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TNO report

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The Netherlands In-Service Emissions Testing Programme for Heavy-Duty 2011-2013

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Samenvatting

In opdracht van het Ministerie van Infrastructuur en Milieu voert TNO het steekproefcontroleprogramma voor vrachtwagens en bussen uit. In dit programma meet TNO, op regelmatige basis, de uitlaatgasemissies van deze voertuigen om te onderzoeken of zij aan de EU typekeuringsnormen voldoen en of zij ook in de praktijk schoon zijn.

In dit rapport wordt verslag gedaan van het steekproefcontroleprogramma voor vrachtwagens en bussen voor de jaren 2011 – 2013. Gedurende deze periode was het programma vooral gericht op de praktijk NO_x en NO_2 uitstoot van de bedrijfswagens. In Nederland worden namelijk op een aantal locaties de Europese limietwaarden voor de concentratie van NO_2 in buitenlucht nog steeds overschreden. Bedrijfswagens hebben een groot aandeel in de lokale uitstoot.

Belangrijkste conclusies over Euro VI vrachtwagens en bussen

De Euro VI bedrijfswagens vertegenwoordigen vanaf de inwerkingtreding van de Euro VI wetgeving op 1 januari 2014 een groeiend aandeel van de Nederlandse voertuigvloot. Gezien de strenge emissie-eisen van de Euro VI wetgeving, hebben Euro VI voertuigen de potentie een grote bijdrage te leveren aan de verbetering van de lokale luchtkwaliteit. In het steekproefcontroleprogramma 2011-2013, waarvan dit rapport verslag uitbrengt, heeft TNO daarom vooral Euro VI voertuigen gemeten.

De belangrijkste conclusies over de geteste Euro VI voertuigen zijn:

1. **Alle door TNO geteste Euro VI voertuigen voldoen aan de eisen die de Europese wetgeving stelt aan emissies van in gebruik zijnde voertuigen.** Hierbij wordt aangetekend dat alleen emissies van ‘jonge’ voertuigen zijn onderzocht. TNO kan nog niet concluderen of de voertuigen gedurende hun levensduur aan de eisen blijven voldoen.
2. **De nieuwe, strenge Euro VI wetgeving heeft gezorgd voor significant lagere praktijkemissies van zware bedrijfsvoertuigen.** Gemiddeld genomen is de NO_x-uitstoot van Euro VI vrachtwagens en bussen in de praktijk sterk afgenomen ten opzichte van Euro V vrachtwagens en bussen. Fabrikanten hebben een grote stap gezet in de reductie van vervuilende emissies. Vooral Euro VI vrachtwagens voor de lange afstand zijn significant schoner dan eerdere generaties.
3. **Euro VI voertuigen voor stedelijk gebruik zijn in de praktijk nog niet in álle gevallen schoon.** TNO heeft, naast de *long-haul*-vrachtwagens, ook een klein aantal distributietrucks en bussen getest. Deze voertuigen zijn schoner dan vorige generaties, maar laten onderling nog een sterk wisselend beeld zien. In een drukke, stedelijke omgeving, met bijbehorende lage gemiddelde snelheden, is één voertuig onder alle omstandigheden schoon; twee andere voertuigen laten in de praktijk nog regelmatig een hoge NO_x uitstoot zien.
4. **De Euro VI regelgeving kan met name op het gebied van stedelijke emissies verder worden verbeterd.** De typische toepassing van voertuigen die opereren in stedelijke omgeving is niet expliciet gereguleerd in de Euro VI wetgeving.

Het steekproefcontroleprogramma voor vrachtwagens en bussen

Achtergrond
Vrachtauto's en autobussen stoten stoffen uit die schadelijk zijn voor de gezondheid. Hierbij gaat het om fijn stof (PM_{10}) en stikstofoxiden (NO_x). Daarnaast stoten ze het broeikasgas CO_2 uit. Gegeven de ambitieuze klimaatdoelstellingen en lokaal optredende overschrijdingen van de normen voor de luchtkwaliteit, wordt hard gewerkt aan het terugbrengen van deze emissies. Daarbij moet de overheid zich kunnen baseren op objectieve gegevens over de emissies van voertuigen in de praktijk. Daarom stelt TNO in opdracht van het Ministerie van IenM in het steekproefcontroleprogramma de emissies van zware bedrijfswagens, zoals vrachtwagens en bussen, onder praktijkomstandigheden vast.

Werkwijze
TNO selecteert in overleg met het Ministerie van Infrastructuur en Milieu elk jaar een aantal typen vrachtwagens om te testen. De selectie vormt een goede afspiegeling van het Nederlandse wagenpark. In het steekproefprogramma van 2011-2013 ging het daarbij vooral om vrachtwagens die zijn uitgerust met een Euro V, EEV of Euro VI motor. Ook werden enkele nieuwe technieken getest, zoals dual-fuel en een volledig elektrisch aangedreven bus.

Waarvoor worden de resultaten van het programma gebruikt?
Met ondersteuning van TNO gebruikt het Ministerie van Infrastructuur en Milieu de inzichten in de praktijkemissies in Brussel om de **Europese Euro VI normstelling met name op het gebied van stedelijke emissieprestaties verder te verbeteren**, zodat vrachtwagens niet alleen op papier schoner worden, maar ook onder praktijkomstandigheden. Verder dienen de inzichten als **onderbouwing van nationale beleidsmaatregelen**, zoals de Euro VI subsidieregeling. Daarnaast worden de resultaten van de emissiemetingen gebruikt voor het jaarlijks vaststellen van emissiefactoren, die de basis vormen voor **luchtkwaliteitsberekeningen**.

Het meetprogramma in 2011-2013

Voertuigselectie: focus op Euro V en Euro VI voertuigen
Sinds 1 januari 2014 moeten nieuwe vrachtwagens en bussen voldoen aan de strengere Euro VI normen voor de uitstoot van schadelijke uitlaatgassen. Vooruitlopend op de Euro VI wetgeving is TNO in 2013 begonnen met het testen van Euro VI voertuigen en zijn in totaal 12 Euro VI voertuigen getest. In de periode voor 2013 lag de focus van het programma vooral op de op dat moment courante Euro V en EEV voertuigen, waarvan er 10 zijn getest. Op deze manier verkrijgt het Ministerie een goed beeld van de praktijkemissies van voertuigen die de komende jaren het wagenpark zullen domineren.

Emissiemetingen met het Portable Emissions Measurement System (PEMS)
Om de emissies van voertuigen in praktijkomstandigheden te meten, voert TNO metingen uit met het zogenaamde Portable Emissions Measurement System, kortweg 'PEMS', zie onderstaande figuur. Met dit systeem, dat wordt aangesloten op de uitlaat van het voertuig, kunnen de uitlaatgasemissies tijdens het rijden nauwkeurig worden gemeten. Na de uitvoering van de testritten analyseert TNO de data. Een meetsessie van één voertuig bestrijkt een periode van ongeveer twee weken en de eigenaar kan het voertuig gedurende deze periode niet inzetten.

Emissiemetingen met het Smart Emissions Measurement System (SEMS)
Een PEMS meting is nauwkeurig, maar ook arbeidsintensief en relatief duur. Daarom heeft TNO op verzoek van het Ministerie een meer laagdrempelig systeem ontwikkeld: het Smart Emissions Measurement System, of SEMS. Na installatie van SEMS kunnen voertuigeigenaren het voertuig blijven gebruiken voor de dagelijkse inzet. Waar PEMS gebruik maakt van uitlaatgasanalyse-apparatuur, maakt SEMS gebruik van sensoren om emissies te 'screenen'. Hoewel SEMS hierdoor minder nauwkeurig is, maakt het een lange periode van data-acquisitie tegen relatief lage kosten mogelijk en verschaft het een voldoende betrouwbare indicatie van de praktijkemissies van een voertuig. Bij grote afwijkingen kan worden overwogen alsnog een PEMS meting uit te voeren.

Metingen met Remote Emission Sensing (RES)
Remote Emission Sensing (RES) betreft een instrument dat emissies van passerende voertuigen langs de weg kan meten. Er zijn experimentele metingen gedaan om te zien of dit type meting nuttig kan zijn voor het vastleggen van de praktijkemissies. Een belangrijke vraag daarbij is of zogenaamde *high-emitters* kunnen worden gedetecteerd omdat deze, bij het schoner worden van het wegverkeer, een relatief grote bijdrage kunnen hebben aan de totale uitstoot.

Resultaten, conclusies en aanbevelingen

1 Verbeteringen in de Euro V wetgeving hebben geleid tot een verbetering van de praktijk NO_x emissies van de tweede generatie Euro V dieselvoertuigen

Zware voertuigen met een Euro V dieselmotor hebben zeer uiteen liggende en gemiddeld hoge NO_x emissies. In een aantal gevallen en vooral bij lage rijsnelheid zijn deze amper lager dan de emissies van Euro III voertuigen. Deze inzichten waren al in 2010 duidelijk en zijn meegenomen in de Nederlandse emissiefactoren. EEV dieselvoertuigen vertonen hetzelfde emissiegedrag voor NO_x als Euro V voertuigen. Dat betekent dat EEV voertuigen met dieselmotoren geen voordeel brengen als het gaat om NO_x uitstoot.

De Euro V wetgeving is in 2005 en 2009 in verschillende stappen geïmplementeerd. In 2009 zijn de eisen rondom NO_x emissies en monitoring van de emissies door het voertuig zelf (OBD) verscherpt, zonder dat de limietwaarden zijn veranderd. Als gevolg hiervan is een tweede generatie Euro V motoren op de markt gekomen met vooral onder stedelijke condities een gemiddeld lagere NO_x uitstoot.

2 Euro V vrachtwagens met dual-fuel technologie leveren een verlaging van de uitstoot van NO_x, maar stoten meer broeikasgassen uit

In Nederland zijn dual-fuel vrachtwagens, onder bepaalde voorwaarden, toegestaan. In het testprogramma is de uitstoot van twee Euro V vrachtwagens met een dual-fuel systeem onderzocht met PEMS. De focus van het meetprogramma lag op de uitstoot van methaan, vanwege het hoge aardopwarmingsvermogen, alsook op de uitstoot van NO_x. De testvoertuigen bestonden uit één dieselvoertuig met een achteraf gemonteerd (retrofit) dual-fuel systeem dat CNG gebruikt als tweede brandstof, het andere voertuig heeft een meer geavanceerd dual-fuel systeem dat met medewerking van de fabrikant is ingebouwd en naast diesel LNG gebruikt als tweede brandstof.

De resultaten tonen aan dat de NO_x uitstoot van de voertuigen in dual-fuel bedrijf ongeveer 10 tot 20% lager ligt dan in dieselbedrijf. Maar door de uitstoot van substantiële hoeveelheden methaan met een hoog aardopwarmingsvermogen is de totale equivalente CO_2 uitstoot uit de uitlaat tot wel 50% hoger dan de totale CO_2 uitstoot tijdens dieselbedrijf. Hierbij wordt aangetekend dat het meer geavanceerde dual-fuel systeem een lagere uitstoot van methaan heeft. Toch blijft de totale uitstoot van broeikasgassen (CO_2 equivalenten) hoger in dual-fuel bedrijf. De Euro VI wetgeving heeft impliciet voorzien in een aanscherping van de eisen voor de totale equivalente CO_2 uitstoot door strengere limieten op te nemen voor de uitstoot van methaan van dual-fuel voertuigen. Het wordt aanbevolen om de uitstoot van nieuwe generaties dual-fuel voertuigen te blijven monitoren.

3 Eerste resultaten Euro VI zijn veelbelovend: moderne vrachtwagens en bussen zijn gemiddeld fors schoner dan vorige generaties

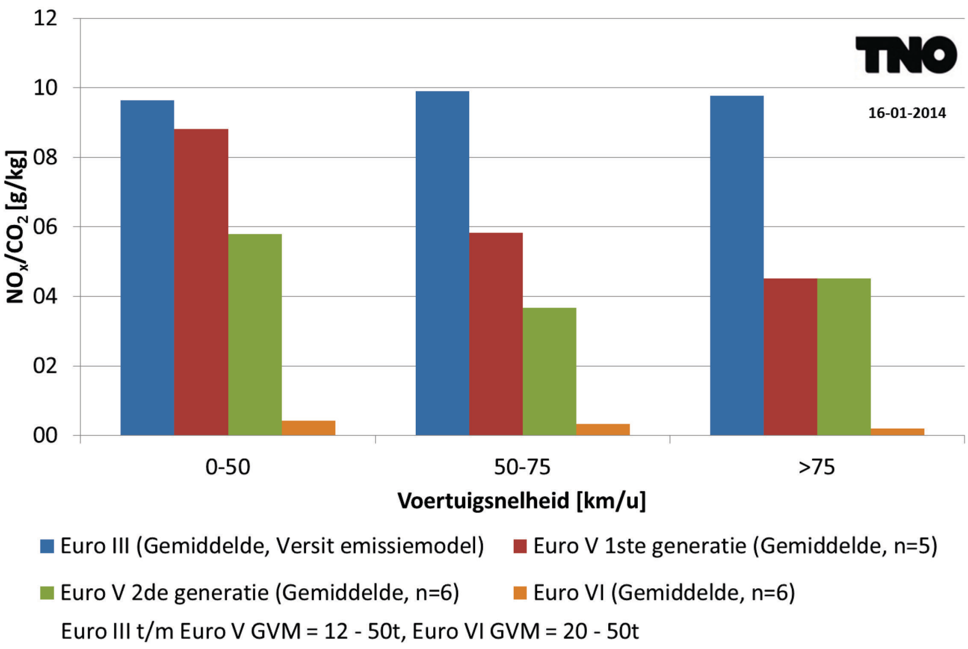
Op 1 januari 2014 is de nieuwe, strenge Euro VI wetgeving van kracht geworden. In de Euro VI wetgeving zijn de emissielimieten flink aangescherpt en is een praktijkemissietest onderdeel geworden van de typekeurtest.
Anticiperend op de Euro VI normen hebben voertuigfabrikanten nieuwe motoren en een combinatie van geavanceerde emissiereductiesystemen ontwikkeld. De

belangrijkste systemen zijn het zeer efficiënte roetfilter voor de reductie van fijnstof, en voor de reductie van uitstoot van NO_x de SCR-katalysator en systemen voor uitlaatgasrecirculatie, vaak aangeduid met Exhaust Gas Recirculation of EGR.

In 2011-2013 heeft TNO 12 Euro VI voertuigen gemeten. Op testroutes die worden voorgeschreven door Euro VI wetgeving voldoen alle gemeten Euro VI voertuigen aan de emissienormen. Euro VI vrachtauto's voor lange afstand hebben in de praktijk– dat wil zeggen: op ritten met een groot aandeel snelwegkilometers – een zeer lage NO_x uitstoot en zijn dus erg schoon.

Fijnstof is in de PEMS testen niet gemeten, omdat hiervoor nog geen gereglementeerde methode bestaat. Op basis van de robuuste roetfiltertechnologie die wordt toegepast op de huidige Euro VI voertuigen mag, echter, worden aangenomen dat de uitstoot van fijnstof sterk wordt teruggedrongen en weinig gevoelig is voor de rijomstandigheden. Een beperkte set experimentele meetgegevens bevestigt deze aanname. De inspanningen van wetgevers én voertuigfabrikanten werpen in Euro VI hun eerste vruchten af.

