. Monitoring van de emissies van zware bedrijfswagens over de levensduur, waaronder ook van bussen geeft inzicht in trends van de emissies over de levensduur van voertuigen en inzicht in de effectiviteit van de Europese emissiewetgeving.

Summary

In the framework of the in-service testing programme for heavy-duty vehicles for the Ministry of Infrastructure and Water management, the nitrogen oxide emissions (NO_x) of five Euro VI busses for public transport were measured during real-world operation during everyday' s use with the Smart Emissions Measurement System 'SEMS' [TNO 2016a]. Each measurement on a bus represents a different situation at a different public transport operator. Furthermore, the NO_x emissions of two Euro VI buses have been extensively measured with the Portable Emissions Measurement System 'PEMS'. This system is prescribed for type approval and in-service conformity testing of emissions, but can be used for non-formal emissions testing as well. All seven buses have a first generation Euro VI diesel engine with an SCR catalyst for the reduction of the NO_x emissions and a diesel particulate filter for the reduction of the particulate matter emissions of the diesel engines.
The engines of the seven busses tested, represent 64% of the Euro VI engines types in public transport buses registered in the Netherlands beginning 2018. Result of the measurements is that for the seven different situations the average NO_x emissions varied during normal operation between 0.3 g/km to 2.9 g/km and from 0.2 to 1.9 g/kWh. For three out of the seven situations the average NO_x emissions were higher than the limit value for the official European on-road emissions test for heavy-duty vehicles and engines. It must be noted that the limit value is applicable for the conditions that are prescribed for the formal European on-road bus test with PEMS[2].

Two buses, each tested over the formal EU PEMS bus test, have a conformity factor that is lower than the applicable limit value. Additionally, the conformity of the vehicles tested with SEMS is screened with an indicative non-formal test. After an initial high screening value for one bus, another bus with the same engine type showed a low screening value when the bus was taken from daily operation and tested over the prescribed bus trip. The high average real world NO_x emissions of some of the buses and the chance of temporarily high emissions show that there is still a difference between the real world and formal test conditions. The Euro VI standard does not lead to NO_x emissions sustainably below the 'Euro VI emissions level' under all conditions.

Since the introduction of the formal EU PEMS emissions test for type approval and in-service conformity for heavy-duty vehicles in 2013, a special test trip exists for city buses. The difference of the NO_x emissions over the formal test using a bus trip and those of real world operation is probably caused by the additional test requirements of the formal test that lead to exclusion of substantial representative data from the test evaluation [TNO, 2018a]. Recently, these additional requirements have been improved and make the formal test more stringent for vehicles with Euro VI engines that enter the road on September 2019 ('step D'). This also applies to city buses. This is, amongst others, the result of the input of the Netherlands in the working group discussions in Brussels.

[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.

A final improvement of Euro VI is expected in 2020 (‘step E’).
Emission measurements will show the effect of these improvements on real world emissions.

Background
Previous investigation [TNO 2016b], showed that heavy-duty vehicles with Euro VI diesel engines on average have significant lower pollutant emissions than the previous generations of vehicles. Measurements on relatively new trucks and a few buses have shown on average low real world NO_x emissions. Also in other applications, diesel engines are on average cleaner than earlier generations.

For Euro VI certification, manufacturers of trucks and buses have to conduct a formal road test with portable test equipment at type approval and for checking the in-service conformity over the useful life of vehicle. This road test is seen as an important part of the certification process that has contributed to the on average low NO_x emissions of Euro VI diesel engines in the real world.

In previous investigation it was also found that in urban operation some vehicles were not as clean as one would expect based on the emission limits that apply for the Euro VI standard. It was recommended to test extra vehicles that operate mainly in urban areas, because especially under those driving conditions NO_x emissions varied a lot between vehicles and usage. By measuring the emissions of heavy-duty vehicles in urban operation it can be checked whether the Euro VI standard is effective for these representative conditions and whether urban driving conditions have an effect on the emissions level of NO_x. To follow up on the recommendation, the NO_x emissions of refuse vehicles and buses have been measured during real world operation. The NO_x emissions of refuse collection vehicles are reported in [TNO, 2018b]. The measurements showed a large variation of the NO_x emissions. Also the emissions of five public transport buses were measured during real world usage and previously also two buses were tested with the mobile emissions measurement system PEMS on the public road. The results of the seven buses are summarized in this report.

Real world NO_x emissions vary
There is a spread in the level of the observed real world NO_x emissions of the buses which depends on how each vehicle is operated and on the conditions. For comparable road tests with PEMS on two buses under heavy conditions, one bus showed high NO_x emissions whereas the other bus showed low NO_x emissions. This implies that low NO_x emissions under heavy driving conditions at low speed and load are technically possible.

NO_2 fraction
For two of the buses, the NO_2 emissions have been measured. The fraction of the NO_2 emission in the total NO_x emissions was about 30% for the bus with the high NO_x emission and about 50% for the bus with the low NO_x emissions.

Ammonia emissions
The measured average tail-pipe ammonia concentrations of five buses vary from 1 to 5 ppm. This is lower than the limit of 10ppm that applies for the average concentration of ammonia over a formal type approval test on an engine test bed. For one bus, temporarily high concentrations were measured.

In this case, half-hourly concentrations exceeded 10ppm up to 100ppm. Above 20pmm the accuracy of the measurement is limited and therefore only gives an indication of high ammonia concentrations.

EU legislation, monitoring and trends

On 1 September 2019 ‘step D’ of the Euro VI standard comes into force.
This step further tightens the Euro VI standard and mainly comprises improved test requirements for the road test with PEMS. The improvements aimed at more emphasis of ‘urban’ and ‘low load’ operation. It is not yet clear what this means for real world NO_x emissions levels. Also vehicles with a high mileage haven’t been tested yet. Continuation of the monitoring of 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.

Contents

1 Introduction

Background
Contracted by the Ministry of Infrastructure and Water management, TNO runs the in-service emissions testing program for heavy-duty trucks and buses.
In this program TNO measures on a regular basis the tail-pipe emissions of these vehicles, to investigate how much these vehicles emit in the real-world and to screen the emissions performance with regard to EU in-service conformity.
Data obtained within the programme leads to valuable insights in environmental performance of heavy-duty vehicles in the real-world and its trends and is used as input for the Dutch model for the direct pollutant emissions of heavy-duty vehicles.

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

Because of the nature of this problem, the risk mainly exists for applications and situations were operations at low average speeds and low engine loads are common, such as for urban driving with lots of stop-and-go driving, city buses, distribution vehicles, traffic jams and also for refuse collection vehicles.
Given this risk, questions rose about the emission levels of NO_x of buses, refuse collection vehicles and also regular trucks with a Euro VI engine in real-world operation. The NO_x emissions of refuse collection vehicles and buses were measured during real world operation in 2017 and the observed NO_x emissions of refuse collection vehicles have been reported in [TNO, 2018b]. The measurements showed a large spread in real world NO_x emissions levels. The cause, on the one hand, is the large differences in operations of refuse collection vehicles with varying load and driving patterns which may lead to cool down of the SCR catalyst and on the other hand, the lack of formal European test requirements for refuse collection vehicles.

In addition, the emission database needed to be updated with data of Euro VI diesel busses so that new emission factors can be determined from a reliable set of real-world emissions data.

Buses for public transport
In the Netherlands 5147[3] buses for public transport are registered of which 1480 have Euro VI certified engines.