Euro VI vrachtwagens voor lange afstand hebben een significant lagere NO_x uitstoot dan vorige generaties vrachtwagens

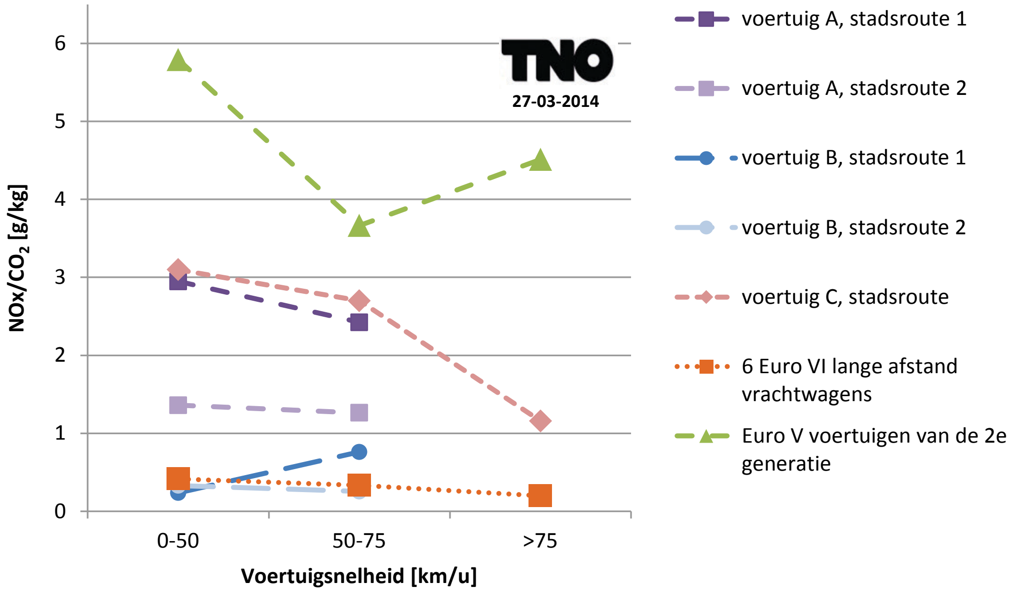


4 Euro VI distributietrucks en Euro VI bussen zijn in de praktijk nog niet in álle gevallen schoon

Hoewel ook de geteste distributietrucks en bussen aan de Euro VI wetgeving voldoen, laten praktijkmetingen zien dat deze voertuigen nog niet in álle gevallen schoon zijn. TNO testte drie voertuigen van dit type tijdens typische dagelijkse inzet. Die inzet kenmerkt zich door een hoog stedelijk karakter, met bijbehorende lage gemiddelde snelheden, relatief veel dynamiek en regelmatig aan- en uitschakelen van de motor. In dit soort omstandigheden is dikwijls sprake van een lage gemiddelde zogenaamde 'motorlast' en daardoor lagere uitlaatgastemperaturen. Hierdoor is het systeem, dat de NO_x uitstoot verlaagt, minder effectief.

Twee van de geteste voertuigen lieten onder deze omstandigheden, in vergelijking met de eerder geteste lange-afstand vrachtwagens, een relatief hoge en bovendien erg wisselende NO_x uitstoot zien. Het aantal geteste voertuigen voor stedelijke distributie en personenvervoer is, echter, nog klein. In vervolgonderzoek zal daarom nader naar deze categorie voertuigen worden gekeken.

Onder zware stedelijke omstandigheden hebben sommige Euro VI voertuigen nog een relatief hoge en erg wisselende NO_x uitstoot, op lange-afstand ritten zijn de geteste Euro VI vrachtwagens zeer schoon



De luchtkwaliteit is in veel steden nog een actueel probleem: zo kampte Nederland in april 2014 nog met smog. Omdat vrachtwagens en bussen in steden samen verantwoordelijk zijn voor een groot deel van de vervuilende emissies, wordt aan Euro VI voertuigen – ook op basis van eerdere metingen – een groot verbeterpotentieel toegedicht. Als juist in steden de praktijkemissies van deze voertuigen hoger zijn dan verwacht, kan dat leiden tot bij te stellen verwachtingen ten aanzien van de stedelijke luchtkwaliteit.

5 De Euro VI regelgeving kan met name op het gebied van stedelijke emissies verder worden verbeterd

Uit de metingen blijkt dat Euro VI voertuigen in de praktijk niet in alle gevallen zeer schoon zijn. Bij een typisch stedelijke inzet, lieten enkele voertuigen nog een hogere NO_x uitstoot zien. Dit terwijl de voertuigen wel voldoen aan de Euro VI emissiewetgeving. Een mogelijke oorzaak is dat de typische toepassing van voertuigen in stedelijke omgeving niet expliciet is gereguleerd in de Euro VI wetgeving. Wel onderzocht TNO een Euro VI voertuig dat onder alle stedelijke omstandigheden schoon was, hetgeen laat zien dat Euro VI voertuigen in de praktijk in typisch stedelijke inzet schoon kunnen zijn.

Met ondersteuning van TNO zal het Ministerie van Infrastructuur en Milieu de testresultaten in Brussel gebruiken om de Euro VI regelgeving met name op het gebied van stedelijke emissieprestaties verder te verbeteren. Zo zetten het Ministerie en TNO zich samen in voor lage emissies onder alle representatieve praktijkcondities, zodat milieudoelen op het gebied van binnenstedelijke luchtkwaliteit kunnen worden behaald.

Summary

Commissioned by the Ministry of Infrastructure and the Environment of The Netherlands, TNO conducts the in-service testing programme on heavy-duty vehicles. In this programme TNO measures on a regular basis the tail-pipe emissions of heavy-duty vehicles to determine whether the emissions comply with the EU type-approval standard and to determine if the vehicles are clean in the real-world, under representative conditions. The Ministry and local governments also use the insights and data from the programme to develop local, national and international policies for the realisation of the environmental targets in the field of air-quality and climate.

The programme of 2011-2013 mainly aimed at the real-world NO_x and NO_2 emissions of heavy commercial vehicles, because in the Netherlands the EU limit values for the concentration of NO_2 in the ambient air are still exceeded on some locations and commercial vehicles have a relative large share in the local emissions. Already in advance of the date of entry into force of the Euro VI legislation on January 1st, 2014 the Euro VI commercial vehicles represent a growing share in the Dutch vehicle fleet. The Euro VI legislation for heavy commercial vehicles became more stringent, mainly with a goal to contribute to the improvement of local air-quality and that is why the focus of the testing programme was on the real-world emissions of Euro VI heavy commercial vehicles.

The main conclusions and recommendations about the in-service and real-world emissions of Euro VI heavy commercial vehicles are the following:

1. **All Euro VI vehicles tested by TNO comply with the EU standard for in-service conformity.** It has to be noted that only new vehicles have been tested. It can’t be concluded whether vehicles will still fulfil the requirements over the useful life of the vehicle. Monitoring of the emissions over the useful life of Euro VI vehicles in the follow-up of the programme is recommended.
2. **The new and more stringent Euro VI legislation has led to significantly lower real-world emissions of the heavy commercial vehicles.** On average, the NO_x emission of Euro VI trucks and buses has decreased sharply compared to Euro V trucks and buses. Manufacturers have made a large step with the reduction of pollutant emissions from the tail-pipe. Especially the Euro VI long haulage trucks are much cleaner than preceding generations.
3. **Not all Euro VI vehicles that are used in an urban environment have a low tail-pipe emission of NO_x under all representative circumstances.** Next to the long haulage trucks, TNO has also tested a small sample of distribution trucks and buses. These vehicles are cleaner than previous generations, but still show strongly varying NO_x emissions. In busy urban driving conditions, with given low driving speeds, one vehicle is very clean, while two other vehicles still regularly show high NO_x emissions. For derivation of reliable emission factors and insight in real-world performance for these types of vehicles, more measurement data are needed. It is therefore recommended to focus the measurement programme on smaller

heavy-duty vehicles and applications which operate under more difficult, but still representative conditions, like city buses and distribution trucks.

4. **The Euro VI legislation can be improved, mainly on emissions under urban driving conditions.** The emissions of vehicles that typically operate in an urban environment are not explicitly regulated in the Euro VI emission legislation.

With support of TNO, the Ministry of Infrastructure and the Environment will use the test results of the programme in Brussels to further improve the emission legislation with the ultimate goal to reduce emissions at the source, especially in representative urban situations. In this way the Ministry and TNO work together to achieve the targets for air-quality for the densely populated urban areas in the EU and the Netherlands.

Contents

1 Introduction

1.1 Background

Road Transport is of great economic importance for the Netherlands. With large ports on the North Sea and a dense network of roads, rail-, water- and airways The Netherlands logistic infrastructure serves as a gateway for the transport of goods and people from all over the world to the inner lands of Europe and vice versa. These activities and all local activities, all increased by economic growth, come with an environmental burden to the region, mainly for air quality. Already in the previous century the Ministry of the Environment recognized this situation and introduced, amongst others, national policies with the aim to effectively reduce pollutant emissions at the source.

In 1994 the Ministry started the SELA programme (Schone En Lawaai Arme voertuigen) to stimulate the introduction of clean and low-noise heavy-duty vehicles on the market. This programme required vehicles to comply with certain stringent national emission and noise requirements, which were checked by TNO with dedicated test procedures.

In the meantime the EU emission type approval legislation [70/156/EC] developed its procedures and requirements, supported by insights of the national programmes. As a result, EU emission limits have become more stringent over time and the type approval test procedure recently improved by moving from an engine-based laboratory procedure to a procedure also including more real-world oriented requirements [2007/46/EC, 2011/595/EC]. All this resulted in enormous technological improvements, made by the manufacturers which in turn also lead to enormous improvements in air-quality. At the same time also the efficiency of the power-train improved and as a result a gradual decrease of fuel consumption and CO_2 emission can be observed.

In the last decade the concentrations of the pollutants NO_2 and PM_{10} have reduced over time. At the moment in the Netherlands, however, the concentration of NO_2 still exceeds the limits as specified in the EU air-quality directive. This happens mainly in some large cities at local spots near busy roads, where traffic is the major contributor to the air-pollution. The cities have taken special measures to achieve the required reduction of the concentration of NO_2 at these local hot spots. These measures are necessary on top of the gradual reduction of the source emissions which is enforced through the EU emission regulation, for instance for road vehicles. To achieve the targets for ambient NO_2 concentrations, the cities therefore not only rely on the effectiveness of their own measures but also rely on the effectiveness of the EU emission regulation for road vehicles.

Today, the EU emission legislation for heavy-duty vehicles is still under development and although it has advanced substantially over time, results of the in-service testing programme performed with the current generation of vehicles (Euro V and VI) showed that the EU emission legislation still requires some further refinement to guarantee the so needed low-pollutant emissions at the source.

1.2 Aim and approach

The general aim of the Netherlands in-service testing programme for heavy-duty vehicles is to gain insight into trends in real-world emissions of generations of heavy-duty vehicles, under the usage conditions relevant for the Dutch situation.

More specifically the aims of the programme are:

- to assess the real-world emission performance with a focus on the NO_x and NO_2 emissions. In the view of air-quality problems in Dutch city centres, in particular urban or low speed driving conditions are considered.
- to check the conformity of vehicles in-service against the applicable requirements as laid down in the EU emission legislation [582/2011/EC].
- to collect information to establish emission factors for the (inter)national models which calculate pollutant emissions and are used for air-quality predictions.
- to evaluate the in-service conformity procedure for the type of truck using latest Euro V and Euro VI emission technologies, and
- to extend the knowledge needed for the development of methods to effectively regulate real-world emissions in the EU.

For this investigation, TNO used a Portable Emission Measurement System (PEMS) for determination of the real-world truck emissions. PEMS is introduced in the Euro V and Euro VI heavy-duty emission legislation for determination of 'in-service conformity' [582/2011/EC] and as such is a widely accepted method to measure real-world emissions and determine the in-service emission performance.

PEMS, in the case the gas-PEMS measures the exhaust gas components NO_x, NO_2, CO_2, CO and HC and can alternatively measure CH_4 when an additional analyser module is placed. The measurements can take place driving the truck on the road in normal traffic. As such, PEMS yields estimates for real-world emissions performance of the investigated vehicle. PEMS does not yet include a validated method to measure PM (particulate matter).

Next to PEMS, a new method is applied [Vermeulen et al. 2012c] called SEMS (Smart Emission Measurement System). The SEMS method measures $NO_{x,}$ NH_3 and O_2 in the exhaust.

For determining realistic emission factors, detailed insight in the composition and typical distributions of the emissions of the Dutch fleet is necessary. Amongst others, knowing how many vehicles fall into the high emitter category is essential. For this purpose, TNO investigated the possibilities for gaining insights in the emission behaviour of representative samples of the fleet using Remote Emission Sensing (RES).

1.3 Structure of the report

In **Chapter 2** the test programme set-up and the methodology for testing real-world of tail-pipe emissions is discussed. This includes the vehicle selection, the emission measurement method and the data evaluation methods are described.

Chapter 3 discusses other activities that were executed in the programme, that contributes to the evaluation of real-world emissions of heavy-duty vehicles.

In **Chapter 4** the results of the test programme are presented and discussed. This is discussed for:

- in-service conformity tests. The test programme results are presented for the measurements performed according the formal rules of the EU in-service conformity (EC/582/2011 and amendments).
- real-world emission tests on Euro V and Euro VI heavy-duty diesel vehicles.
- real world emission tests of Euro VI vehicles operating in an urban environment
- real world emission tests on dual-fuel trucks
- real-world emissions of NO_2 of Euro VI diesel vehicles
- the additional items are discussed which have been investigated next to the regular PEMS programme. The additional items are: the development of a Smart Emission Measurement System, Road-Side Emission measurements (RES) and emission modelling with Versit+.

Chapter 5 summarizes the conclusions and recommendations obtained in the programme.

2 Method for measuring emissions in the real-world

The methods used for measurement and analyses of the emissions are described in this chapter. First an overview of the EU emission legislation is given for the stages Euro V and VI. Thereafter, criteria for vehicle selection as well as the total selection are discussed. Then the method for checking the in-service conformity and the method for determination of the real-world emissions is discussed. Finally, it is discussed how results during the entire programme are disseminated.

2.1 Large changes in EU emission legislation from Euro V to Euro VI

With the introduction of Euro VI in the EU emission legislation, not only the limits for the gaseous emissions were lowered. Also introduced in Euro VI were:

- New test cycles, the WHTC and the WHSC. Especially, the transient WHTC has changed a lot compared to the former ETC. A cold start was included, the results over the cold started WHTC has to be weighted with the hot started WHTC. Furthermore, the normalized engine load has decreased substantially and is generally found more representative for heavy-duty operation.
- A completely new procedure for in-service conformity testing, which now has to be performed in the real-world with PEMS.
- A revised procedure for the measurement of particulate matter.
- A new procedure for the measurement of particle number, together with a limit setting.
- Requirements to limit off-cycle emissions.
- Determination of fuel consumption and CO_2 emissions.

The tables below gives an overview of the differences between Euro V and Euro VI legislation.

Table 1: Overview of the most important changes in EU emission legislation from Euro V to Euro VI

Euro V 'first generation'	**Euro V 'second generation'**	**Euro VI**
2005-2008	2008-2013	2014...
ETC NOx: 2.0 g/kWh		WHTC NOx: 0,46 g/kWh
ETC PM: 30 mg/kWh For EEV: 20mg/kWh		Improved PM procedure (PMP) WHTC PM: 10 mg/kWh New PN procedure (PMP) WHTC PN: $6.0x10^{11}$ /kWh
OBDI	OBDII	OBD with access to OBD, vehicle repair and maintenance information
		New reference fuel specifications for diesel (B7), petrol (E10), ethanol (E85), LPG and biomethane
	NO_x control measures	NO_x control measures
	ISC with PEMS optional	ISC with PEMS mandatory, CFmax=1.5
		Control of Off-cycle emissions
		Measurement of CO_2 and fuel consumption
Test cycles ETC, ESC, ELR	Test cycles ETC, ESC, ELR	Test cycles WHSC, WHTC

The table below shows the gradual changes in Euro V emission legislation and the codes used for the sub-stages.

Table 2: Overview of Euro V and Euro V EEV sub stages

Popular name	Letter	Row	OBDI	OBDII	Durability and ISC	NO_X control***
Euro V	D	B2(2008)	Y	-	Y	-
Euro V	E	B2(2008)	Y	-	Y	Y
Euro V	F	B2(2008)	-	Y	Y	-
Euro V	G	B2(2008)	-	Y	Y	Y
Euro V EEV	H	C	Y	-	Y	-
Euro V EEV	I	C	Y	-	Y	Y
Euro V EEV	J	C	-	Y	Y	-
Euro V EEV	K	C	-	Y	Y	Y

2.2 Selecting the right test vehicles

The vehicle selection was defined to serve on multiple goals:

Representativeness
The emission data is used for modelling the heavy-duty vehicle emissions in the Netherlands. For this on-going work, emission data is required from vehicles in-service and which have a large share in the Dutch vehicle fleet. The engine type and sales numbers thereof, are the primary criteria used to select the vehicles. Additional criteria are representative engine power and vehicle type.

Emission class
When a new emission stage enters into force, the focus of the selection shifts to that new emission stage. During the programme reported here, Euro VI came into force in 2014, but already in 2013 the first vehicles appeared on the market due to a tax incentive for those vehicles. The focus of the programme therefore shifted from Euro V to Euro VI in 2013.

Technology
When new or alternative technologies enter the market, for instance using an alternative fuel, the programme aims to assess the emissions under real-world driving conditions. Examples for this programme are the two vehicles with dual-fuel technology, running diesel and natural gas which have been tested and a pure electric vehicle which has been tested on a test track. In an extension of the programme busses have been tested with an alternative and innovative powertrain. These tests focussed on the applicability of those concepts in real-life city bus operation. Amongst the concepts are plug-in hybrid, pure electric and hydrogen electric vehicles. The outcome will be reported in a separate report, due to be expected half 2014.

Sources
The heavy-duty test vehicles are obtained from various sources. To find the right vehicles, TNO uses a dataset which is purchased annually from RDW. The dataset contains sales and vehicle information and information about the owner. This enables TNO to correspond with owners of targeted vehicles about possible cooperation for the test programme. The dataset is provided under strict legal conditions preserving privacy of the owner. Additionally, TNO uses its network with transport companies, dealers, importers and manufacturers to find the right vehicle.

The following sources are used to obtain test vehicles:
- Vehicles of private owners or transport companies. This is the most used and preferred way to obtain vehicles, since the vehicles are most probably used in normal service. The availability of those vehicles for testing depends on the willingness of the (fleet-) owners to cooperate with the programme and the availability of the vehicle itself, as most vehicles are efficiently scheduled for transport operation. However, most owners are happy to provide a vehicle. The programme provides a financial compensation for the time the vehicle is lend to TNO.
- Rental vehicles. Rental vehicles are expected to be subjected to normal use and conditions like the privately or company owned vehicles.

– <u>Vehicles provided by the manufacturer.</u> When a vehicle is hard to obtain, for instance because it is very new or it was only recently introduced on the market the manufacturer is asked to supply a vehicle. These vehicles are often from the trial fleet of the importer or manufacturer. In some occasions these vehicles are carefully inspected by the manufacturer before they take part of the test programme.

Detailed information of the vehicle is requested from the owner. This includes information like history of maintenance, repairs and modifications. Detailed technical information about the vehicle itself is obtained from the OEM or the importer. The OEM is asked to provide the type-approval documents for the vehicle and engine (installation) certification. Additionally, information is requested, as often needed, to evaluate the PEMS test results. In some cases the manufacturer was asked to provide hardware for the installation of the PEMS system. In a few occasions the exhaust namely had such a complicated shape that mounting the exhaust flow meter was very hard and in a few of these cases the manufacturer provided his own special build PEMS connection piping.

Table 3: Overview of heavy-duty vehicles tested in the programme 2011-2013, excluding the buses tested for the zero emission bus program.

TNO Test code	EU Emission class	EU Veh. Cat. 2007/46/EC	Fuel	Vehicle	Rated Power [kW]	Remarks
M	VI Prototype	N3	EN590	Rigid + Trailer	300-400	Prototype
N	V B2(G)	N3	EN590	Tractor Semi-trailer	300-400	
P	V B2(G)	N3	EN590	Tractor Semi-trailer	200-300	
Q	EEV C(K)	N3	EN590	Tractor Semi-trailer	300-400	
R	EEV C(K)	N2	EN590	Rigid	100-200	
S	V B2(G)	N3	EN590	Tractor Semi-trailer	300-400	
T	V B2(G)	N3	EN590	Tractor Semi-trailer	300-400	
U	VI	N3	EN590	Tractor Semi-trailer	300-400	
V	V B2(G)	N2	EN590	Distribution truck	100-200	
W	EEV C(K)	N2	EN590	Distribution truck	100-200	
X	VI	N3	EN590	Tractor Semi-trailer	300-400	
Y	VI	N3	EN590	Rigid + Trailer	200-300	
Z	EEV C(K)	N3	Dual Fuel Diesel / CNG	Tractor Semi-trailer	300-400	Dual fuel and 100% diesel
AA	EEV C(K)	N3	Dual Fuel Diesel / LNG	Tractor Semi-trailer	300-400	Dual fuel and 100% diesel
AB	-	M3	Electricity	Standard Bus	-	Pure Electric Vehicle
AC	VI	N3	EN590	Tractor Semi-trailer	300-400	PEMS and SEMS
AD	VI	N3	EN590	Tractor Semi-trailer	300-400	PEMS and SEMS
AE	VI	N3	EN590	Tractor Semi-trailer	300-400	PEMS and SEMS
AF	VI	N3	EN590	Tractor Semi-trailer	300-400	PEMS and SEMS
AG	VI	N3	EN590	Garbage truck	200-250	no PEMS, only SEMS
AJ	VI	M3	EN590	City bus	200-250	PEMS and SEMS
AK	VI	M3	EN590	City bus	200-250	PEMS and SEMS
AL	VI	N2	EN590	Distribution truck	100-150	no PEMS, only SEMS

The test vehicles are inspected before the start of the testing and after the testing and specific information is taken from the vehicle. The inspection includes a reading of the error codes of the on-board diagnostics (OBD) system where the occurrence of emission related malfunctions is checked. If necessary, repairs are made. When problems are observed with the emissions during the measurements, another check of the OBD is done after the test programme, to exclude that OBD errors appeared during the measurements. Furthermore, samples are taken from the fuel and the reagent (AdBlue).

2.3 Measuring tail-pipe emissions with PEMS

This paragraph presents the method of on-road testing with PEMS (Portable Emission Measurement System).

European type approval for emissions of Euro V truck engines is obtained from tests performed on prescribed engine cycles on an engine test bed under laboratory conditions. For the determination of real-world emissions of in-use vehicles, execution of engine tests on an engine test bed may very probably not be representative. With the introduction of PEMS, or Portable Emission Measurement System, it has become possible to monitor emissions of vehicles in normal traffic situations. In 2011 the EU Directive [582/2011/EC] was introduced which describes on-road emission tests using PEMS for checking the conformity of vehicles in-service for Euro V (Annex II, optionally) and Euro VI (Annex XII, mandatory).

PEMS is a system to measure the gaseous exhaust gas emissions of a vehicle. The measurements can take place on the road in normal traffic. Next to the in-service conformity PEMS yields estimates for real-world emissions performance of the investigated vehicle.

PEMS measures the mass emission of the exhaust gas components NO_x, NO_2, CO_2, CO and HC. The fuel consumption can be calculated from the emissions using the carbon balance method. For the measurement of PM no system is commercially available. However, at the moment a few prototype instruments are under investigation by the EU (DG-JRC) for possible inclusion in the in-service conformity measurements. Furthermore, the PEMS logs ambient conditions, the ECU data stream and GPS vehicle speed. The total PEMS setup is able to deliver the emission data in g/s, g/km, g/kWh or g/kgCO_2 for instance.

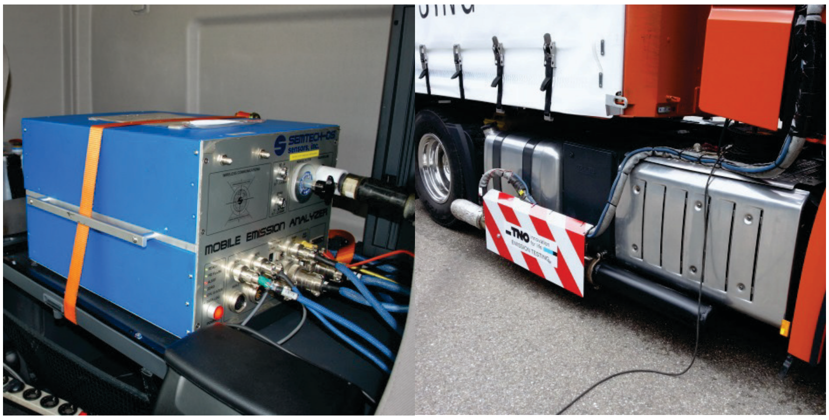


Figure 1: Two important PEMS parts: the integrated gas analysers and PEMS control unit (left) and the exhaust flow meter (right) mounted on the tail-pipe of a heavy-duty vehicle.

2.4 Measuring the emissions with a Smart Emission Measurement System

Next to PEMS, a new method is applied [Vermeulen et al. 2012c] called SEMS (Smart Emission Measurement System). The SEMS method measures $NO_{x,}$ NH_3 and O_2 in the exhaust. O_2 correlates well with CO_2 for diesel vehicles and this theoretic relation is used to estimate the CO_2 concentration from the measured O_2 concentration. The ratio of NO_x and CO_2 proved to be a good indicator for the emission level of NO_x.

The emission data obtained over a test trip can be collected in speed intervals (speed binning) to reveal the emission behaviour over the operational speed range of a given type of diesel vehicle. The first results have been reported in [Vermeulen et al., 2012c]. A merit of this system is that it can run autonomously for a longer period of time (days-weeks). Therefore SEMS can monitor emissions that occur during all conditions that occur in the real-world.

2.5 A specified set of test trips

Using the gas-PEMS and in some cases the SEMS, all vehicles were tested, driving a set of specified trips.

Aim of the specified trips was to meet the following requirements:
- represent typical Dutch urban, rural and motorway conditions and applicable for testing with different payloads;
- yield results that are comparable with the results that were obtained during the previous PEMS measurement programmes (2009-2011);
- assess the effectiveness and robustness of the procedures currently being used for in-service conformity legislation [EC/582/2011] and being developed for the future Real-Driving Emissions legislation;
- and assess the relation of in-service conformity legislation and Real-Driving Emissions legislation with real-world emissions for typical Dutch driving conditions.

Resulting from these requirements the following trips were defined and used in the test programme:
- <u>Reference trip</u>: a fixed trip used for each test vehicle. This enables the comparison of all test vehicles. The trip is started with a warm engine and aftertreatment, directly after a warming-up period, a trip over the same route as the reference trip, until stable engine oil and coolant temperature is reached.
- <u>EU trips</u>: The trips are designed and chosen according the trip requirements of EC/582/2011, see Table 4.
- <u>Alternative trips</u>: In addition to the trips above, for specific goals or questions alternative trips have been designed and driven. Examples are:
  - bus trips. Chasing city busses in real operation with actual bus stops and door openings to simulate boarding (without people actually boarding).
  - a trip with a 15 minute idle period and a 15 minute period with the engine shut off. This was executed to investigate the effects of the cooling down of the aftertreatment on the emissions. Occasionally, a longer idling period was used of two hours. Furthermore, a few trial runs were done with shorter trips for the N2 truck class.

The trips are normally driven with 55% of the maximum payload. Maximum payload is defined as the difference between the maximum technically permissible laden mass taking account of an eventual trailer and maximum axle loads and the weighted empty vehicle mass in running order. To investigate the possible effect of payload, and as an effect higher or lower engine load during driving, in some occasions trips were also driven with 10% or 100% of the maximum payload.

Table 4: Overview of trip requirements according to the in-service conformity legislation [582/2001/EC].

Vehicle category	Trip duration percentage (± 5%)		
	Urban	**Rural**	**Motorway**
M1 and N1	45	25	30
N2	**45**	**25**	**30**
N3	**20**	**25**	**55**
M2 / M3	45	25	30
M2 / M3 M3 of Class I, II or Class A	70	30	0

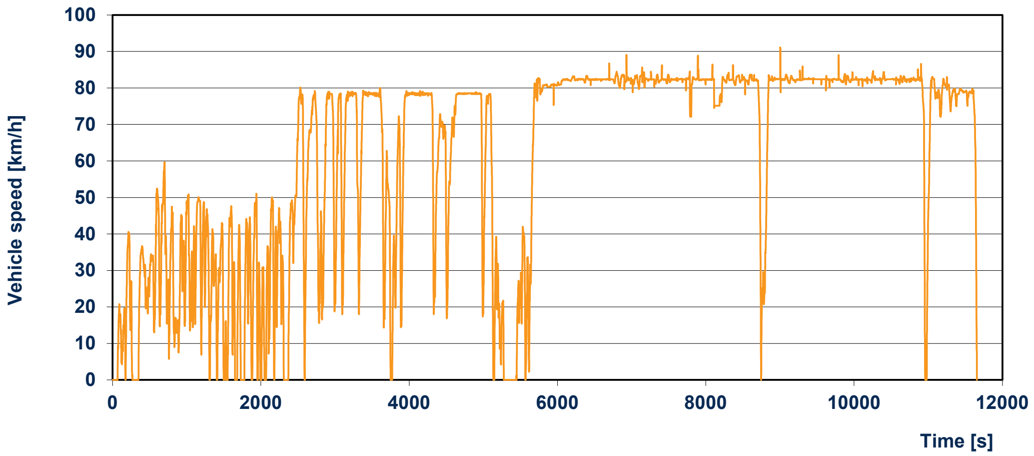


Figure 2: Example of a speed trace of the N3 trip which has shares of urban, rural and motorway according to Euro VI specifications.

2.6 Checking the in-service conformity

This paragraph presents an overview of the procedure for checking the conformity of engines and vehicles in-service, applying the in-service conformity rules for testing and the pass-fail method to determine the Conformity Factor (EC/582/2011 and amendments), using PEMS.

The method is introduced in the EURO V and Euro VI heavy-duty engine emission legislation for determination of in-service conformity. ‘In-service conformity’ in this matter can be explained as: does the vehicle in-service comply with the emission standards under comparable conditions as if its engine would be tested on an engine test bed. The ‘in-service conformity’ method was originally designed to check if vehicles in-service and on-the-road are in conformity with their original type approval over the engine test. For Euro VI the check of ‘in-service conformity’ using PEMS is mandatory. For Euro V it is allowed to use PEMS as an alternative test method for the regular engine test bed method for checking ‘in-service conformity’.

Pass-fail evaluation
The pass-fail evaluation method has been applied, using the EMROAD tool (version 5.1 build 8). This tool can upload emission data from PEMS and CAN data from the vehicle in an Excel workbook to calculate the conformity factors (CF) according to the in-service conformity rules. A Conformity Factor (CF) is the fraction of the calculated emission value according to the given data-evaluation method, of the ETC limit value in case of Euro V engines and the WHTC in case of Euro VI engines. A CF of 1.5 for NO_x means for Euro V that an equivalent of 1.5 times 2.0 g/kWh = 3.0 g/kWh is the result of the pass fail evaluation for the given regulated emission component. Vehicles are not allowed to emit more than 1.5 times the emission limit value under the for the in-service conformity procedure prescribed conditions and data-evaluation rules. For Euro VI engines the same CF is applicable. However, it now applies to the Euro VI WHTC limit values. For NO_x: 1.5 times 0.46 g/kWh = 0.69 g/kWh. Generally for in-service conformity checking, more than one vehicle should be analysed to determine whether the vehicle type is compliant with the in-service conformity requirements. In this programme only one vehicle per type was tested and therefore the results are indicative only.

The table below shows the basic settings as used for the pass-fail data evaluation with EMROAD. The CO_2 averaging window method was always used for the data-evaluation. The work window method was used whenever reliable CAN data stream was available with data from engine torque an speed. The method calculates the average emissions over windows as large as the CO_2 mass that would have been emitted during an ETC test (Euro V) or WHTC test (Euro VI) or over windows as large as work would have been produced by the engine over the given test cycles. In the EU legislation criteria are defined to exclude windows from the dataset, see also the table below.

Table 5: EMROAD data evaluation settings for the calculation of the Conformity Factor according to the proposed pass fail method.

EMROAD version	5.1 build 8
Reference quantity	Work or CO_2, depending on the availability and quality of the broadcasted ECU signals needed for the calculation of work.
Reference torque	As provided by the manufacturer or ECU
Torque calculation method	Method 3 (using % torque, reference torque and friction torque)
Reference cycle	ETC (Euro V) or WHTC (Euro VI)
CO_2 estimation	CO_2 and work provided by OEM or work or CO_2 estimated from brake specific fuel consumption (EMROAD): 200g/kWh used
Data exclusion	Engine coolant temperature < 70 ºC, Altitudes > 1500 m, 10^{th} percentile of the maximum values of the valid windows Power threshold: on (15-20%)
Time-alignment	On
Fuel density	0.84 kg/litre, (EN590 market fuel)
Vehicle speed	GPS vehicle speed
Conformity Factor	1.5

Cold engine operation and high altitudes are excluded from the pass-fail analysis. Furthermore, windows with a very long duration or low power are excluded. A power threshold excludes windows where the average power in a window is below a certain percentage of the rated power. A maximum for the window duration also excludes windows with a very low average power because at a low average power it takes a long time before the CO_2 reference mass is reached.

What remains after exclusion of data is a set of ‘valid windows’ of which the single window with the largest value of 90 percentile of the data is taken to calculate the CF for each regulated emission compound.

2.7 Real-world emissions

To determine the real-world emissions, PEMS provides instantaneous mass emissions of the emission compounds in gram/second. These can be converted in:

- gram/kilometre with the vehicle speed measured by the GPS or in
- gram/kilowatt-hour when the data stream of the ECU provides accurate signals for engine torque and engine speed, or in
- g/kgCO_2 which is convenient when engine work isn't available. Both g/kWh and g/kgCO_2 allow the comparison of the often very different engine sizes of heavy-duty vehicles. With these units the emission is related to a parameter which indicates a certain amount of engine output, either work or CO_2 emission. Engine work and CO_2 emission are strongly related through engine efficiency, see further on in this paragraph for an example.