<u>Goal of the emissions testing programme on Euro VI buses</u>
The goal of the testing programme is to determine obtain data of and insight in the emissions levels of the Euro VI buses under the real-world conditions. The data and insights are used for several purposes:

- to update the Dutch emissions factors for buses. To be able to do so, insights are needed in the dependencies of the emissions levels in relation to vehicle type, vehicle conditions and driving conditions.
- to determine trends of emissions of different emissions generations of buses over time: are buses becoming cleaner for each new generation and is this in line with the EU emissions standard? Does the applicable EU emission standard lead to sustainably low emissions under all normal conditions of use?
- to screen the conformity of the vehicles in-service. Do vehicles that are in-service in the Netherlands meet the formal EU requirements for in-service conformity?

<u>Approach</u>
To determine the real-world NO_x emissions of buses for public transport, two buses were extensively tested over formal test trips and typical representative bus routes with PEMS (Portable Emissions Measurement System) and five buses were equipped with a Smart Emission Measurement System (SEMS) and tested over a long period of time during daily operation at the public transport operator.
A selection of Euro VI buses was chosen with engines that ranked the highest in terms of number of registrations in the Netherlands. Selected buses are standard (12m) and articulated (18m) diesel engine powered buses for city and or rural operation. To screen the in-service conformity of the buses a special routine is followed that initially uses the SEMS to get ‘an indication’ of the in-service conformity under conditions that are comparable to conditions required for the formal testing with PEMS, The results is used to decide on follow-up testing over a formal test trip using SEMS or formal test conditions (formal test trip using PEMS).

[3] Kennisplatform CROW, milieuposter OV bussen 2018, RDW open database 2018.

2 Emissions measurement programme

The emissions measurement programme is aimed at determining the real-world NO_x emission levels of Euro VI buses. Throughout the multi-annual programme f or the Ministry of Infrastructure and Water management, the tail-pipe NO_x emissions of these Euro VI buses were measured using SEMS and PEMS.
This report summarizes the results from the programme of the measurements with both instruments.

SEMS is a sensor based emission measurement system developed by TNO.
This instrument was used to measure the tail-pipe NO_x emissions and a range of vehicle/engine parameters to be able to characterize the typical operation of buses. In this way, for the group of vehicles, weeks of data per vehicle could be collected under normal conditions of use at the public transport operators. Five buses with Euro VI diesel engines were tested with SEMS.

PEMS is the formally prescribed instrument for testing the emissions for EU type-approval and in-service conformity. PEMS measurements can take place on the road in normal traffic and thus yield estimates for real-driving emissions performance of the investigated vehicle. Two buses with a Euro VI diesel engine were tested with PEMS [TNO, 2014a], [TNO, 2014b] and [TNO, 2014c].

2.1 Relevance of public transport buses for local air quality

Buses are a separate category in Dutch air-quality assessments, with a large technology differentiation. Cities can enter the public transport bus routes and frequencies, together with actual bus fleet into the NSL monitoring tool with adjusted emission factors which represent the local situation. Already for many years TNO has assessed the emission performance of common public transport buses, and common technology combinations, including popular retrofit options. Buses play an important role in large and busy cities, because they operate in the city centre, converging on central bus stations which may have several thousands of buses passing per day. On these access routes, the buses have been the dominant source for the air-quality problems and the replacement of Euro-V to Euro-VI and electric buses has been key in meeting the air quality standards. An update of the Euro-VI emission factor with the latest measurement data will help with accurate air-quality assessments.

2.2 Fleet of buses in the Netherlands

In the Netherlands 12.041 vehicles marked as ‘bus’ are registered[4]. This comprises buses for public transport, coaches and privately owned buses. All are EU category M2 or M3. The RDW open database does not allow the segmentation in types of buses and therefore does not allow an exact distinction between buses for public transport and privately owned buses.

[4] RDW Open Database vehicle registrations, May 2018

Kennisplatform-CROW annually publishes the 'Milieuposter OV-bussen'.
This poster [CROW, 2018] provides information of the distribution of public transport buses over the legislative emission stages per concession and provides some general fleet data as well. Spring 2018, there are 5147 public transport in use in the Netherlands. 1580 (31%) of these buses have certified Euro VI engines. 2746 (53%) EEV and 530 (10%) are Euro V, IV and III. Finally, there are 291 full electric buses and 604 EEV buses that run on natural gas.

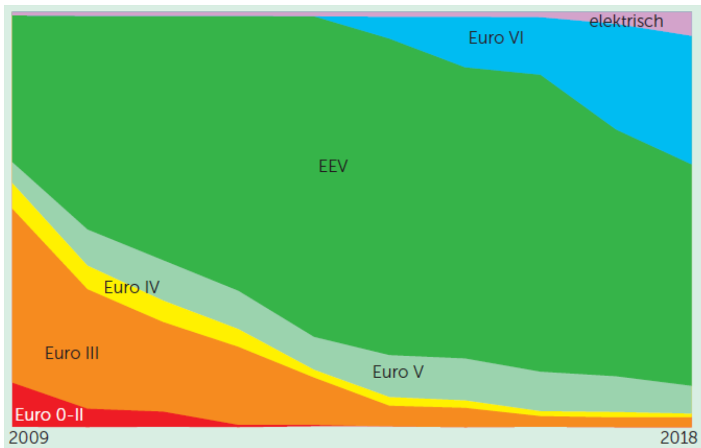

Figure 1: Development of the Netherlands fleet of buses for public transport.
Source Kpvv-CROW 2018.

From the RDW database, a ranking of best sold Euro VI engine types for 12 and 18 m buses (excluding coaches, special and old buses from the selection) could be derived based on the database record 'cilinderinhoud' (engine capacity in cm^3).

Table 1: Ranking of Euro VI bus engines and bus types in NL registration and tested engines.

Euro VI Engine type	Registered[1] engine capacity [cm^3]	Registered[1] bus length [m]	% of Euro VI engines of PT-buses registered [1] in NL 05/2018	# Tested, Type of test
Cummins ISB6.7	6700	12	**35 %**	2, SEMS
FPT Cursor 9	8710	12	(16 %)	-,-
Daimler OM936	7698	12	**10 %**	2, PEMS
Daimler OM470	10677	18	**11 %**	1, SEMS
FPT Tector7	6728	12	**4 %**	1, SEMS
DAF MX11	10837	18	(4 %)	-,-
FPT Cursor 9	8710	18	**3 %**	1, SEMS
MAN D08	6871	12	**1 %**	1, PEMS
Total % of types of Euro VI engines in public transport buses covered			**46 %**	

[1]RDW Open database, May 2018

2.3 Test vehicles

The next two tables show the specifications of the tested vehicles for vehicles tested with SEMS (Table 2) and PEMS (Table 3). For all tested vehicles the malfunction indicator light was off at the general vehicle check that is performed before and after the test period.

All seven vehicles run on diesel. The selection covers 64% of the bus engines with a Euro VI engine in public transport buses. One ‘bus length and engine combination’ that is ranked second in the registrations could not be obtained for the testing programme. The selected buses are a mix of five 12m and two 18m buses. Two buses are clearly ‘regional’ buses meaning that the primary operation is between cities with minor operation in the cities, rather than continuous operation in the cities. The operation of the test vehicles probably does not fully represent the operation of the Dutch fleet of buses with a Euro VI diesel engine. The tested buses are relatively new with odometer readings of 11500km to 209109 km. There was probably little influence of ageing of emissions control systems on the level of the NO_x emissions for the tested vehicles. The dataset lacks vehicles with higher odometer reading and therefore possible ageing effects are probably not included or to a very little extend. All buses have a first generation, i.e. step A, Euro VI diesel engine. Two buses have engines using ‘SCR only’ (no EGR) concept for the control of tail pipe NO_x emissions.