Because PEMS trips deliver a lot of data and insight is needed in the emissions over the speed range of the vehicle, TNO developed the vehicle speed binning method VESBIN.

> The primary purpose of the VESBIN method is to facilitate the use of large amounts of PEMS data as input to calculate emission factors for urban, rural and motorway conditions and to gain insight into the emission behavior over the speed range of a vehicle. The method collects all emission data belonging to a defined speed interval and determines the average emissions for every interval over the complete speed range of a truck.

As preparation for the binning method PEMS data of the trips were pre-processed with EMROAD. EMROAD performs a data quality check and aligns the test signals. Data with a cold engine, i.e. coolant temperatures below 70°C are excluded from the evaluation. There were no big altitude differences during and between the trips. Vehicle speed bins with a width of 5 km per hour were selected to distinguish emission data for low, intermediate and high vehicle speeds easily. In each bin of vehicle speed, the emissions [g/s] and CO_2 [kg/s] or engine power [kW] from the data points belonging to that speed bin are collected. In the end the average speed within a bin, the average emissions in [g/kg CO_2] or [g/kWh] and the amount of data points within a bin are calculated.

The binning method can also be used to estimate brake specific emissions in gram per kilowatt-hour.

In the box below a calculation example is given to explain the binning method;

Example binning method calculation:

$$gNOx\ per\ kgCO2 = \frac{\sum_{v=vi}^{v=vi+5} NOx[g/s]}{\sum_{v=vi}^{v=vi+5} CO2[kg/s]}$$

Data points in a bin: 1 g/s NO_x, 10 kg/s CO_2
1 g/s NO_x, 0.1 kg/s CO_2
(In reality many more data points are needed)

Weighing of the contribution to the total emission in a bin:
Sum of the emissions / sum of the CO_2
=> (1+1) / (10+0. 1) = 0.2 [gNO_x/kg CO_2]

And not: Arithmetic average of the specific emissions
(1/10+1/0.1) / 2 = (0.1+10)/2 = 5.1 [g/kg CO_2]

The CO_2 specific emission results can be related to brake specific emission results assuming a constant average engine efficiency and fuel consumption. With an average engine efficiency of 40% (BSFC = ~210 g/kWh), the g/kg CO_2 results can be divided by 1.5 to get a corresponding g/kWh result. Lower average engine efficiencies lowers this factor and would thus increase the brake specific results accordingly.
For Euro V the NO_x emission limit of 2.0 g/kWh would amount 3.0 g/kg CO_2.
When the ISC conformity factor of 1.5 is taken into account, this would amount to 4.5 g/kg CO_2.
For Euro VI the NO_x emission limit of 0,46 g/kWh would amount 0.7 g/kg CO_2.
When the ISC conformity factor of 1.5 is taken into account, this would amount to about 1.0 g/kg CO_2.

2.8 Dissemination of results during the course of the programme

Results are disseminated during the course of the programme in different ways and with different purposes

Individual vehicle results

The results of each vehicle tested with PEMS is reported in an elaborate measurement report and shared with the manufacturer. The goal is to be able to open up a discussion about the results when necessary and to learn to understand specific emission behaviour and the possible causes for it. The reports describe the method applied, the results, conclusions about the in-service conformity and real-world emission performance of the specific test vehicle and show the results of the vehicle compared to that of other vehicles tested of the same emission class. The report is first send in draft form to the manufacturer so that he can comment on the results or request specific measurement data to investigate the results. The draft report is concluded once all parties agree upon the correctness of the results and conclusions.

In two occasions during the programme problems were found with emission levels exceeding normal real-world values and exceeding the provisional (Euro V) limits for in-service conformity. In one occasion the insights and discussion have led to a modification of the emission control software of the newly produced vehicles of the type tested. In the occasion where a very high real-world emission was detected (on another brand of vehicle) the manufacturer declared that the engine is certified to comply with Euro V under formally required test conditions. These test conditions for Euro V contain no formal requirements for real-world emissions or in-service conformity tests with PEMS on the road.

EURISEC: An international collaboration checking the emission conformity of engines and vehicles in-service.
The results of the in-service conformity tests have also been presented on a regular, annual basis in the EURISEC working group. EURISEC is a cooperation between three European member states in the field of in-service conformity testing of road vehicles falling under the scope of 2007/46/EC. The member states, Sweden, Germany and the Netherlands started their national programmes to investigate road vehicle emissions many years ago. The main goal of these programmes is to investigate the conformity of vehicles in-service with the emissions regulations. The motivation for such programmes is the EU emission regulation (582/2011/EC, article 11 paragraphs 5, 6 and 7) which allows Member States to perform their own testing programmes for in-service conformity. The results of these programmes should be taken into account by the type-approval authorities. The reason for this provision is that Type Approval Authorities are not fully independent. The TAA is contracted by the manufacturer to perform the certification.

During the testing programme of 2011-2013 working group meetings have been held in Stockholm, the-Hague and Berlin. The scope of the working group is the in-service conformity of the emissions of passenger cars (M1), vans (N1) and heavy-duty vehicles (N2, N3, M2, M3).

ERMES: an international collaboration for the improvement of emission models for road traffic
The insights of the programme are shared within the international ERMES working group. This group consists of experts on vehicle emissions of different Member States who share data and knowledge about the emissions of road vehicles with a purpose to make national and international emission models more reliable and accurate in an efficient way.

EU working groups
On behalf of the Ministry of Infrastructure and the Environment, TNO takes place in working groups in Brussels in which the foundations for new emission legislation are made. Data of the test programme is used to support the discussion within the

working groups, to develop effective and efficient procedures to be used for type approval of heavy-duty engines and vehicles.

National stakeholder meetings
Each year a national stakeholder meeting is organized. Invited are Dutch importers, delegates of Ministries with involvement in the topic, Environmental organisations, automotive trade organisations and the Dutch Road Administration Authority.

In the stakeholder meeting the results of the programme are shown and discussed and other stakeholders are invited to present their view or policy. The main goal of these meetings is to involve the stakeholders in the developments in the environmental aspects of road traffic and to make them aware of the importance hereof and at the same time giving stakeholders a possibility to share their view on the developments.

3 Other activities

Next to the common activities of the heavy-duty testing programme, like testing of the in-service and real-world emissions with PEMS, the programme is used to perform the measurements which are the basis for the determination of the Dutch emission factors for heavy-duty vehicles. Furthermore, in the programme ad-hoc questions about emissions can be answered by performing special or dedicated measurements. Finally, the programme constantly monitors for possibilities to develop new methods which could improve or simplify the generation of emission data.

In 2011-2013, two of such methods have been under investigation, namely SEMS (Smart Emission Measurement System) and Remote Emission Sensing (RES). The progress of the work for the both emission measurement options is reported in this chapter in the paragraphs 3.1 and 3.2 respectively and in [Vermeulen et al., 2012c] and [Kuiper, 2012].

The programme contributes to the development of the Dutch emission model Versit+ HD through the generation of emission data and the selection of test vehicles which are needed to fill the data gaps. This is discussed in 3.3.

The programme has been extended with measurements on innovative bus concepts. The goal of these measurements is to gain experience with the measurement of energy consumption of such concepts and to determine the real-world applicability of these concepts in real operation in bus concessions in the Netherlands. The programme is a follow-up of the monitoring programme of seven buses which ran in pilots where those buses have been operated in real use.

3.1 The Smart Emission Measurement System ‘SEMS’

The Smart Emission Measurement System ‘SEMS’ proves an effective tool to screen diesel vehicle NO_x and NH_3 emissions
The method, which uses a standard automotive NO_x and ammonia sensor, was evaluated in the programme by performing simultaneous measurements on some trucks with PEMS and SEMS together. The measurement system proved to correlate well with PEMS, which can be seen as an accurate reference measurement [Vermeulen et al., 2012c]. The method is less accurate than PEMS, but its merit to simply measure more and longer at lower costs increases the overall representativeness of the data, because more of the often variable emission behaviour is captured.

Background on SEMS
The Euro V requirements for diesel engines for trucks and buses have shown not to guarantee low NO_x emissions during real-world (mostly urban) driving conditions. A change in the Euro V test cycle or the development and introduction of specific off-cycle provisions (Euro VI) to improve real-life urban emission behaviour would take too much time due to the EU legislative process to play a role in the remaining year of registration of new Euro V vehicles. Furthermore, it would take years before the fleet is refreshed with the cleaner Euro VI vehicles.

At the request of the Dutch Ministry of Infrastructure and Environment a smart measurement system was developed to judge the real world NO_x emission of heavy-duty vehicles. The measurement system uses a NO_x - O_2 sensor for the measurement of the tail pipe concentration of NO_x and to estimate the tail pipe concentration of CO_2 for diesel engines. A GPS measures the time-based vehicle speed profile over the test trip. Furthermore, a special data-evaluation method helps to reveal emission performance over the speed ranges of a vehicle. The method is based on collecting (binning) emissions of NO_x and CO_2 in speed intervals and calculates the CO_2 specific NO_x emissions for each interval.

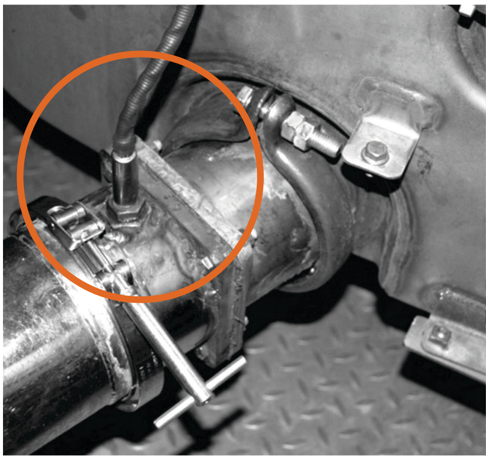


Figure 3: The NO_x - O_2 sensor installed at the tailpipe of a Euro VI heavy-duty vehicle.

Figure 4: The sensor and data-acquisition unit which logs the sensor data, GPS data and optionally the CAN data.

Possible applications of the method are:

- National approval schemes, like for dual-fuel vehicles, retrofit systems for heavy-duty vehicles and possibly also inland vessels.
- As a method to be used in public procurement to regularly check vehicles or to apply a pass-fail method with special requirements.
- In-service conformity screening. A simple method to perform more tests to screen for vehicles not in conformity or for erratic emission behaviour.
- Input for emission modelling for the determination of emission factors. The extensive data can be complementary to the data measured with more accurate and expensive systems, like PEMS.

Below an example is given of the first full SEMS measurement on a vehicle during real duty. 20h of data was recorded during one week of operation. Previous measurements with SEMS as reported in [Vermeulen et al., 2012c] where mainly done to validate SEMS against PEMS over short test trips.

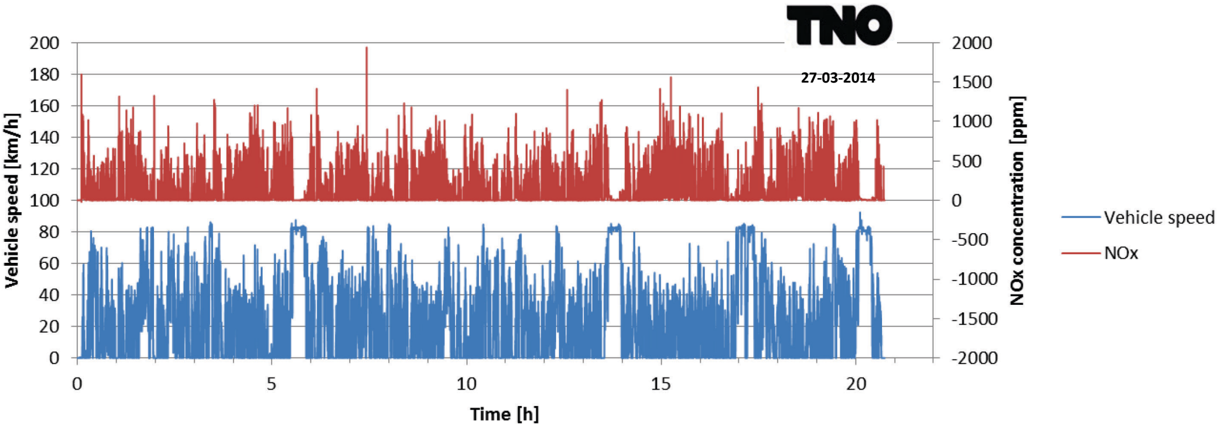


Figure 5: Trace of the vehicle speed and the tail-pipe NO_x concentration as measured by SEMS during real duty of a distribution truck. Clearly visible are the low NO_x emissions at motorway speeds around 80 km/h. This vehicle still proves sensitive to vehicles speed, as is also demonstrated by the calculated CO_2 specific emissions, see Figure 7.

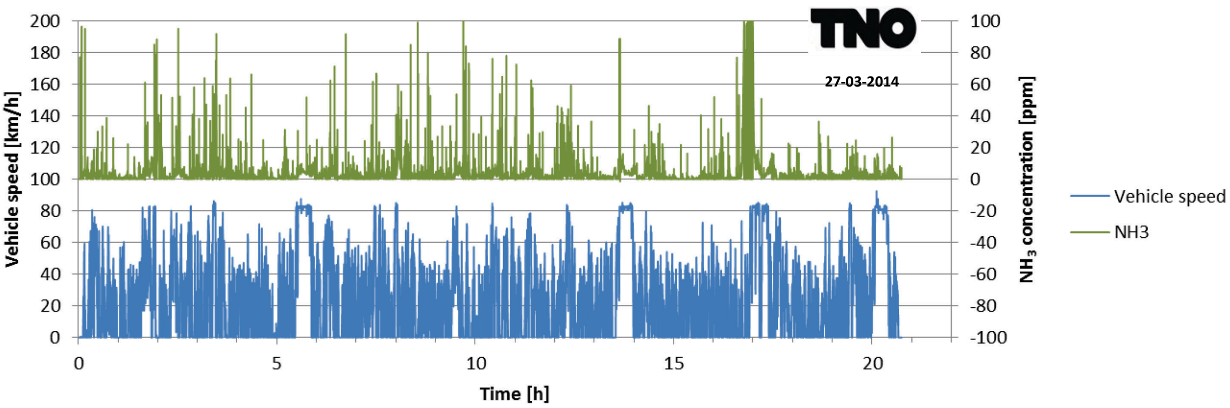


Figure 6: Trace of the vehicle speed and the tail-pipe NH_3 concentration as measured by SEMS during real duty of a distribution truck.

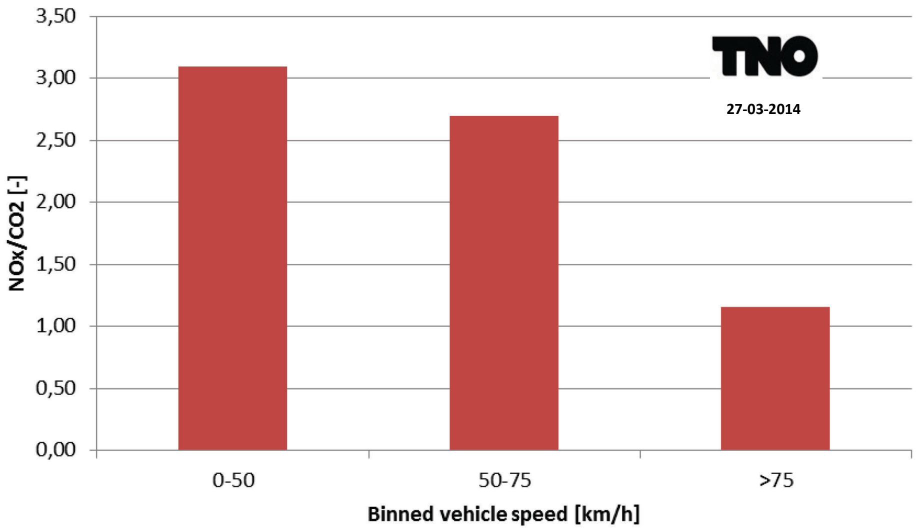


Figure 7: The signals as measured with SEMS converted to meaningful results. The levels of NO_x emissions depicted here can be compared to conventional g/kWh levels as explained in section 2.7. A level of 1.5 times the Euro VI limit for NO_x, which is used for in-service conformity, compares to a level of approximately 1.0 g/kg NO_x/CO_2. The figure shows that in real-world, the ISC NO_x emission level is clearly not obtained. Causes can be found in the differences between the determination of in-service conformity and real-world emissions: the operating conditions during the SEMS measurements differ from the in-service conformity operating conditions.