Table 2: Specifications of the vehicles tested with ‘*SEMS*’.

TNO vehicle code	Vehicle	Fuel, EU emission norm	Type	Mass empty in running order GVW Test mass [kg]	Max. Engine power [kW]	Emission control	Odometer reading	Axle config.
IV142 SEMS	Iveco Bus Crossway (CXX OV IJsselmond)	Diesel, Euro M3, VI-A	12m, city and regional	11107, 17800, -	235	FPT Tector 7, SCR, DPF, AMOC	123665	4x2
VD143 SEMS	VDL Citea SLFA-180 GVB	Diesel, M3, Euro VI-A	18m, city bus	17150, 29000, -	228	FPT, SCR, DPF, AMOC	139000	6x2
VD145 SEMS	VDL Citea LLE-120 Arriva	Diesel, M3, Euro VI-A	12m, regional	9350, 14870, -	182	Cummins, EGR, DOC, DPF, SCR, AMOC	70140	4x2
MB168 SEMS	MB Citaro G Qbuzz	Diesel, M3, Euro VI-A	18m, city bus	16406, 28745, -	265	EGR, DOC, DPF, SCR, AMOC	209109	6x2
VD170 SEMS	VDL Citea LLE-120 CXX/RNET	Diesel, M3, Euro VI-A	12m, city bus	9300, 14870, -	182	Cummins, EGR, DOC, DPF, SCR, AMOC	n.a.	4x2

EGR: Exhaust Gas Recirculation, SCR: Selective Catalytic Reduction, AMOC: ammonia oxidation catalyst.

Table 3: Specifications of the vehicles tested with '*PEMS*'.

TNO vehicle code	Vehicle	Fuel, EU emission norm	Type	Mass empty in running order GVW Test mass [kg]	Max. Engine power [kW]	Emission control	Odometer reading	Axle config.
MB128/ MB133 PEMS[1]	MB Citaro Qbuzz	Diesel, M3, Euro VI-A	12m, city bus	11500, 18745, 14460 (~half payload)	222	EGR, DOC, DPF, SCR, AMOC	11500 (128), 36648 (133)	4x2
MA129 PEMS[2]	MAN Lions city Provided by MAN	Diesel, M3, Euro VI-A	12m, city bus	11000, -, 14360 (~half payload)	214	EGR, DOC, DPF, SCR, AMOC	17435	4x2

EGR: Exhaust Gas Recirculation, SCR: Selective Catalytic Reduction,
AMOC: ammonia oxidation catalyst.
[1]MB128 and MB133 are the codes used for two test campaigns with the same bus, and reported in [TNO, 2014a] and [TNO, 2014c].
[2]This test of this bus are reported in [TNO, 2014b]

MB128/MB133

MA129

IV142

VD143

VD145

VD170

MB168

2.4 Euro VI

The table below gives the most important limits and requirements for type-approval and in-service conformity testing with regard to real world NO_x emissions of heavy-duty engines and vehicles. In addition to the NO_x limit for other criteria pollutants limits apply (EC Regulation numbers 595/2009/EC and 582/2011EC and amendments).

Table 4: Overview of Euro VI limits, steps and requirements with relevance for NO_x.

	WHTC engine type approval test test NO_x limit [g/kWh]	PEMS road test for type approval and in-service conformity NO_x conformity factor [-]	Euro VI 'steps'	Entry in to force (all vehicles)	PEMS test lower power threshold, % of rated maximum engine power [%]	PEMS mandatory urban evaluation window	PEMS cold start
Euro VI	0.46	1.5 (1.5x0.46 g/kWh=0.69 g/kWh)	Step A	31/12/2013	20	N	N
			Step B	1/9/2014	20	N	N
			Step C	31/12/2016	20	N	N
			Step D	1/9/2019	10	Y	N
			Step E	t.b.d. ~1/9/2020	10	Y	Y

2.5 SEMS, Smart Emissions Measurement System

For five buses the emission measurements on the road were performed using a sensor-based Smart Emission Measurement System (SEMS) [TNO 2016a]. This system uses an automotive NO_x sensor, GPS and a data-acquisition system to record the sensor data and CAN data from the vehicle and engine at a sample rate of 1Hz.

The system can operate autonomously and wakes up at ignition/key-on of the vehicle. The system can be stowed away so that normal operation is not hindered by the measurement. The recorded data is send hourly to a central data server.

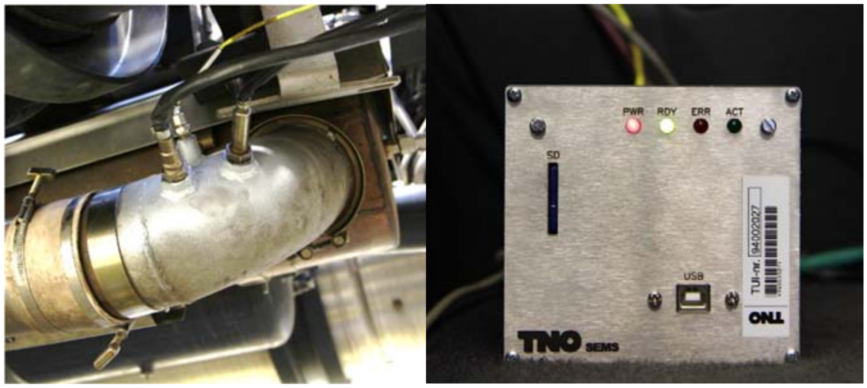

Figure 2: SEMS. Left, calibrated NO_x-O_2 sensor, NH_3 sensor and temperature sensor mounted in the tail-pipe. Right, autonomously running data recording unit with hourly data transmission to a central server via GPRS.

The raw data on the central server is post-processed automatically to filter and check the data. Mass-emissions are calculated combining sensor data and CAN data such as manifold-air flow, fuel rate, engine torque, and sensor O_2 concentration were possible. Testing routines contain the calibration of the NO_x and O_2 signal of the sensors. All raw measured concentrations of the sensor are corrected on the basis of these calibrations. For the vehicles for which no sufficient engine data was available to calculate the work specific emissions, an estimation of the average brake specific fuel consumption and CO_2 emission of a diesel engine was used to estimate the vehicle's emissions in g/kWh. For the other vehicles the engine work is calculated using the signals engine percentage torque, engine friction torque, reference torque and engine speed from the CAN bus. Further information on the measurement method used by TNO and the accuracy can be found in [TNO 2016b].

2.6 PEMS, Portable Emissions Measurement System

For two vehicles the exhaust gas emissions were measured by means of a so-called Portable Emission Measurement System, or PEMS.
PEMS measurements can take place on the road in normal traffic and thus yield estimates for real-driving emissions performance of the investigated vehicle.

With the introduction of PEMS it has become possible to regulate emissions of vehicles in-service. In 2011 the EU regulation 582/2011/EC was introduced which prescribes mandatory emission tests for Euro VI certification using PEMS for checking the emissions on the public road for type approval and to check the in-service conformity of engines over the useful life.

Figure 3: PEMS exhaust flow meter installed on the exhaust of the Mercedes Citaro.