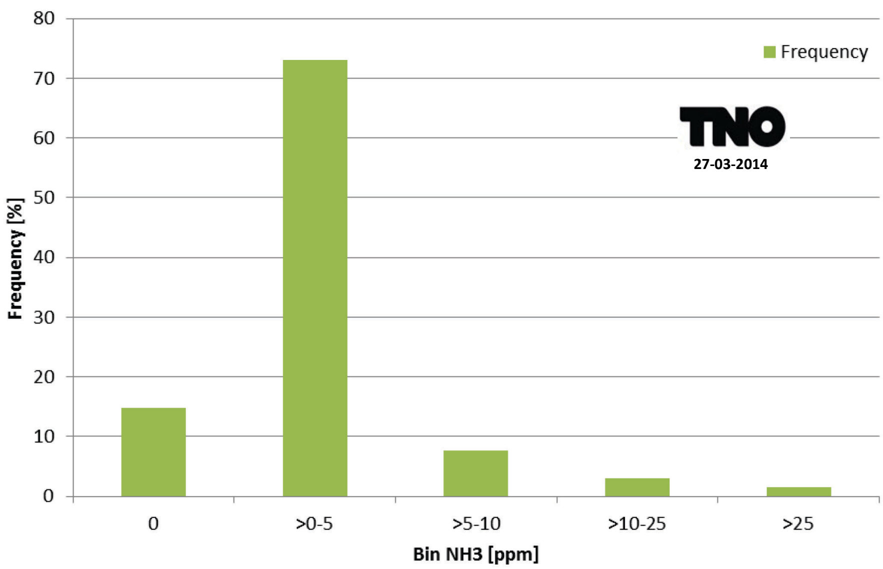


Figure 8: The picture shows the frequency distribution of the ammonia emission of the Euro VI distribution truck. As can be clearly seen in this picture the average concentrations are below 10ppm which is regulated by the definition of a limit for the maximum average tail-pipe concentration during an engine test for Euro VI. A small percentage of time peaks occurs higher than 10 or 25ppm in real world operation for this distribution truck.

3.2 Remote Emission Sensing

High emitters are vehicles that emit much more pollutants than expected, based on their type-approval. This may be caused by deterioration of emission control systems, malfunctions, tampering or by occurrence of conditions not covered by type-approval. Knowing how many vehicles fall into this high-emitter category is essential for determining realistic emission factors and for effectively defining measures aimed at improving air quality.

With the Remote Emission Sensing (RES) unit it is possible to measure the emissions of vehicles in real-world conditions from the side of the road. With special instruments along the side of the road information can be obtained of the vehicle, like it’s speed and acceleration when it passes. With a camera the license plate can be recorded. The gas plume behind the vehicle can be analysed through optical analyses on the presence of NO, CO, HC, CO_2 and an indication of black smoke can be given.

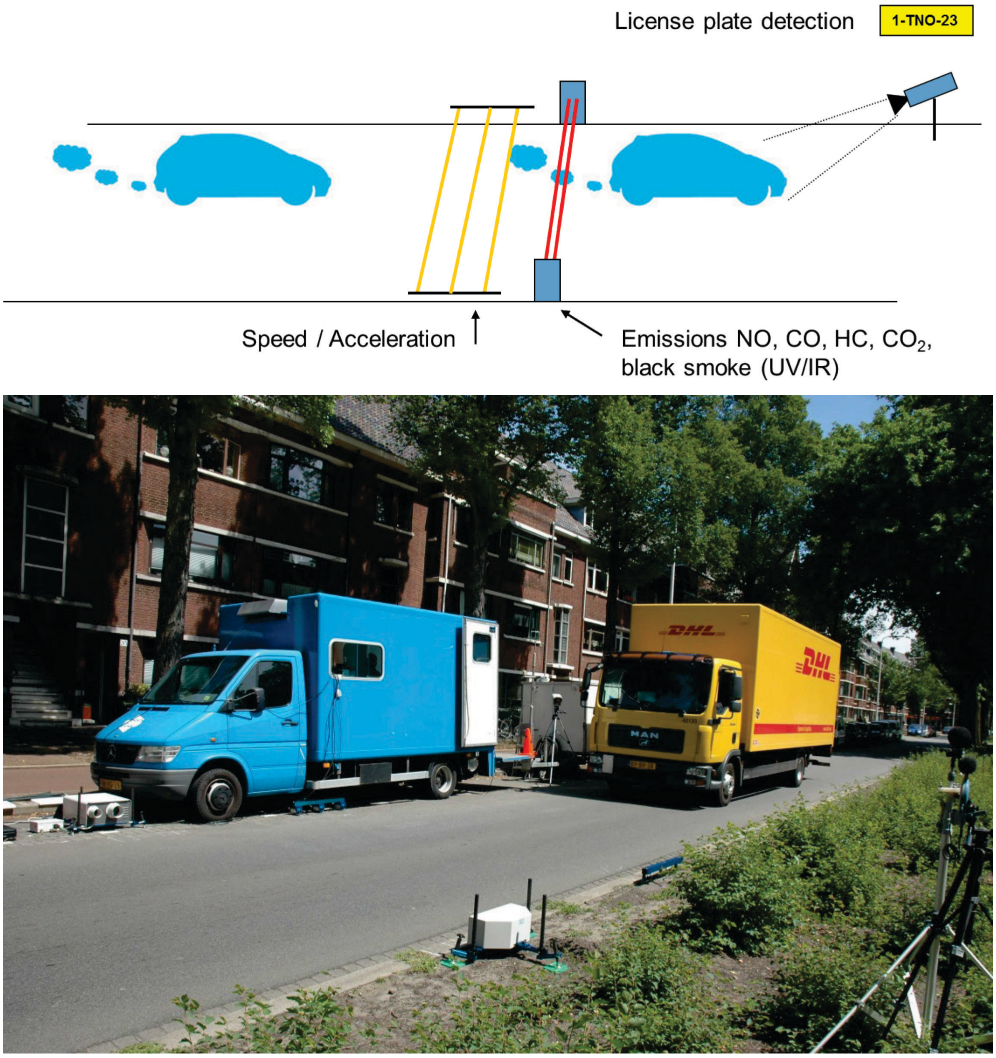


Figure 9: Schematic representation of the measurement set-up and a picture of the experimental set-up of Remote Emission Sensing in The Hague.

One important question still is whether RES is a suitable method for the detection of these so-called high-emitters. I.e. is the system selective enough in the sense that it can distinguish a real high-emitter from a vehicle with a momentarily high emission peak which typically can occur for vehicles with complex aftertreatment and control.

Three measurement campaigns have been executed where RES was used and tested. These measurements were used to determine whether the RES instrument is sensitive enough to identify high emitters amongst heavy duty vehicles. Despite a small sample size, there is evidence that RES can identify high emitters of CO, HC and black smoke (a possible proxy for particulate matter). For NO no high emitters are found, which is due to the large intrinsic scatter in NO emissions. For a small subgroup of vehicles with detailed vehicle information the RES measurements indicate that under driving conditions where the engine is most likely warm, Euro 3 heavy duty vehicles emit more NO than Euro 5 heavy duty vehicles, as expected. The small sample size, however, prohibits a robust statistical analysis and therefore it is not possible to make a quantitative statement on the fraction of high emitters per Euro class. Significantly increasing the number of vehicles with further measurements could alleviate this and make it possible to do a detailed quantitative analysis. The findings are reported in a separate report [Kuiper, 2012].

The experimental tests have shown that high emitters can be identified for CO and HC, emission compounds which are mainly expected from malfunctioning spark ignition vehicles. For NO the intrinsic scatter in the individual heavy-duty vehicle emissions is very large, and it was difficult to distinguish high-emitters. This behavior is known for Euro V heavy-duty vehicles. Individual vehicles typically scatter from low to high NO_x emissions due their intrinsic individual emission performance, but emissions can also be scattered due to cold or partly cold operation where an SCR still does not or only partly reduces NO_x. This cold operation can't be distinguished, but could be avoided by selecting a measurement location where vehicles are most probably driving with a warm engine and aftertreatment, for instance at the exit of a motorway. This directly shows that the location of the RES set up may influence the result. The system lacks an NO_2 measurement which is needed to complete the picture for NO_x emission ($NO+NO_2$). The 'black smoke factor' measurement of RES proved to have a very weak relation with particulate matter and is therefore useless. The measurements performed with RES did not allow a quantification of the amount of high emitters, because the data set was too small.

3.3 Emission modelling to derive emission factors for the Dutch situation

The data of the programme is continuously used as input for the emission model Versit+ HD. The model estimates the Dutch emission factors for: heavy-commercial vehicles, medium commercial vehicles, distribution vehicles and buses.

In 2012 the emission data of the in-service testing programme has been analysed extensively. This resulted in two innovations for the emission model and the emission factors:

First, the Euro V emission class with OBD II (B2G) appeared to have a significantly lower NO_x emission than the preceding subclasses of Euro V (B2D and B2E) [Vermeulen et al. 2012b]. This distinction was observed by comparison of the data of these two groups once enough data was available. This distinction between the two classes of Euro V is now integrated in the emission factors for NO_x and is taken into account in the GCN maps of RIVM as well. The start of the penetration of the fleet with Euro V B2G has been set at the 1st of January 2009. The newly measured Euro V B2G vehicles confirm this distinction between the early and late Euro V. Including this data in the determination of the emission factors led to a decrease on average, with respect to last year.

Second, the emission model for heavy commercial vehicles has been adapted so that emissions can now be predicted, based on engine power and total mass of the vehicle (combination). The merit of the use of large trucks and tractor-trailer combinations with full payload for the transport of goods can now be valued. In the case of higher payload levels, the aftertreatment is also often functioning more efficiently than for smaller trucks with lower payloads.

In the end of the programme in 2013, slowly more data becomes available for Euro VI long haulage vehicles, so that these emission factors can be generated and improved. It still lacks data from the light category of Euro VI and buses. The NO_x emission factors based on the measurement programme are extremely low for long haulage vehicles when the vehicles engine is warm. It is not expected that this will remain so. First of all, the current test programme includes mainly early-adapters and one prototype, complying with Euro VI legislation. They may perform better than the generic production models. Secondly, the vehicles were all new. Some reduction in catalyst efficiency is to be expected over the useful life of the vehicle due to ageing or degradation of the catalyst. Thirdly, Euro-VI is a new type of legislation, manufacturers do not know yet the needed dimensions and robustness of the after-treatment technology. However, it is expected that also in the future Euro-VI trucks will still comply with the emission limits. With the change in technology, the direct NO_2 emissions and fraction of NO_2 in NO_x has increased compared to early estimations for Euro VI, from a few percent to 35% of the total NO_x. It is not clear what exactly causes this increase. Most likely it is caused by one or more active components in the aftertreatment system, it can be the DPF technology, or the clean-up catalyst after the SCR, but also the SCR and the SCR reactions have a large effects on the tail-pipe NO_2 fraction.

The current Euro-VI NO_x emission factors, to be used in 2014 air-quality assessments, are based on the estimated fuel consumption of each vehicle category on each road type. The fuel consumption is translated to engine work, by equating 650 g CO_2 with 1 kWh, and using the Euro-VI NO_x emission limit of 0.46 g/kWh. The additional conformity factor of 1.5 used in heavy-duty in-service conformity is compensated for by two facts: it is a kind of not-to-exceed limit, which is based on a limited part of the test data and the 650 g CO2 per kWh is an overly optimistic, i.e., low, value in real world engine usage, leading to a lower limit on NO_x. Therefore, there is no need to include the conformity factor of 1.5 in the emission factor determination.

3.4 Zero emission busses

The in-service testing programme was extended with measurements on buses with innovative, alternative powertrains. The goal of the measurements is to determine the applicability of those concepts in real operation to help the realisation of the ambitions of ‘Stichting Zero-Emission Bus’ as laird down in the Dutch Green deal. This entails zero-emission bus transport in 2025 in the Netherlands.

New propulsion concepts are being developed which have the merit of zero-emission operation. These concepts have special powertrains which in contrast to conventional diesel buses run on electricity, a mix of diesel and electricity or even on hydrogen. Because these concepts are relatively unknown the Ministry of Infrastructure and the Environment started a pilot programme in a few large cities in the Netherlands where the concepts are operated in everyday ‘s use. This to obtain experience with the operation of these special bus concepts. The concepts under evaluation are the:

- Pure Electric Vehicle (PEV)
- Fuel-cell Electric Vehicle (FCEV)
- Hybrid Electric Vehicle (HEV) which can drive partially without emissions.
- Plug-in Hybrid Electric Vehicle (PHEV)

Because these buses in the pilot ran in different cities under different circumstances the concepts can't be compared. Therefore, the Ministry asked TNO to develop a method to assess the innovative bus concepts on their real-world applicability. Criteria that should be assessed should be measureable, quantifiable and be able to rank the vehicles concepts. The criteria established are:

- autonomous range in electric mode (km)
- driving performance (acceleration, grading, speed)
- effective charging speed (kWh/min)
- passenger capacity (mass, passengers, m^2)
- energy consumption (kWh/km)

Criteria which are identified as important to the operator but are less well quantifiable are:
- passenger comfort (power and type of A/C and heater)
- reliability (percentage up-time)
- ageing battery (loss of capacity over time)

Results are expected half 2014.

4 Results and discussion

In this chapter the results of the emission tests are discussed. The results are analysed in two ways:

1. according the formal procedure for checking the conformity of engines and vehicles in-service [582/2011/EC] with a Portable Measurement System (PEMS) and
2. according alternative methods of emission evaluation for the determination of the real-world emission performance also based on measurements with PEMS.

4.1 In-service conformity

The focus of this programme was on vehicles with engines that are certified as Euro V or Euro VI. The discussed in-service conformity in this chapter focusses NO_x emissions. In general the in-service conformity of the tested Euro V and Euro VI vehicles on the other gaseous emissions measured was good.

The NO_x in-service conformity of the tested Euro V engines is very scattered. For Euro V the formal in-service conformity test with PEMS is optional. When the PEMS test is performed, the limit is a conformity factor (CF) of 1.5. Above CF=2.0 the engine shall be tested on the engine test bed to check the conformity with the type-approval limit of 2.0 g/kWh over the ETC test cycle.

The results presented here are indicative for in-service conformity of Euro V vehicles. As can be observed from the graph in Figure 10 the conformity factor varies a lot from vehicle to vehicle, with conformity factors exceeding 1.5 up to 5 and with a few vehicles which keep well below 1.5.

15 out of 20 vehicles have a conformity factor above 1.5. This is 75% of the tested vehicles.

Two different vehicles of the same type show comparable conformity factors for NO_x, see vehicle pairs (F, W), (P, Z) and (Q, AA), which indicates that the procedure is selective and repeatable with regard to the detection of high emitters.

The NO_x in-service conformity of the tested Euro V engines is very scattered

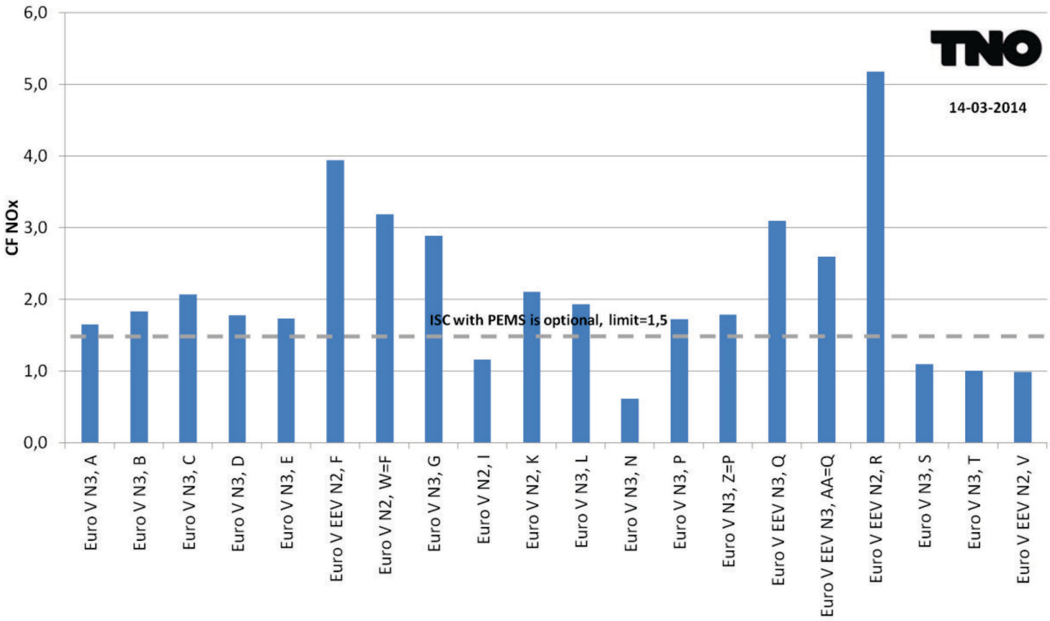


Figure 10: Conformity Factors (90-percentile) for the NO_x emission of Euro V engines. For Euro V engines in-service conformity tests to determine the Conformity Factors for the gaseous emissions are optional and not mandatory. However, a large share of the vehicles exceeds the non-mandatory limit.