Figure 4: PEMS analyzers, additional equipment and payload inside the bus.

2.7 Test fuel

The two vehicles tested with PEMS and the five vehicles tested with SEMS were fuelled according to the operators with regular diesel fuel (EN590 diesel).
The exact compositions of the fuels are not known.

3 Results

3.1 Data set with road tests: PEMS and SEMS

The dataset contains data of:
- PEMS tests on two city buses. Each bus drove two bus lines following a bus during normal operation and M3 bus trips as applicable for in-service conformity testing.
- SEMS tests on five buses. Autonomous measurements as performed during normal operation of the bus.

Most SEMS data is of 12m buses driving regional bus lines or 18m articulated buses driving city bus lines. The dataset with SEMS tests therefore lacks data of city operation with a 12m bus. For all the buses measured with SEMS the average speed ranges from 25.0 km/h for an articulated city bus to 45.6 km/h for a regional 12m bus. The PEMS data is of two 12 m city buses each driving bus lines 8 and 77 in Utrecht. The tests represent the conditions as occurred during the PEMS test of about two to three hours of testing [TNO, 2014a], [TNO, 2014b] and [TNO, 2014c]. Bus line 8 is a typical city bus line, characterized by a low average speed and many stops. Bus line 77 drives from the city centre to smaller towns outside the city and typically makes less stops.

Table 5: Overview of operational characteristics from the dataset of all tested buses.

Test type	TNO vehicle code	Vehicle Type	Time [h]	Distance [km]	Average speed [km/h]	Average engine power [%]	% time speed = 0, engine running [%]	% cold engine, T coolant <70C [%]	Type of operations
PEMS	MB128	12m bus	2.2 / 2.8	29 / 59	13.6 / 21.2	n.a.	41.5 / 27.1	0 / 6.1	City bus, bus line 8 / 77 / M3 tests
PEMS	MA129	12m bus	2.2 / 2.8	29 / 63	13.0 / 23.0	8.5 / 12.3	40.2 / 22.0	0 / 6.0	City bus, bus line 8 / 77 / M3 tests
SEMS	IV142	12m bus	64.9	2934	45.6	15.5	11.0	3.6	Regional bus lines
SEMS	VD143	18m articulated bus	750.0	25125	33.5	16.0	21.4	5.0	City bus lines
SEMS	VD145	12m bus	607.9	22088	36.3	19.7	19.1	5.5	Regional bus lines
SEMS	MB168	18 articulated bus	276.8	6916	25.0	16.6	26.8	7.5	City bus lines
SEMS	VD170	12m bus	531.4	19488	36.7	20.5	19.7	5.8	Regional bus lines / M3 trip

3.2 Average NO_x emissions

The average NO_x emissions were determined in g/kWh and g/km for all data of each bus. The average NO_x emissions vary from situation to situation from 0.30 g/km to 2.9 g/km and 0.24 to 1.9 g/kWh.

By ‘situation’ is meant the combination of bus and operation. At lower average speeds the NO_x emissions tend to spread more. At the lower speeds two buses have different NO_x emissions levels. Where one bus emits the lowest level of NO_x of all tests the other bus emits the highest.

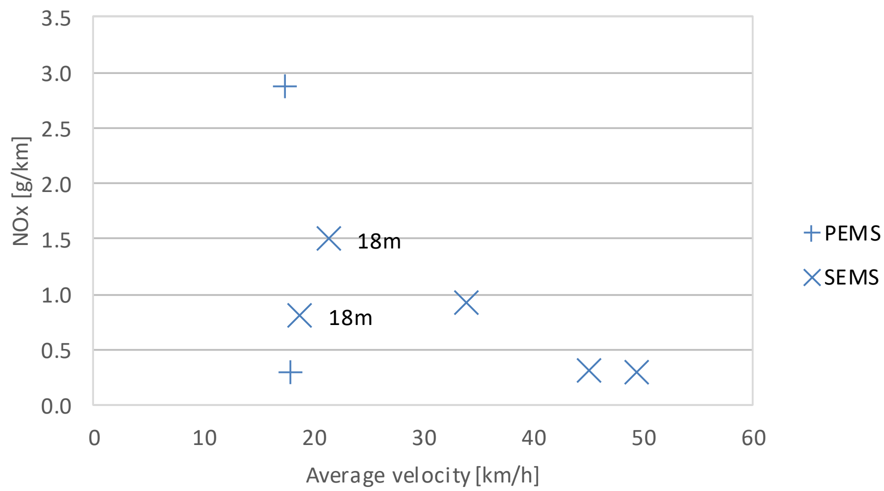

Figure 5: Average NO_x emissions from all the buses from PEMS measurements (average of bus line 8 and 77) and SEMS measurements. The average NO_x emissions vary from 0.3 g/km to 2.9 g/km. For each articulated bus the length of 18m is indicated to distinguish ‘standard’ (12m) and ‘articulated’ buses (18m).

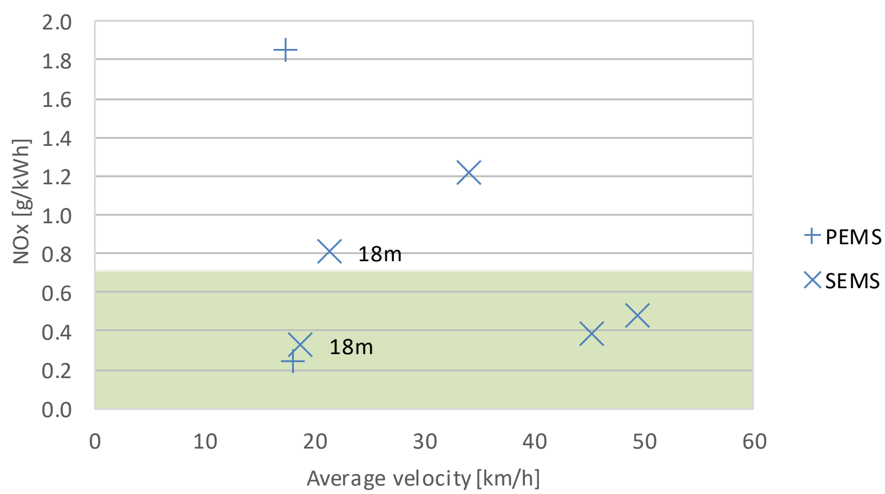

Figure 6: Average work specific NO_x emissions from all the buses from PEMS measurements (average of bus line 8 and 77) and SEMS measurements. For each articulated bus the length of 18m is indicated to distinguish ‘standard’ (12m) and ‘articulated’ buses (18m). The average NO_x emissions vary from 0.24 g/kWh to 1.9 g/kWh. The top of the green area represents a NO_x emission level of 0.69 g/kWh, which is the same level as the limit that accounts for a PEMS test (real-world type-approval and in-service conformity test) for heavy-duty engines and vehicles. The limit for the PEMS road test is composed of the limit for an engine test (WHTC: 0.46 g/kWh) and a conformity factor of 1.5 applied to this limit (0.69 g/kWh = 1.5 x 0.46 g/kWh).

In [SAE, 2018] NO_x emissions levels of four 12m Euro VI city buses were observed of 0.1 to 1.5 g/km and 0.1 to 1.0 g/kWh. Highest values occurred at low ambient temperatures of around -12 °C. The levels are comparable to the levels found for most of the buses reported here, with exception of one bus which clearly has higher NO_x emissions. The average speed for that bus was clearly lower than in [SAE, 2018].