The NO_x in-service conformity of the tested Euro VI engines is good.
For Euro VI the formal in-service conformity test with PEMS is mandatory and needs to be performed at type approval and over the useful life of the vehicle. A minimum of three engines needs to be tested and have a conformity factor under 1.5 to determine that an engine type is compliant with the in-service conformity requirements. The results presented here are indicative for in-service conformity of Euro VI vehicles, as per engine type only one vehicle was measured.

For the tested Euro VI vehicles all engines have a conformity factors for a single tested vehicle which lies below 1.5 and for the given group of tested vehicles even stays below 1.0 with conformity factors going as low as 0.1-0.2, see the graph in Figure 11.

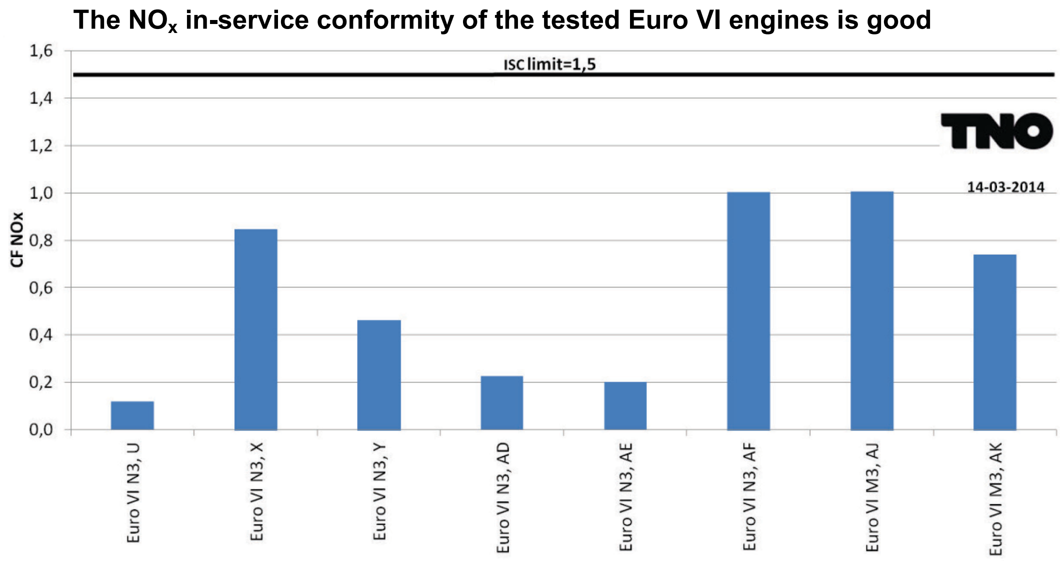


Figure 11: Conformity Factors (90-percentile) for the NO_x emission of Euro VI. All vehicles have an in-service conformity factor below 1.5.

4.2 Real-world emissions

This paragraph presents the analyses of real-world emissions and trends retrieved from the data.

The data is analysed, applying the VESBIN data binning method. This method reveals emission behaviour over the speed range of a vehicle. The results are presented for the vehicles tested in the programme and show trends which can be observed from the complete dataset of tested vehicles in the PEMS programme from 2011 until beginning 2014.

Focus on NO_x emission measurements
The focus is on the NO_x emission, as these emissions are the most relevant emissions for the air quality problems in The Netherlands when it concerns regulated ambient concentrations of NO_2. In the Netherlands, locally on some hot spots in large cities, the NO_2 limits are still exceeded.

The contribution to ambient concentrations of NO_2 from local traffic and especially diesel vehicles is substantial. It is therefore important that these vehicles have a low NO_x emission under urban driving conditions. For Euro V vehicles, however, it has already been proven that the NO_x emission is very sensitive to the operation of the vehicle. Especially under urban, low load driving conditions [Verbeek et al., 2010] the NO_x emission tends to increase significantly and to fall short compared to legislative limits.
In Euro VI legislation large improvements have been made in the test procedure, like the earlier explained addition of in-service conformity with PEMS, which is based on a measurement in the real-world and a new test cycle. Improvements like these aim to reduce emissions of vehicles in-service. However, the technology applied on Euro VI vehicles to comply to the stricter limits, reduce NO_x with SCR and EGR (Selective Catalytic Reduction and Exhaust Gas Recirculation). These systems are known to be still sensitive to operating conditions, with a the risk that real-world NO_x emissions could still fall short. For this reason the programme has a

large focus on the evaluation of real-world NO_x emissions of Euro VI vehicles, since the first Euro VI vehicles appeared on the market as of 2013.

Particulate matter emission reduced effectively
The particulate matter emissions have not been measured, because of the different properties of this compound and because no validated on-board measurement equipment was commercially available. The PM emission differs from the NO_x emission because it is reduced in a different way. PM emissions of a diesel engine are reduced through the application of a particle filter, whereas as earlier mentioned, NO_x is reduced through application of EGR, SCR or both. The technique of the wall-flow type particle filter is applied on 100% of the diesel vehicles as of Euro VI. The filter reduces the PM emission drastically compared to Euro V and the PM emission is expected to be far less sensitive to driving conditions than the NO_x emission.

Little data on the real-world PM emissions of Euro VI vehicles is available though. Experimental tests performed in Sweden[1] on one vehicle, with two prototype measurement systems to measure PM on-board of a vehicle, have shown very low PM mass emissions. This seems to confirm the theory that PM emissions are reduced effectively and are less sensitive to driving conditions, but the dataset is still very weak.

4.2.1 *Real-world emissions of the vehicles tested*

Real-world NO_x emission of Euro V and EEV diesel vehicles is very scattered

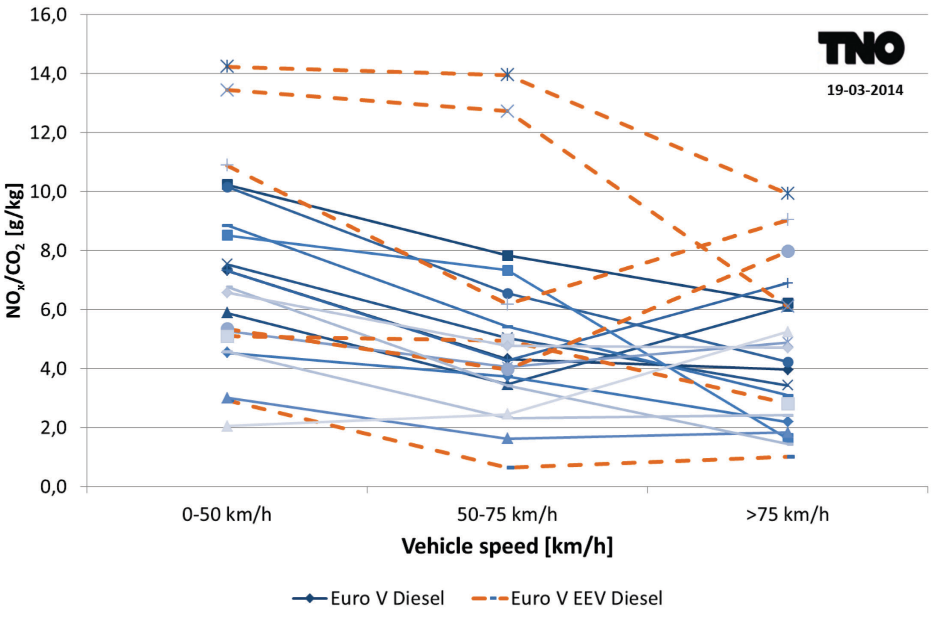


Figure 12: CO_2 specific NO_x emissions of the tested vehicles with Euro V and Euro V EEV diesel engines, over three different speed ranges. The lines between the speed intervals are to distinguish individual vehicles and their trends of NO_x emission over three speed ranges.

[1] AVL – Transportstyrelsen,Sweden, presentation, 16-01-2014

The introduction of the first generation Euro V vehicles did not lead to the presumed reduction of real-world NO_x emissions of diesel engines under urban driving conditions.
Far ahead of the date for entry into force of Euro V in 2009, the first Euro V vehicles already appeared on the market in 2005. This happened under influence of the German Maut system which incentivized vehicles that are certified Euro V. The introduction of these vehicles did not lead to the presumed reduction of real-world NO_x emissions of diesel engines under urban driving conditions

This effect was already identified in the previous programme [Verbeek et al., 2010] and can mainly be attributed to how the SCR of these vehicles system works. An SCR catalyst needs to be at a certain temperature to be able to reduce NO_x effectively. When the load on the engine is relatively low, for instance when the vehicle speed is low and/or when the payload is low, the SCR catalyst may not reach the temperature threshold, above which it can effectively reduce NO_x anymore because the AdBlue dosage must be reduced or even stopped.

Figure 13 shows the average CO_2 specific NO_x emission over different speed ranges, averaged per emission class. For the tested Euro V diesel vehicles of the first Euro V generation, the CO_2 specific NO_x emission is almost twice as high as on rural or motorway driving. The first generation of Euro V diesel vehicles emits under urban driving conditions on average as much NO_x as Euro III vehicles.

Adaptations in the Euro V legislation have led to an improvement of the real-world NO_x emission of diesel engines from the first generation to the final generation of Euro V.
The Euro V legislation has advanced from 2005 to 2009 in different steps. Gradually, a more stringent system was introduced for the control of mainly NO_x emissions. This change included the addition of NO_x measures and the more stringent OBDII.

This change in the Euro V emission legislation has led to a second generation of Euro V engines. As an effect an improvement of the CO_2 specific NO_x emissions was observed for the group of tested N3 vehicles of the second Euro V generation, especially at the lower driving speeds, see Figure 13. This improvement has been taken into account in the Dutch emission factors as determined for this group of vehicles and for the given road category.

Especially under urban conditions, the real-world NO_x emission of the second generation Euro V vehicles has improved as an effect of changes in the Euro V legislation that included the addition of NO_x measures and the more stringent OBDII

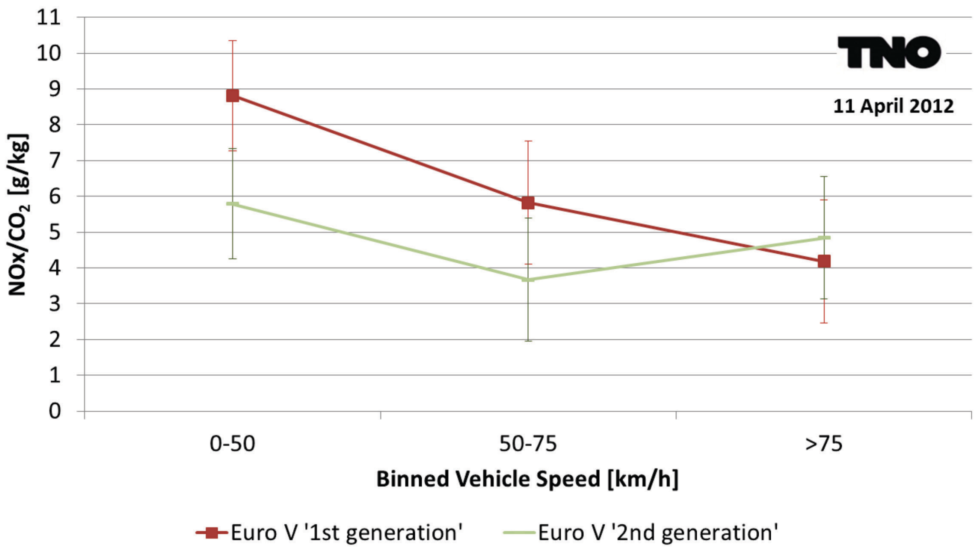


Figure 13: Specific NO_x emission of two generations of Euro V N3 long haulage vehicles.

The Euro VI emission legislation has led to a strong reduction of the real-world NO_x emissions for long haulage diesel fuelled vehicles.
In the programme six Euro VI long haulage tractor semi-trailer combinations were tested and all performed very well in the real-world, as depicted in Figure 14. The results demonstrate a large reduction of the CO_2 specific NO_x emission from Euro V to Euro VI for this group of vehicles.

The NO_x emission reduction can be attributed to the large improvements that were made in the EU emission legislation. These improvements were mainly made based on the real-world emission performance insights of programmes like this, that were brought into the EU and ECE emission legislation development discussions in Brussels and Geneva. The vehicle manufacturers anticipated to the Euro VI legislation with newly developed main stream engines and emission control strategies, widely applying EGR and SCR for the effective reduction of the NO_x emission, see paragraph 2.1.

Long haulage diesel fuelled Euro VI vehicles show a strong reduction of the real-world NO_x emissions

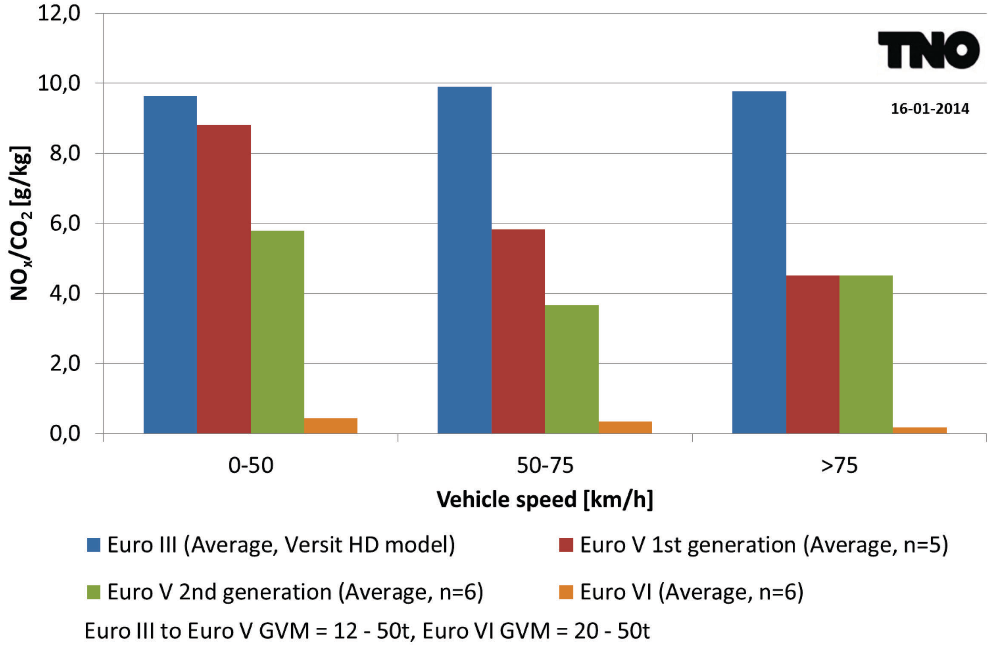


Figure 14: Trend of the average real-world NO_x emissions of heavy-duty diesel vehicles from Euro III to Euro VI, over three different speed ranges. The Euro VI vehicles in this picture are the average of the vehicles tested. These vehicles have a Gross Vehicle Mass from 20 to 50 tonne, whereas the Euro III to Euro V have a GVM of 12 to 50t.

4.3 Real-world emissions of Euro VI vehicles operating in an urban environment

This section presents the results of the first real-world emission tests performed with Euro VI heavy-duty vehicles which typically operate in an urban environment.

Euro VI is expected to deliver a lot when it comes to the reduction of especially NO_x and PM emissions. Emission testing with long haulage applications has already shown the large potential of this new legislation for this category of vehicles, as is demonstrated in this report. These vehicles were tested first because these were the first to come to the market, more than a year ahead of the mandatory date of first registration for Euro VI of January 01, 2014. The early introduction was stimulated in the Netherlands by an incentive programme that subsidised a part of the purchase of clean Euro VI heavy-duty vehicles.