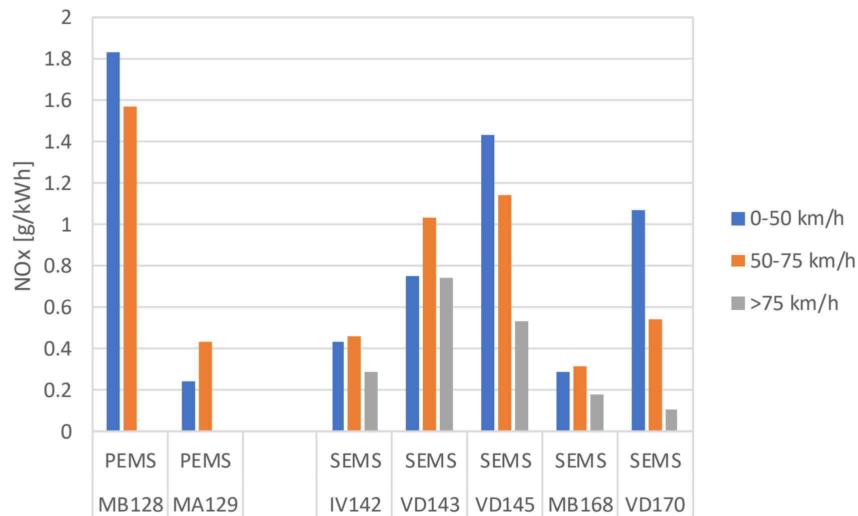

Figure 7: Average NO_x emissions per speed bin for both the road tests performed on two buses with the portable emission measurement system PEMS (left) (average of bus lines 8 and 77) and the tests performed on five other buses with SEMS during real operation (right). Buses can't be compared as the operational profiles differ.

Real-world NO_x emissions levels depend on how a vehicle is operated and on several characteristics of the vehicle itself:

Diesel engines produce NO_x during the combustion process. All Euro VI diesel engines used on heavy commercial vehicles either use EGR (Exhaust Gas Recirculation) combined with SCR (Selective Catalytic Reduction) or 'SCR only' to reduce these NO_x emissions. An SCR catalyst, however, needs to have a certain operating temperature before it can actively reduce NO_x using the reagent urea. The aqueous solution of urea has the tradename Adblue. The SCR catalyst heats up by the hot exhaust gases of the engine. A vehicle driving at a higher engine load has higher exhaust gas temperatures and can heat up a catalyst quicker and to a higher temperature. Vice versa, a diesel engine that runs at a low load, for instance idling has a low exhaust temperature (80-100 °C), may cool down an SCR catalyst below the needed working temperature. Depending on the type of catalyst, the catalyst temperatures need to be at least around 170-200 °C before it can reduce NO_x. Often next to the SCR system, an EGR system is used to reduce the NO_x emissions of the diesel engine. In case the SCR system is not warm enough to effectively reduce the NO_x of the diesel engine the EGR is still able to reduce the NO_x emissions although not as efficient as the SCR.

Catalysts have a thermal inertia which means that it takes time to warm up and it also takes time to cool down when the engine does not produce much exhaust heat, for instance when the vehicle is idling. How much NO_x is actually reduced at a certain moment therefore also depends on the history: what happened before that moment. For an effective SCR catalyst operation it is beneficial that periods of low speed and low load be preceded by periods with higher speeds and loads. Frequent higher load operation may help to keep the SCR catalyst warm enough. Additionally, catalysts can buffer urea and NH_3.

Urea which has been dosed to the catalyst at temperatures above about 200°C, can take care of NO_x conversion in the temperature range of 150-200°C (even when there is no urea injection in this period). Some vehicles clearly showed low average NO_x emissions due to intermittently driving low loads and speeds and higher loads and speeds.

For the buses measured, the average speeds vary as do the resulting exhaust gas temperatures. The 18m buses clearly have higher exhaust gas temperatures than the 12m buses at the same average operational speeds. This is mainly caused by the high relative engine power for these 18m buses at he given operational speeds. For the 18m bus the power to mass ratio is lower (smaller engine compared to the mass of the bus) which probably explains the relative high engine powers. In one case (MB168) it is know that the bus services heavy bus lines with lots of passengers. The buses are often fully loaded which means that average engine power was higher due to the higher ‘payload’. Typically, the buses that run high average speeds and loads show lower NO_x emissions.

For the two city buses that were tested at a low average speed (bus line 8), the NO_x emission were found to differ substantially. The high NO_x emission of one vehicle can be explained by the relatively low exhaust gas temperature.
The other bus, at nearly the same average speed exhibits slightly higher exhaust temperature resulting in very low NO_x emissions. Both vehicles have higher exhaust gas temperatures at higher average speeds. For the vehicle with higher NO_x emissions at low speeds this results in a decrease of the emissions level but still remains high compared to other vehicles. Both vehicles behave differently, have different NO_x emissions levels under comparable conditions. The vehicle with the low emission shows, that under the given conditions in principle low NO_x emissions levels are technically achievable.

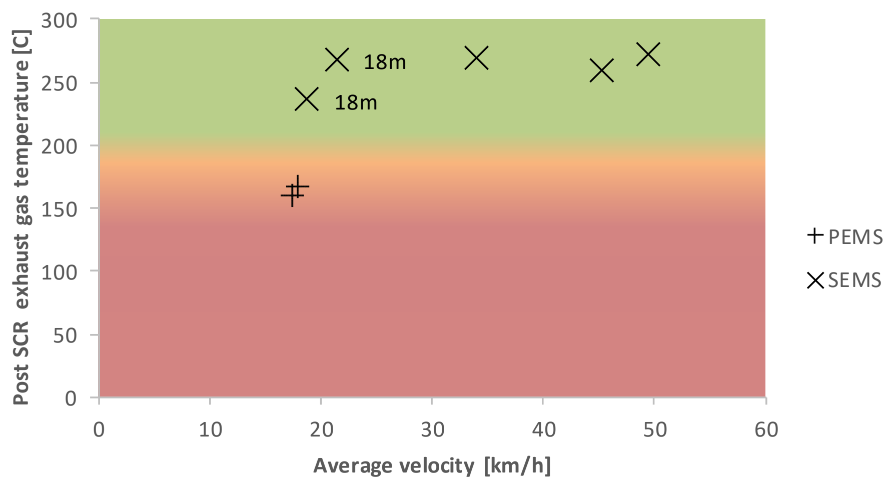

Figure 8: Average tail pipe exhaust gas temperature. The two 18m articulated buses clearly have on average higher exhaust gas temperatures at the given average speed. This is probably caused by the lower power-to-mass ratio of these buses and possibly also due to the on average higher payload (amount of passengers).

The following aspects determine the real-world emission levels:

- Concept and layout of emission control system. Basically for Euro VI two layouts are used, one with EGR and one without:
  - EGR, DOC, DPF, SCR, AMOC
  - DOC, DPF, SCR, AMOC
- Thermal management: the use of isolation helps heat retention. The fuel injection timing strategy can be used to retain more heat in the exhaust, at the cost of fuel efficiency.
- Positioning of aftertreatment: catalyst housings for buses are usually located in the back of the bus very close to the engine. For the operation of the SCR this has the advantage that the catalyst can warm up more quickly and has better heat retention.
- Materials, dimensions, coatings of catalysts.
- Control strategy; base and auxiliary emission control strategy, taking account of formal requirements, durability and other trade-offs such as fuel consumption and Adblue consumption.
- Engine displacement and power relative to the vehicle mass and duty profile. Smaller, low powered engines have the advantage that engine loads are on average higher for a given operation and consequently exhaust gases and catalysts can warm up faster and stay warm at lower speeds. This is shown by the lower power to mass ratio of the tested 18m buses which is respectively 14 and 16 kW per ton of empty vehicle mass and for the tested 12m standard buses around 20 kW per ton.

3.3 Contribution of cold engine operation

The measurements performed during real operation of the buses have been analysed to determine the contribution of cold engine operation to the total NO_x emissions of each vehicle.

For this purpose, the cold engine is defined as an engine that has a coolant temperature lower than 70 °C, in analogy with the EU PEMS test requirements[5]. In principle, cold engine operation happens after a cold engine start or a semi-cold engine start after a certain cool down and soak period. During this period, the catalyst of the emission control system also cools down. For the SCR catalyst this might mean that it has cooled down to or stabilized to below it's working temperature which generally lies above 160-180 °C depending on the catalyst exact formulation. Hence, after a cold start the SCR needs to warm up again to its working temperature by means of the hot exhaust gases before it can effectively reduce NO_x from the diesel engine. As discussed in paragraph 3.2 the temperature of the SCR system can drop to below working temperature during operation due to preceding low load, low speed operation. Relative low exhaust gas temperatures during low load, idling and decelerations cause the SCR temperature to decrease.

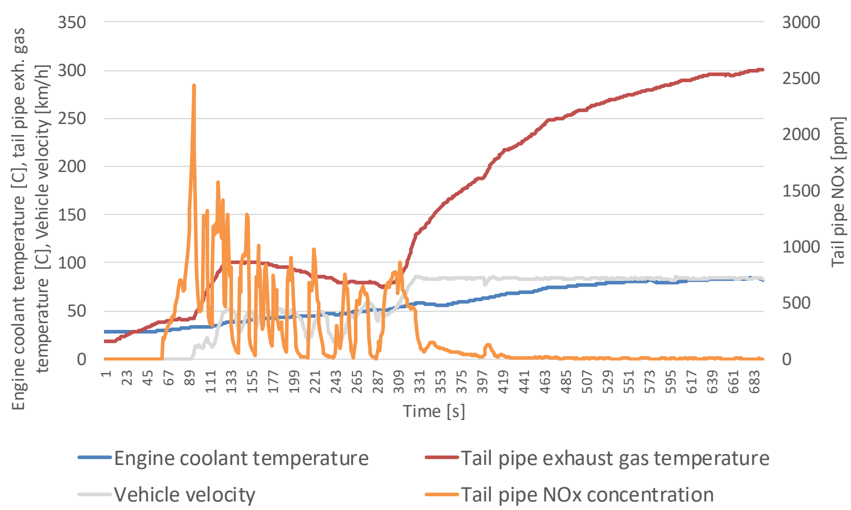

Figure 9: Example of warm up behaviour after a cold start for a bus with a Euro VI diesel engine with SCR and EGR. The NO_x concentration reduces clearly when the tail pipe exhaust gas temperature warms up to above 150 °C.

Three of the five buses also have EGR (Exhaust Gas recirculation) to control the NO_x emissions of the diesel engine. The EGR system is able to reduce engine NO_x emissions quite soon after a cold start. The EGR is prone to fouling due to condensation of slurry onto internal parts of the EGR system, especially when engine components are still cold. This is the main reason for a manufacturer to deactivate the EGR for a short period of time after a cold start. Such a strategy is allowed by EU Regulation if it is used to protect the engine system. The strategy is called an auxiliary emission strategy and needs to be reported to the type approval authority.

For the five Euro VI diesel buses measured during real operation, the cold engine operation causes 70 mg/km to 260 mg/km of tail-pipe NO_x emissions. This is 20 to 40% of total average NO_x emissions, the fraction also depends on the level of emissions with a warm engine.

[5] EC Regulation 2011/582 and amendments

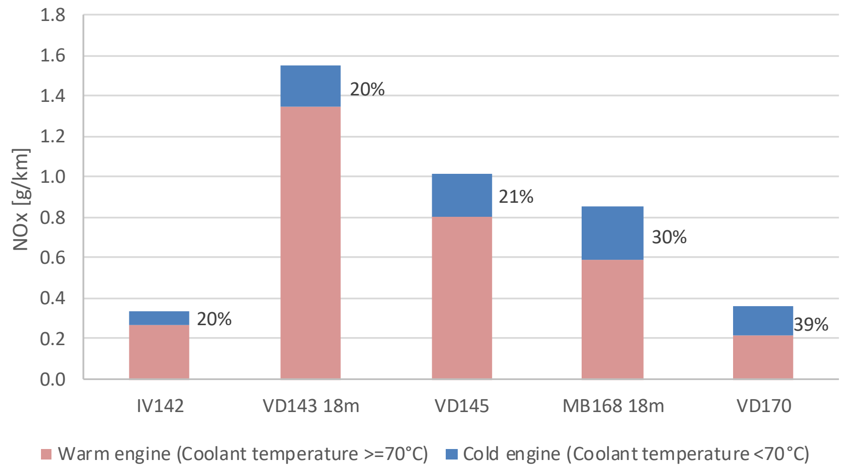

Figure 10:Total average NO_x emissions and the contribution of the cold start.

3.4 Half hourly average emissions

The dataset showed that NO_x emission levels can vary over time, also when the engine is warmed up. Possible causes have been discussed in 3.2.
The most common cause for a temporal increase of the NO_x emissions levels is at or just after periods when the engine is operated at a low load low, speed for a longer period of time such that the SCR can cool down to below its working temperature. To show the variation in emission levels, the average NO_x emissions have been averaged for 30 minute periods. The graph below shows the distribution of the emission levels and shows that indeed temporarily NO_x emissions levels can be elevated. When the level of 1gNOx/kgCO_2 is taken as a reference that is comparable to the emissions level of the Conformity Factor for NO_x it can be seen that a substantial share of emissions is higher than this value. The real world emissions level is not the same as the Conformity Factor as obtained over a road test with PEMS. The data just shows that real world emissions of the buses tested exceed the level that is required under formally prescribed test conditions of the road test. For emissions, it means that still locally systematically high emissions events may occur if conditions are unfavourable for the reduction of NO_x from a diesel engine.