However, vehicles which typically operate in an urban environment, like buses and distribution vehicles, have only just started to arrive on the market, as of the date of entry into force of Euro VI was due January 01, 2014. Given the importance of these vehicles for urban air-quality and the problems with the earlier generation of vehicles, the programmes last part focused on the execution of real-world emission tests to find out how Euro VI vehicles perform on their real-world NO_x emissions, during their typical urban operating conditions.

To determine the real-world emission of NO_x, two Euro VI city buses were tested with PEMS over real bus trips. Furthermore, one 12 tonne Euro VI distribution truck was tested with SEMS for a week in real service.

The results of the NO_x emissions are presented in Figure 15. The results clearly show that, compared to the average emissions of Euro V vehicles of the 2nd generation, NO_x emissions of Euro VI city buses and distribution trucks improve. However vehicle B and C in the picture, did not obtain the low NO_x emission as was seen for earlier tested Euro VI long haulage vehicles. Vehicle A performed clearly better and was able to maintain a low NO_x emission well under 1 g/kg of CO_2 under all circumstances. This proofs that maintaining a low NO_x emission under all circumstances is technically possible.

Two vehicles are thus clearly more sensitive to the typical operation in a city centre with generally busy traffic. Under these circumstances, the low engine load typically causes low exhaust temperatures under which the NO_x reduction systems are less effective. The NO_x emissions for these vehicles decrease with higher speed and with higher payload. This was shown for other test trips that were performed, though not depicted in the figure below.

Euro VI NO_x emissions improve compared to Euro V, certainly for the long haulage application, though under severe city operating conditions, the emissions still scatter and are relatively high in some occasions

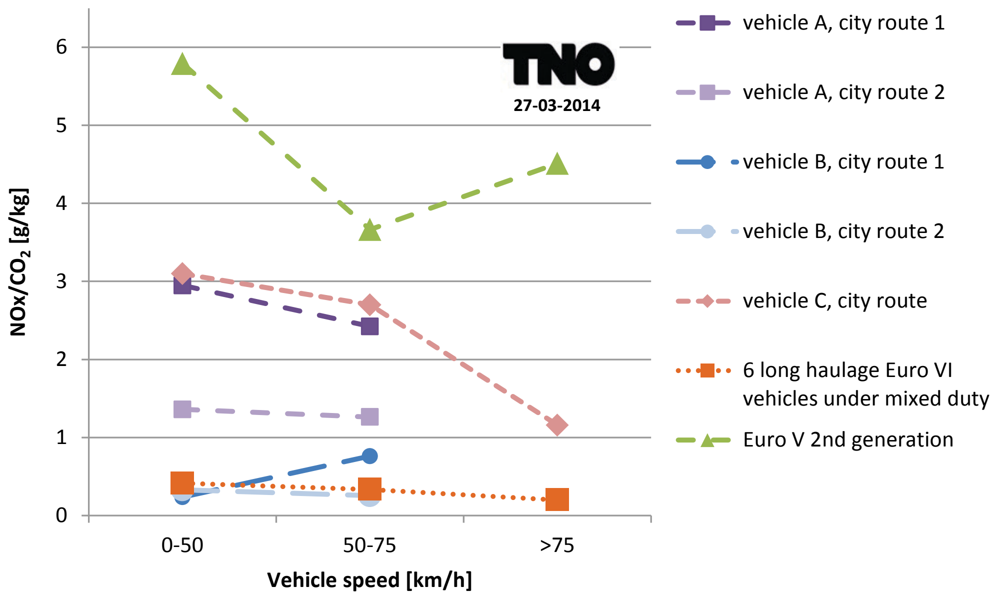


Figure 15: CO_2 specific NO_x emission of Euro VI vehicles in real-world operation in an urban environment. Two city buses and a distribution truck are presented. For reference the average emissions of Euro V trucks of the 2nd generation and Euro VI long-haulage trucks are presented as well.

4.4 Euro VI still needs refinement to control urban real-driving emissions

In the Netherlands the average ambient concentrations for NO_2 have decreased in the recent years. Locally, however, the limits are still exceeded, especially in urban areas and along busy roads [RIVM, 2013] and also there is some uncertainty in the predictions for target year 2015, which is a year the Netherlands has to fulfil the derogated EU air-quality standards.

The introduction of the Euro VI standards for the control of tail-pipe emissions of heavy-duty vehicles is one of the measures in the EU designed to reduce the real-world emissions of air pollutants such as particulate pollutants (PM) as well as ozone precursors such as nitrogen oxides (NO_x) and hydrocarbons, see article I, paragraph 4 of [2011/595/EC]. Paragraph 6 of that article states;"…In particular, a reduction in NO_x emissions from heavy-duty vehicles is necessary to improve air quality and to comply with limit values for pollution and national emission ceilings…"

Euro VI came with stricter limits and large changes in the test procedures (see paragraph 2.1) to reduce especially the real-world emissions. One of the goals of the Dutch heavy-duty emissions testing programme is to monitor the real-world emissions and the effectiveness of the EU legislation.

The measurements on the Euro VI vehicles that typically operate in an urban environment have shown that low real-world NO_x emissions are still not guaranteed. Especially the measurement results of two vehicles show that NO_x emissions can increase when the vehicles operate in heavy urban traffic that are relevant for their specific everyday operation. For one of these vehicles it was also demonstrated that, under formal test conditions, the vehicle complies with the Euro VI limit for in-service conformity and has a conformity factor well below the required 1.5, see paragraph 4.1.

Possible causes can be found in the way the engines and vehicle are certified in a type approval procedure. In these procedures the emissions under typical urban driving conditions are namely not explicitly controlled. Emissions are controlled over a laboratory test though, where the engine is run over a test cycle which consists of a mix of urban, rural and motorway conditions and where the emissions are averaged over the complete cycle.

The new PEMS test is added to the type approval and was introduced to check the conformity of the engine in-service on the road. This means that the 'PEMS' procedure was designed to check the emissions of the engine mounted in a vehicle under conditions that are to a certain extend comparable to the laboratory test. Like for the laboratory test of the engine, emissions of the on-road PEMS test are thus averaged. For the PEMS test this happens within so-called 'averaging windows'. These windows have a duration which is comparable to the duration of the original test cycle. Furthermore, some windows are not used for the final determination of the conformity. Windows are excluded where the average engine power is low (<15% of maximum power). This means that when a vehicle drives at lower speeds, e.g. at heavy urban traffic, data is not taken in the evaluation for in-service conformity. Also 10% of the highest windows are excluded from the evaluation. The so-called exclusion criteria were originally introduced to keep the PEMS test comparable with the laboratory test. This means that operating conditions which are possibly critical to achieve low urban emissions are not taken into account in the current procedure for in-service conformity. It should be remarked that the PEMS test was meant as procedure to check the in-service conformity of the engine and not to check the real-world emissions.

Another notable issue is that of the selection of the test vehicle for the PEMS test. A vehicle has to be selected which is the most representative vehicle type where the engine type is installed in. In type approval documents it was found that in the case of the city buses the certified engine type was tested in a long haulage truck over a long haulage test route, because the parent engine of the certified engine type is mostly applied in a long haulage truck and thus selected as the most representative vehicle type. Despite its very different application, the bus engine falls within the same family as the parent, which means that according to the formal requirements for in-service conformity, the engine as mounted in a city bus may never have to be tested over normal bus operation or bus routes.

The above disquisition pleads for further improvement of the Euro VI legislation, if the reduction of NO_x emissions under urban conditions is needed to improve the local air quality. In 2013 and 2014 the PEMS procedure for in-service conformity is under evaluation of a EU working group. This group evaluates the effectiveness of the PEMS procedure and the pass/fail evaluation method and investigates the possible need and improvements of the procedure for the control of real-driving emissions (RDE).

The results of the vehicles driven under representative urban conditions typically show high NO_x emissions in some occasions, which demonstrates that low real-world emissions in the city are still not guaranteed with Euro VI. Another vehicle driven under representative urban conditions demonstrated that lower NO_x emission under all representative urban driving conditions are technically possible.

If further measures would be required to control emissions under representative urban driving conditions, the test procedure should explicitly control urban emissions to a level which is achievable given readily available technology to control emissions under these circumstances. This could be taken into account in the discussions that are currently on-going in the EU where next to improvements for in-service conformity also a procedure to control Real Driving Emissions (RDE) is considered.

4.5 Real-world emissions of dual-fuel trucks on diesel and natural gas.

In the test programme two dual-fuel heavy-duty vehicles were tested with PEMS. In the Netherlands retrofit dual-fuel trucks are allowed on the road once the system supplier has shown that his system is able to fulfil Euro V diesel emission limits on the applicable Euro V engine test, the European Transient Test Cycle ETC. To monitor the real-world emission performance of vehicles equipped with these engines retrofitted with a dual-fuel system, tests have been performed with PEMS on the road to also check the real-world emissions. This was done with a focus on hydro-carbons (especially methane, since it has high GWP) and NO_x emissions.

The two vehicles tested differ in dual-fuel system. Both run on diesel or in dual-fuel operation. System A is a real retrofit. It uses compressed natural gas (CNG) as second fuel. System B can be seen as technically more advanced and is a system mounted under control of the OEM. This system uses liquefied natural gas (LNG) as second fuel. Vehicles A has an engine certified Euro V in diesel mode only and vehicle B has an engine which is also certified Euro V as dual-fuel. System B typically doses higher rates of natural gas than system A.

Various trips were driven with different payloads and repeated in diesel mode and dual-fuel mode to enable a comparison of the real-world emission performance of the two fuel modes. The standard gaseous emissions, including methane (CH_4) were measured and analysed according the formal in-service conformity method (Annex II of 582/2011/EC) and according to alternative methods to judge the real-world emission performance. This has led to the following conclusions.

In dual-fuel operation the tested trucks:
- emit somewhat (10-20%) less NO_x than in diesel operation.
- emit less direct CO_2 than in diesel operation due to the lower energy specific CO_2 emission of the blended natural gas.
- emit substantial amounts of methane (CH_4), which has a GWP of 34[2]. When this GWP for methane is taken into account for the determination of a CO_2 equivalent emission at the tail-pipe, the vehicles emits more CO_2 (up to 50%) than in pure diesel operation.
- The level of emission of CO_2 in dual-fuel operation depends on the dual-fuel technology. The vehicle with a more advanced OEM dual-fuel system emits less methane than the retrofit system, but still the total equivalent CO_2 emission is higher than in diesel mode.

High methane emissions more than cancel the CO_2 benefit of the natural gas in dual-fuel operation

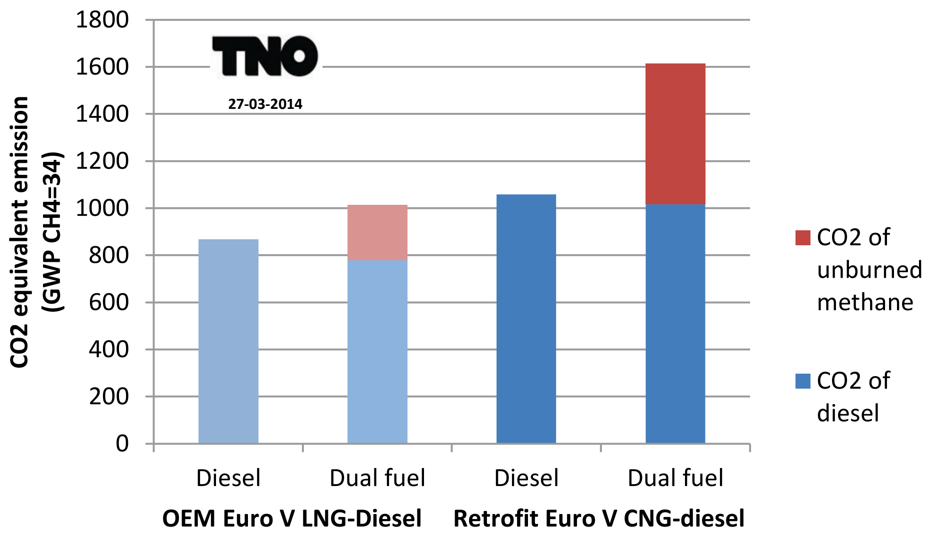


Figure 16: Tail-pipe CO_2 emissions and CO_2 equivalent emissions from unburned methane from the tail-pipe of two Euro V dual-fuel concepts: 1) a system developed under control of the OEM (B) and 2) a retrofit dual-fuel system (A).

The methane emissions result from incomplete combustion of the diesel-gas mix in the combustion chamber and valve timing (overlap) of the dedicated diesel engines

[2] GWP value and lifetimes from 2013 IPCC AR5, for a 100-year time horizon of methane. Older 2007 IPCC AR4 gives a GWP of 25 for a 100-year time horizon of methane.

on which the dual-fuel systems were mounted. Vehicle B has a methane catalyst, a somewhat more advanced mixture control and lambda control and is able to reduce the methane emission more than vehicle A, which has a rather basic retrofit system.

Improvements are being made in Euro VI emission legislation and UNECE R49 and will include limits for the methane emission. The limits depend on the amount of methane blended in the test cycle. OEMs have to anticipate the more stringent Euro VI approach by application of more advanced technology to reduce the methane emissions.

- Type 1: Gas/diesel energy ratio >90% → gas emission limits for CH_4 (500 g/kWh) and NMHC (160 mg/kWh)
- Type 2: Gas/diesel energy ratio 10-90% → THC emission limit proportional to ratio (~200 - 500 mg/kWh)
- Type 3: Gas/diesel energy ratio <10% → diesel emission limits for THC (160 mg/kWh)

It is recommended to monitor the emissions with a focus on methane emissions of dual-fuel technology for Euro VI.

4.6 Real-world NO_2 emissions of diesel engines with Euro VI technology

The concentration of NO_2 in outside air is regulated in the EU. The gaseous emissions of vehicles are also regulated in the EU. However, in this case a cap is put on the tail-pipe emission of NO_x, which is the sum of NO and NO_2. Both NO and NO_2 contribute to the ambient concentration of NO_2, because NO also takes part in the chemical reactions in which an equilibrium of NO and NO_2 is reached under given atmospheric conditions and the presence of other chemical components. The importance of NO_2 for local air-quality is acknowledged to be larger than that of NO and therefore the NO_2 fraction in the NO_x emission of road vehicles is a separate and important input for the models that estimate the air-quality.

Because the directly emitted NO_2 of road vehicles is important for local air-quality the programme aims to monitor the trend of the emission of this compound over the legislative stages and for the applied emission reduction technologies. The programme mainly focuses on the NO_2 emission of Euro VI, as robust emission factors for the NO_2 emissions of Euro V engines have already been established.

The level of the emission of NO_2 from the tail-pipe of a diesel engine is influenced by a number of processes:

- The NO_2 formation in the engines combustion chamber. The NO_2 fraction is largely influenced by the temperature of combustion. Lower combustion temperatures tend to result in a somewhat higher NO_2 fraction of the engine out emission. On average, however, the NO_2 fraction of engine out diesel exhaust gas is relatively low.
- The NO_2 formation in oxidation catalysts and to a lesser extend also in ammonia slip catalysts (ASC). An ammonia slip catalyst is in fact an oxidation catalyst, but less active. Both the oxidation catalyst and the ammonia slip catalysts are found on Euro VI vehicles.

- The chemical reactions within the SCR catalyst to reduce NO and NO_2. There are a number of reactions which take place in the SCR to reduce NO_x to elemental nitrogen. The dominant reaction is with NO. The fastest reaction is the one with an equal amount of NO and NO_2 present in the exhaust gas. This reaction is responsible for the promotion of low temperature SCR of NO_2. Low temperature SCR is needed to achieve the required low Euro VI emission levels and low NO_x emissions at low driving speeds. The engine out NO_2 which is generally low, is often increased on purpose with an oxidation catalyst up stream of the SCR to achieve a higher share of NO_2. This is required for the fast low temperature reaction.
- NO_2 used for the oxidation of soot in a DPF. Soot is oxidized at relatively low temperatures with NO_2. At higher temperatures also O_2 is used for the oxidation of soot.

Most Euro VI engines have a complicated aftertreatment system to reduce the NO_x and PM emissions involving an oxidation catalyst, DPF, SCR and ammonia slip catalyst. Below a typical system set-up is shown for a Euro VI long haulage truck or city bus. This set-up is used by most manufacturers on most long haulage vehicles and buses. One manufacturer uses a different set-up on his long haulage trucks without EGR.