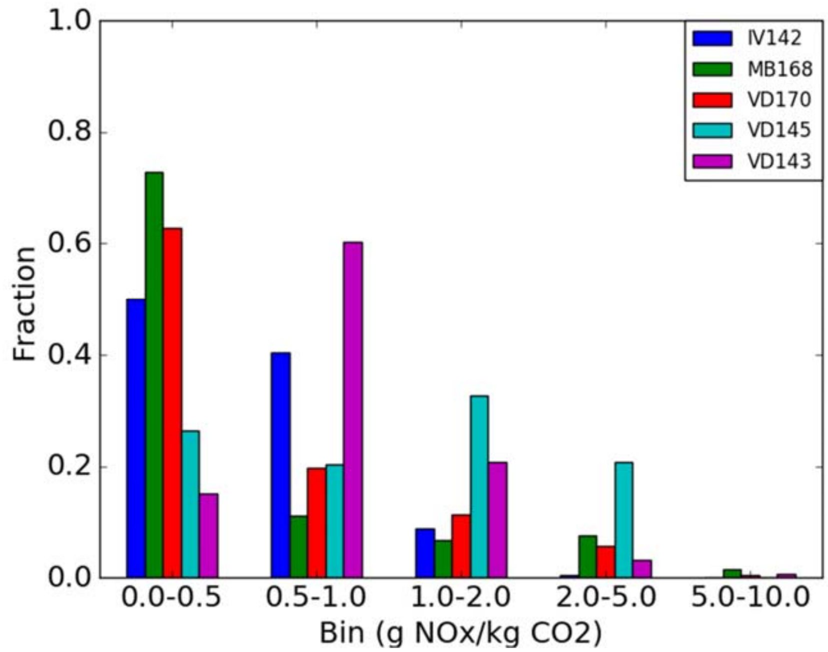

Figure 11: Distribution of 30 minute average CO_2 specific NO_x emissions. For a diesel engine a level of 0.7 $gNO_x/kgCO_2$ is almost the same as 0.46 g/kWh, the limit for the WHTC engine test for Euro VI engines. 1 $gNO_x/kgCO_2$ is almost the same as 0.69 g/kWh, the equivalent of the conformity factor of a real world PEMS test for type approval and in-service conformity. A substantial share of these 30 minute average windows lies above 1.0 $gNO_x/kgCO_2$.

When the data is divided in windows with an average above and below approximately 0.7 g/kWh (0.46 g/kWh x a CF of 1.5) it is shown how much of the time the buses in the real world emit more than the limit as set for the formal tests.

This way, individual buses can’t be compared directly as driving routes and conditions differ. The percentage of half hour durations with emissions above 0.7 g/kWh varies between buses and their operational profiles, from 10 to 53%.

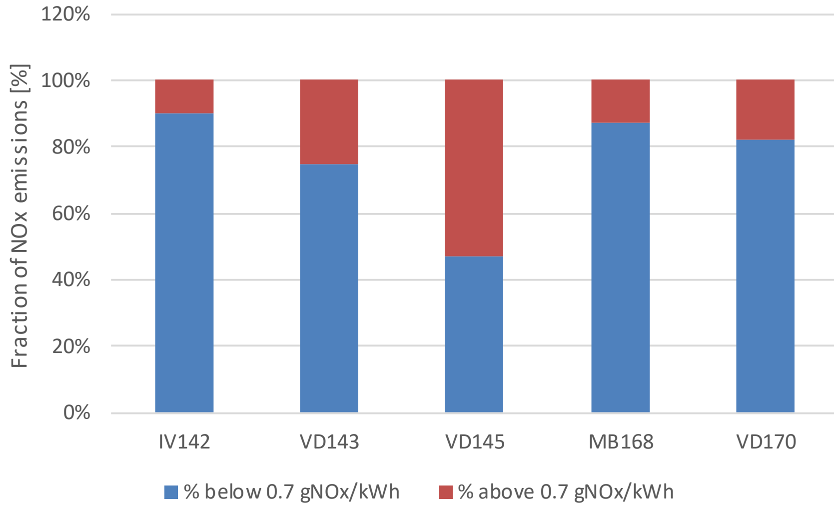

Figure 12: The half hourly NO_x emissions can be divided in a share below 0.7 g/kWh and a share above 0.7 g/kWh. Individual buses can't be compared as operational profiles differ.

3.5 NO_2 emissions

For the PEMS tests of the two 12m diesel buses also the NO_2 emissions were measured and thus provide insight in the level of NO_2 emissions for the Euro VI diesel engines as used in the buses.

The buses emit a substantial share of NO_x as NO_2. The MB128 with higher NO_x emissions has a lower share of NO_2 emissions of around 30% whereas the other bus, the MA129 has lower NO_x emissions and a higher share of NO_x emissions of around 65%. For the MB128 the NO_2 levels vary somewhat and this variation seems related to the variation in overall NO_x emissions more than for the MA129.

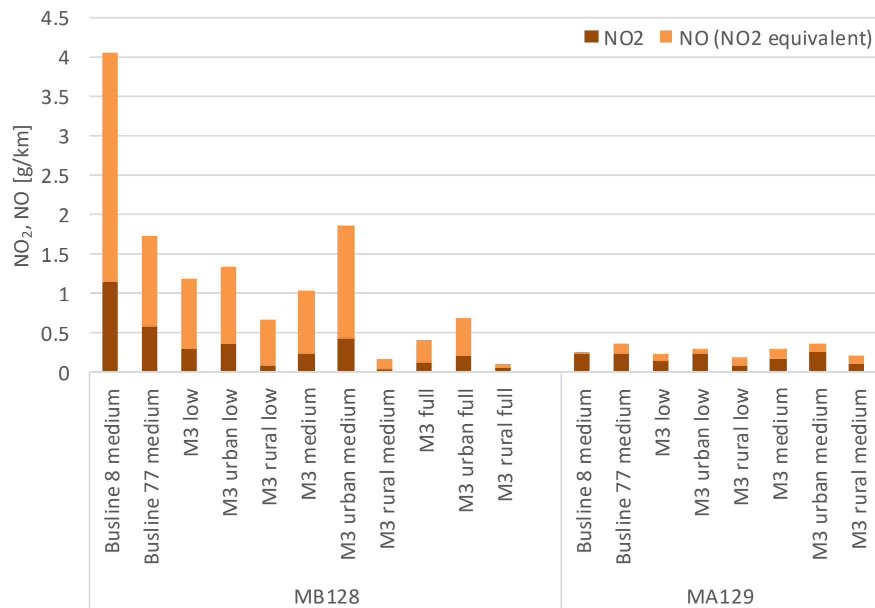

Figure 13: NO and NO_2 emissions for two buses over several test trips. NO is expressed in NO_2 equivalents, NO and NO_2 add up to NO_x. Low, medium and full indicates the payload level used during the test.

3.6 In-service conformity screening

For the PEMS tests with the two buses also a formal M3 bus trip was driven.
A conformity factor can be determined for those tests. Formally, at least three tests are necessary to check the in-service conformity. The PEMS test therefore only indicates the emissions performance of given bus tested in relation to the conformity factor limit of 1.5 for the sample of at least three buses.

TNO also has developed a screening test that is comparable but not exactly the same as the formal test [TNO, 2016a]. It uses the data as obtained with the SEMS device during real world operation and applies the same data evaluation rules as used for the formal road test with PEMS. I.e. 'Work-based Moving Averaging Windows' are calculated.

The evaluation method for the screening of NO_x emissions calculates a so-called SEMS factor ('SF') and comprises, in analogy with the formal requirements, the following criteria:

- Only data were the engine coolant temperature is higher than 70 °C.
- A lower power threshold of 20%, going stepwise to 15% in the case the number of valid windows is lower than 50%.
- A minimum of 50% valid windows
- Application of the 90% rule, exclusion of 10% of windows with the highest emissions
- Determination of a SEMS factor, a factor relative to the NO_x emission limit value for the WHTC engine test cycle of 0.46 g/kWh.

– A follow-up decision criterion for the SEMS Factor of 1.5. When the SF is higher than 1.5 during real world operations, the vehicle or a vehicle with an engine of the same type is tested over the formally applicable test trip, for city buses that is the M3 trip. If again the SEMS factor is higher than 1.5, a PEMS test is performed according to all formal requirements.

Table 6: Overview of the results of the in-service screening tests with SEMS and PEMS.

TNO vehicle code	SEMS SF NOx-90%	SEMS SF NOx-90% ISC M3 bus trip	PEMS CF NOx-90% ISC M3 bus trip
MB128	-	-	<1.5
MA129	-	-	<1.5
IV142	<1.5		
VD143	<1.5		
VD145 -> see VD170	>1.5		
VD170, follow up test of VD145 with same engine type		<1.5	
MB168	<1.5		

3.7 Ammonia emissions

The tail pipe ammonia concentration is measured by an automotive ammonia sensor. This sensor has limited accuracy, especially at higher concentrations above 20ppm. Ammonia concentration results are therefore indicative.

Ammonia emissions are evaluated by determination of the total average concentration, maximum half hourly concentrations and the % of windows of average half hourly concentrations exceeding 10ppm. 10ppm is the limit for the average concentration during a half hour engine test and formally only accounts for that test. However, in this way the evaluation indicates whether or not the real-world this 0 ppm average is exceeded and how often. For the buses tested, the average tail-pipe ammonia concentrations are low and in the order of 1 to 5 ppm. Half hourly concentrations still exceed 10ppm for 3 out of 5 buses for 1 to 6% of all the half hourly periods.

Table 7: Summary of the results of the measurement of the tail-pipe ammonia concentrations. The results are indicative, as the sensor used for the measurement is not accurate above 20ppm.

TNO vehicle code	Average ammonia concentration [ppm]	Maximum half hourly average ammonia concentration [ppm]	% of windows of half hourly average ammonia concentration exceeding 10ppm [%]
IV142	4.8	14	6.4
VD143	1.2	10	0.1
VD145	1.4	20	1.1
VD170	1.8	90	1.6
MB168	1.8	4	0.0

4 Conclusions

Tail-pipe NO_x and NH_3 emissions of five public transport buses with a first generation Euro VI diesel engine were examined using a Smart Emission Measurement System and tail-pipe NO_x and NO_2 emissions of two buses were examined using a Portable Emissions Measurement System.

The measurements were done to:

- determine the real world NO_x, NO_2 and NH_3 emission levels. This information is necessary for the calculation of the Dutch emissions factors for the category of public transport buses.
- investigate the effectiveness of applicable emission legislation in achieving consistently low real world NO_x emissions levels and provide the knowledge base for discussion on improvements of this legislation.
- determine NO_x emission trends over the different generations of heavy-duty engines and
- screen the in-service conformity.

The following conclusions can be drawn:

- The vehicle sample represents 64% of the Euro VI engines types in public transport buses registered in the Netherlands beginning 2018. The dataset contains five standard 12m buses and two 18m articulated buses. The dataset lacks real world SEMS data of 12m city buses running typically city operations, a 12m city bus with a well sold engine type could not be obtained for emissions testing. However, with two city buses PEMS tests were performed over two typical bus routes, one typical city bus route and one combined city-regional bus route. Odometer readings of the buses show that the sample of seven buses contains mostly relatively new buses.
- In-service conformity of NO_x emissions has been screened using 'PEMS'. Two buses ran a formal M3 PEMS trip and have conformity factors over a single test trip below 1.5. This value is the limit for a minimum test sample of three vehicles per manufacturer per vehicle type.
- Five buses were screened during real world operation in an alternative way, using a similar data-evaluation method as the formal 'PEMS' test. One vehicle did not pass the initial screening. Retesting a vehicle with the same engine type, over the formal test route, lead to a Screening Factor below 1.5, meaning that no further tests needed to be performed to check the in-service conformity of this particular engine type.
- Real world NO_x emissions levels vary for each case (bus and usage). For the seven buses and their usage patterns, the average NO_x emissions vary from 0.3 g/km to 2.9 g/km and 0.2 to 1.9 g/kWh. At lower average speeds the NO_x emissions tend to spread more. At the lower speeds, which represent more severe conditions with regard to reducing NO_x emissions, two buses have different NO_x emissions levels. Where one bus emits the lowest average NO_x of all tests, the other bus emits the highest.

- The observed average real world NO_x emissions show that there are cases where the average NO_x emissions are higher than one might expect based on the limit of the in-service conformity road test, which for NO_x is 0.69 g/kWh[6]. Three out of seven buses have average NO_x emissions in the real world that exceed 0.69 g/kWh.
- Temporal NO_x emissions, expressed as half hourly averages, show a substantial spread which means that half hourly emissions for all five buses tested in daily operation can be higher than 0.69 g/kWh, the limit of the in-service conformity road test. The share of half hourly windows that exceeds 0.69g/kWh during real world operation varies between buses and their operation from 10 to 53%.
- On average the engine power of buses is low and in many cases lies below the 20% threshold that is set for evaluation of the formal road test with PEMS. This may have caused the observed temporal and average NO_x emissions levels exceeding 0.69 g/kWh. Next to an engine test, bus engines for city buses are formally tested in a road test using ‘PEMS’ over a bus trip (‘M3 trip’) which contains a substantial part of urban driving (70%). Still for first generation Euro VI engines (Step A), periods with low engine power below 20% are excluded from evaluation of the in-service conformity. This will change in 2019 with entry into force of step D (01 sept 2019). With step D, the power threshold is reduced to 10% which means that a larger share of engine operation, especially the for NO_x emissions critical low load operation, will no longer be excluded from the formal test. With Step D, the 90% rule remains. This means that 10% of periods with the highest NO_x emissions are still deleted from the evaluation of the PEMS road test for type-approval and in-service conformity.
- Real world NO_2 emissions have been measured for two 12m buses. The buses emit a substantial share of NO_x as NO_2. One bus with higher NO_x emissions has a lower share of NO_2 emissions of around 30% whereas the other bus has lower NO_x emissions but a higher share of NO_x emissions of around 65%.
- Real world ammonia emissions have been measured with an automotive ammonia sensor. This sensor measured average tail pipe ammonia concentrations of 1 to 5ppm of the five buses during daily operation. Half hourly emissions however can increase up to concentrations near 100ppm. In the range above 20ppm the sensor is not accurate, so the data can only be used as indicative.
- Buses with a high mileage haven’t been tested. Continuation of the monitoring of the emissions of trucks and buses reveals trends of the emissions over the lifetime of the vehicles and the effectiveness of the EU emissions legislation.

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

5 References

[CROW, 2018] G. van Kesteren, Kennisplatform CROW, *Milieuprestatie ov-bussen 2018, 10 jaar milieuprestatie ov-bussen in beeld*

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

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

[TNO, 2014a] Spreen et al., *On-road emission measurements with PEMS on a Mercedes Citaro Euro VI bus*, TNO report TNO 2014 R10534, 28 March 2014

[TNO, 2014b] Spreen et al., *On-road emission measurements with PEMS on a MAN Euro VI bus*, TNO report TNO 2014 R10570, 2 April 2014

[TNO, 2014c] Spreen et al., *NOx and PM emissions of a Mercedes Citaro Euro VI bus in urban operation*, TNO report TNO 2014 R11307, 30 September 2014

[TNO, 2016a] Heine, 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, 10 October 2016

[TNO, 2018a] Vermeulen, R.J., Ligterink, N.L.I., *Evaluation of the EU real-world PEMS test for heavy-duty vehicles*, TNO report TNO 2018 R11328, 15 November 2018.

[TNO, 2018b] Vermeulen, R.J. et al., *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 10313v2, 15 June 2018

6 Signature

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