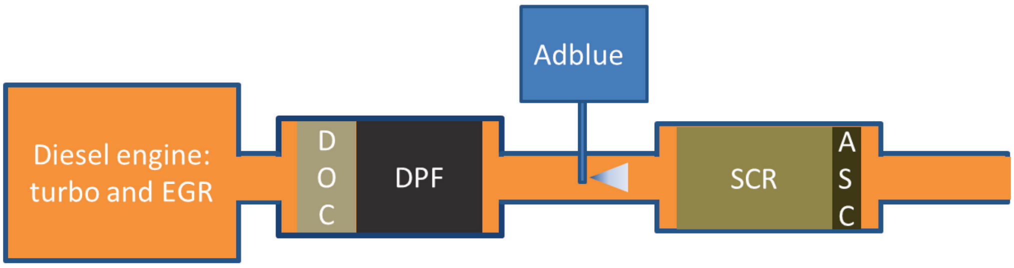


Figure 17: Typical set-up of an exhaust gas aftertreatment system for an N3 or M3 Euro VI diesel engine, consisting of a Diesel Oxidation Catalyst, a Diesel Particle Filer, a Selective Catalytic Reduction catalyst and an Ammonia Slip Catalyst.

In the pictures below the emission of NO and NO_2 is presented as an average for all Euro VI vehicles tested. This is done for different categories of operation, namely:

- the part of an urban trip where the engine is started cold (5-20 ºC) and warmed-up. The criterion for this warm up period is a coolant temperature below 70 ºC.
- the warm part of the urban trip, characterized by an engine operating with a coolant temperature higher than 70 ºC.
- the whole rural trip, operated with a warm engine.
- the whole motorway trip, operated with a warm engine.

Obviously, the sum of NO and NO_2 emission is the highest for the cold urban trip, because the SCR system has to warm up during this trip, before it can effectively reduce NO_x. For the warm trips the absolute NO_x emission is clearly lower. However, the share of NO_2 increases, from 20% for the cold trip to 40-80% for the warm trips. The increased NO_2 fraction can be explained by the fact that the exhaust gas is treated by the different catalytic components which gain activity when they warm up, generally leading in this case to a somewhat higher NO_2

fraction than can be expected from a conventional diesel engine. How this higher share of NO_2 is established exactly, is not known as many different processes take place almost at the same time.

The sum of NO and NO_2 emission is the highest for the cold urban trip

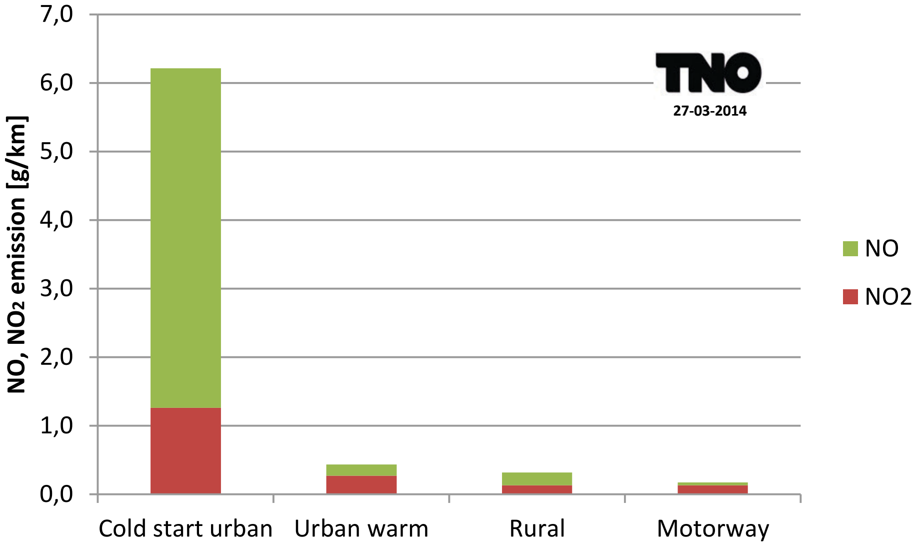


Figure 18: NO and NO_2 emissions of the Euro VI heavy-duty diesel vehicles, averaged for all vehicles and per type of operation. NO and NO_2 are calculated as NO_2 equivalent.

The share of NO_2 increases, from 20% for the cold trip to 40-80% for the warm trips

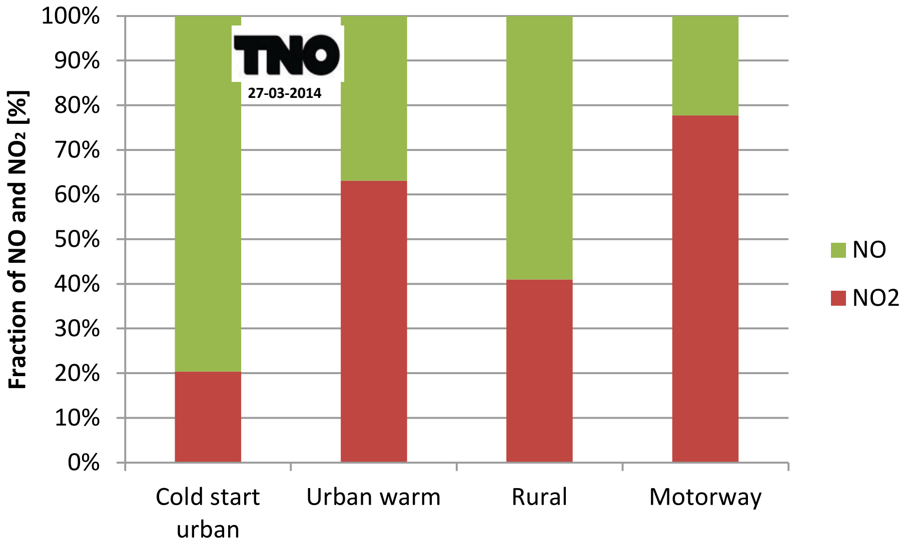


Figure 19: NO and NO_2 fractions in the NO_x emission of the Euro VI heavy-duty diesel vehicles, averaged for all vehicles and per type of operation.

Not only differences between vehicle operation conditions have been found, also individual vehicles have NO_2 emissions that differ from each other. Especially for warm operating conditions of the engine and the aftertreatment the scatter of the

NO_2 fraction is large, from 0% NO_2 to 100% $NO_{2.}$ The large scatter may be explained by the differences in the aftertreatment. However, at warm conditions both the measured NO and NO_2 concentration are so low that the measured fractions are not very accurate.

5 Conclusions and recommendations

A three year measurement programme has been executed to determine in-service conformity and real-world tail-pipe emissions of the latest generations of heavy-duty vehicles. The attention of the programme was on the emissions of NO_x by Euro V and Euro VI vehicles because of the importance for local air-quality and the exceeding of air-quality limits which still occurs in the Netherlands.

Conclusions

Euro V

- The introduction of the first generation Euro V vehicles did not lead to the presumed reduction of real-world NO_x emissions of diesel engines under urban driving conditions. The first generation of Euro V diesel vehicles emits, under urban driving conditions, on average as much NO_x as Euro III vehicles.
- EEV trucks on diesel show the same behaviour as the Euro V vehicles, meaning that EEV for diesel engines has no additional benefit, when the emission of NO_x is concerned.
- The latest generation of Euro V heavy-duty long haulage trucks on diesel that were tested, showed a significantly lower NO_x emission in urban operation than the first generation. This can be attributed to changes/improvements within the Euro V legislation that came into force in 2009.

Euro VI

- All tested Euro VI vehicles comply with the Euro VI in-service conformity requirements, meaning they have in-service conformity factors below the limit of 1.5.
- The first Euro VI long-haulage vehicles that arrived on the market showed a very low NO_x emission in the real-world, compared to Euro V. Also at low driving speeds emissions are very low and well-controlled.
- Vehicles that typically operate in an urban environment, also show an improvement in NO_x emissions, compared to Euro V. However two of these vehicles, did not obtain the low NO_x emission as was seen for the tested Euro VI long haulage vehicles. The third vehicle of this type performed clearly better and was able to maintain a low NO_x emission under all circumstances. This proofs that maintaining a low NO_x emission under all circumstances is technically possible, though some vehicles are still sensitive to driving conditions.
- The good results for the Euro VI long-haulage trucks show that Euro VI has made a large progression. Next to the improvements on the test cycles and the lower limits, especially the introduction of an on-road PEMS test for in-service conformity proved effective for this group of vehicles. For other categories, however, Euro VI in its current state does not control all relevant representative driving conditions which may especially be important for urban air quality. To control this, additional measures may be needed as part of the Euro VI type approval legislation to regulate real-driving emissions.
- The Euro VI technology seems to change the NO-NO_2 composition towards a higher NO_2 fraction for diesel exhaust, compared to Euro V. This increase can probably be attributed to the reactive components in the aftertreatment system which tends to increase the NO_2 fraction. It must be noted that in most cases the

absolute levels of NO_2 are still very low due the low overall NO_x emission of most Euro VI vehicles under most driving conditions. Furthermore, the values for the NO_2 fraction are less accurate than before, because the low emissions of Euro VI vehicles can be measured less accurate.

Dual-fuel

- In recent years dual-fuel technology has been offered to the market. This technology enables operation of a diesel engine in a mixed diesel-gas mode. This might come with economic benefits for the user due to lower costs for gaseous fuel. The two tested dual-fuel long haulage trucks, which run on diesel and natural gas, showed a decrease of NO_x emissions in dual-fuel mode of around 10 to 20%. On the other hand, in dual-fuel mode they showed a high methane emission. This high methane emission, with its Global Warming Potential of 34, diminishes the greenhouse gas benefit of the natural gas which stems from the lower energy specific CO_2 emission of natural gas. A diesel truck with a retrofit system showed CO_2 equivalent tail-pipe emissions up to 50% higher than in diesel mode, whereas the system installed under control of an OEM showed somewhat lower equivalent CO_2 emissions. However, the CO_2 equivalent emission of this vehicle is in most cases still over the CO_2 emissions in pure diesel mode. For Euro VI a very stringent methane limit value is applicable, so this phenomena does no longer occurs with Euro VI..

Green-deal for city buses

- The ambitions of the green deal is to have for zero emissions bus transport in 2025. It is not well known how new bus concepts, which are needed to achieve this goal, are applicable in real operation. Knowledge is needed about the concepts, which allow the comparison of the applicability of those concept in real-life operation. Tests have been performed, which bring up insights in the new parameters which are needed for the comparison, like energy consumption in kwh/km (instead of diesel consumption), electric range and charging time for pure electric and also plugin hybrid electric vehicles. These are all relevant parameters when total-cost-of-ownership is considered and also when CO_2 emissions are concerned.

On-going development of EU legislation

- The data as obtained during the programme was brought in the EU working discussions where new emission legislation is being developed. This has led to significant improvements, as obtained in the Euro VI legislation.

Recommendations

- The Euro VI vehicles that were tested in this programme where almost new vehicles at the beginning of their useful life. Nothing is known about possible degradation of Euro VI technology over time. Therefore monitoring of the emissions over the useful life of Euro VI vehicles is recommended.
- The focus of the Euro VI tests of the programme was on the first Euro VI vehicles that arrived on the market. These were mainly long-haulage trucks with well-developed main-stream engines of the large truck manufacturers. This long-haulage application proved to perform well, but typical operating conditions are possibly less critical. Therefore, the focus should shift to smaller heavy-duty vehicles and applications which operate under more difficult, but still

representative conditions, like city buses and distribution trucks do. A limited set of data is already available and show scattered NO_x emissions. For derivation of reliable emission factors and insight in real-world performance of these vehicle types, more measurement data are needed.

- Given the typical emission behaviour of Euro VI vehicles, with periodic high emissions events triggered by low speed or low load driving, by cold start operation, by short excursions of the emission or history effects that influence the emission level, it is required to measure over longer periods of time to capture all representative driving conditions. The SEMS system proved very useful for this and is a relative cheap tool to fill this need. Additionally, SEMS could be used to screen for high emissions before the more expensive PEMS is to check the in-service conformity according the formal requirements. It could also be investigated whether SEMS can be extended with more sensors to measure other critical exhaust components, like particulate matter or methane.
- The working group discussions on the development of a special procedure for Real Driving Emissions are held in 2013-2015 and in 2013 the data of the programme already proved useful for the evaluation of options for an RDE procedure. It is recommended to bring the latest data on the real-world performance under typical urban operating conditions into these discussions. An RDE procedure could potentially guarantee low emissions under all circumstances, and could thus help to further improve inner-city air quality.

6 References

Relevant European Regulations and Directives:

[582/2011/EC], [2011/595/EC], [2007/46/EC], [2005/78/EC], [70/156/EC] and amendments: http://eur-lex.europa.eu/nl/index.htm

Literature:

[Kuiper, 2012] Kuiper, E, et al., *Resultaten van Remote Emission Sensing metingen aan HD voertuigen,* TNO rapport nr. TNO 2014 R10641, Juni 2012.

[Riemersma, 2000] Riemersma, I.J.R., Rijkeboer, R.C., Jordaan, K, *Final Report In-Use Compliance Programme, Trucks 1998 – 2000*, TNO report nr. 00.OR.VM.077.1/IJR, Nov. 2000.

[Riemersma, 2009] Riemersma, I.J.R, Vermeulen, R.J., *Final Report on the In Use Testing Program for Heavy Duty Vehicles* 2001-2006, TNO report nr. MON-RPT-033-DTS-2009-00038, Jan. 2009.

[RIVM, 2013] M.C. van Zanten et al., Monitoringsrapportage NSL 2013, RIVM rapport 680712005/2013, 2013.

[van Goethem et al., 2013] Sam van Goethem, Gert-Jan Koornneef, Stefan Spronkmans, *Performance of Battery Electric Buses in Practice: Energy Consumption and Range*, TNO report TNO 2013 R10212, 5 February 2013.

[Verbeek et al., 2010] Verbeek, R, Vermeulen, R.J., Vonk, W., Dekker, H.J. “*Real World NO_x emissions of Euro V vehicles*”, TNO Science and Industry, Report number MON-RPT-2010-02777, 11 November 2010.

[Vermeulen et al. 2012a] Robin Vermeulen, Willar Vonk, Ernst Kuiper, Norbert Ligterink, Ruud Verbeek The Netherlands In-Service Testing Programme for Heavy-Duty Vehicle Emissions 2011, TNO report TNO 2012 R10561, 17 August 2012.

[Vermeulen et al., 2012b] Vermeulen, R.J. Vonk, W., Dekker, H.J. et al. *Real-world NO_x emissions of Euro V and Euro VI heavy-duty vehicles*, TNO report TNO-060-DTM-2012-01193, 11 April 2012.

[Vermeulen et al., 2012c] Vermeulen, R.J., Ligterink N.E., Vonk W.A., Baarbé H.L., TAP Paper 49: *A smart and robust NO_x emission evaluation tool* for the environmental screening of heavy-duty vehicles, 19th International Transport and Air Pollution Conference 2012, Thessaloniki, Greece, 26-27 November 2012.

[Vermeulen et al. 2013b] Vermeulen, R.J. Vonk, W., Ivens, T, Ligterink, N., The Netherlands In-Service Testing Programme for Heavy-Duty Vehicle Emissions 2012, TNO report TNO 2013 R10753, 23 May 2013.

[Vermeulen et al. 2013c] Vermeulen, R.J. Vonk, W., Ivens, T, Ligterink, N.,The Netherlands In-Service Testing Programme for Heavy-Duty Vehicle Emissions 2012: summary report, TNO report TNO 2013 R10960, 20 November 2013.

7 Signature

Delft, 26 May 2014

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A Abbreviations

A/F	Air-Fuel ratio
CAN	Communication Area Network
CF	Conformity Factor
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DF	Dilution Factor
ECU	Engine Control Unit
EFM	Exhaust Flow Meter
ESC	European Steady state Cycle
ETC	European Transient Cycle
FID	Flame Ionisation Detector analyser
FS	Full Scale
GPS	Global Positioning System
ISC	In Service Conformity
IUC	In Use Compliance
N_2O	Nitrous oxide
NDIR	Non-Dispersive Infrared analyzer
NDUV	Non-Dispersive Ultraviolet analyzer
NH_3	Ammoniac
NO	Nitric oxide gas
NO_2	Nitric dioxide gas
NO_x	Nitric oxides gases
NTE	Not To Exceed
O_2	Oxygen
OCE	Off Cycle Emissions
PEMS	Portable Emission Measurement System
PM	Particulate Matter
PN	Particle number
PFS	Partial Flow Sampling
QCM	Quartz Cristal Microbalance
SAE	Society of Automotive Engineers
TEOM	Tapered Element Oscillating Microbalance
THC	Total Hydrocarbons
WHSC	World Harmonized Steady state test Cycle
WHTC	World Harmonized Transient test Cycle