Earth, Life & Social Sciences
Van Mourik Broekmanweg 6
2628 XE Delft
P.O. Box 49
2600 AA Delft
The Netherlands

www.tno.nl

T +31 88 866 30 00
F +31 88 866 30 10

TNO report

TNO 2014 R10534

On-road emission measurements with PEMS on a Mercedes Citaro Euro VI bus

Date	28 March 2014
Author(s)	[redacted]
Copy no	TNO-060-DTM-2014-00079
Number of pages	30 (incl. appendices)
Sponsor	[redacted] Ministry of Infrastructure and the Environment Directorate-General for Environment and International Coordination P.O. Box 20901 2500 EX THE HAGUE
Project name	Netherlands In-Service Testing Programme for Heavy-Duty Vehicles
Project number	033.27092

Summary

Goal of the emission measurement programme
Commissioned by the Dutch Ministry of Infrastructure and the Environment, TNO regularly performs measurements to determine the in-use emission performance and durability thereof of vehicles in the Netherlands. The main goal of this measurement programme is to gain insight into trends in real-world emissions of heavy-duty vehicles under conditions relevant for the Dutch situation.

Selection of the vehicle
A fleet of Mercedes Citaro Euro VI city buses was launched in the city of Utrecht by the end of 2013. As this was the first large fleet of Euro VI city buses in the Netherlands and Utrecht faces significant air-quality challenges, the Ministry and TNO selected a Mercedes Citaro for an emission test. The vehicle is fitted with a diesel oxidation catalyst (DOC), diesel particulate trap (DPF - continuous regenerating), an SCR-catalyst, an ASC-catalyst and an exhaust gas recirculation system (EGR) to reduce gaseous and particulate matter emissions.

The test programme
For the measurements, TNO used a Portable Emissions Measurement System, or PEMS. The focus of the PEMS measurements lies on NO_x and NO_2 emissions[1], as the air-quality limits for these compounds are locally still exceeded in the Netherlands.

The vehicle was tested at a payload of 10, 41 and 100% and on three different trip types: a Euro VI trip, TNO's reference trip and Utrecht bus routes 8 and 77, the two latter of which are representative for everyday operation.

Data analysis
PEMS data was analysed according to the formal in-service conformity method as prescribed by regulation 582/2011/EC. Also, TNO used the so-called vehicle emission speed binning method (VESBIN) to calculate real-driving emissions for urban, rural and motorway conditions and to gain insight into the emission behaviour over the speed range of the vehicle.

Conclusions
The tested vehicle fulfils the requirements laid down in the Euro VI emission regulation, i.e. it does not exceed the Euro VI in-service conformity limits. Its emission performance has, however, shown to be very sensitive to driving conditions with low average engine load. On a demanding city-center bus route, TNO measured NO_x emissions that are high compared to NO_x emissions encountered in all other Euro VI heavy-duty vehicles tested in this programme [Vermeulen, 2013]. This indicates that the test trip as prescribed by the Euro VI emission legislation does not necessarily yield representative real-world emissions of this specific vehicle.

[1] The emission compound NO_x is composed of NO and NO_2. In EU vehicle emission regulation the tail-pipe NO_x emission is regulated whereas in EU air-quality regulation the ambient concentration of NO_2 is regulated. NO_2 is more harmful, but NO also contributes to the formation of NO_2.

The next paragraphs further detail these findings.

It has to be noted that all other tested Euro VI vehicles in the test programme so far were long-haulage trucks and that, therefore, those vehicles have not been tested on a trip with the urban character and driving style of a city-center bus route.

Conclusions regarding the vehicle's real-world emissions

Real-world NO_x and NO_2 emissions of the tested vehicle
Compared to the average NO_x emissions of previous emission stages, the CO_2-specific NO_x emissions of the tested vehicle are on average at a low level.
The NO_2 fraction of the tested vehicle is relatively low as well. Compared to other Euro VI vehicles TNO tested so far, the Mercedes Citaro performs well at vehicle speeds between 50 and 75 km/hr and above 75 km/hr and is a medium performer in the 0-50 km/hr speed range.

The NO_x emission of the tested vehicle is however very sensitive to driving conditions with an average low engine load. Driving the vehicle at low payload or at low speeds has a significant adverse effect on this vehicle's NO_x emissions.

Comparison with Euro V EEV city bus tested in 2010
In the lower speed range the Euro VI Mercedes Citaro has 20 to 80% lower NO_x emissions on bus route 77 compared to the CO_2-specific NO_x emissions of the Euro V EEV bus tested on that same route in 2010. At speeds from approximately 40 – 70 km/hr, the emissions of the Euro VI Mercedes Citaro are comparable to those of the Euro V EEV bus. It has to be noted that the Euro V EEV bus performed very well compared to the other Euro V vehicles tested.

Emission performance on a city-center bus route
The Mercedes Citaro was also tested on bus route 8, containing a much larger share of urban operation than route 77. Route 8 is a relatively short bus route serving the city center of Utrecht with many stops and a low average speed. Compared to the emissions in other test trips, the vehicle's CO_2-specific NO_x emissions for bus route 8 are very high, reaching an average value of almost 3 g/kg and an average distance-related NO_x emission of 4 g/km.

It should be noted that in the past no emission measurements on route 8 have been performed. This Euro VI vehicle was the first vehicle to be tested on route 8. Route 8 was selected as it is representative for a significant number of routes the operator's timetable contains.

Conclusions regarding the in-service conformity

NO_x
The Conformity Factor for NO_x over an M3 Class I Euro VI trip at a payload of 41% is 1.0 and thus below the legislative limit of 1.5. The Conformity Factors for NO_x over the Euro VI trip with alternative payloads are 0.7 at a payload of 100% and 1.4 at a payload of 10%.

The values for the Conformity Factor for NO_x emissions of this vehicle are higher than values encountered in most Euro VI heavy-duty long-haulage trucks tested before.

CO
The Conformity Factors for CO are low and steady (about 0.1) over all trips.

HC
The Conformity Factors for HC are below 1.5, but this measurement has a low accuracy.

General observation
Although the vehicle does not exceed Euro VI limits for in-service conformity, in many occasions the NO_x emissions of the tested vehicle are higher than those recently encountered when measuring Euro VI long-haulage vehicles under their typical driving conditions. The high NO_x emissions occurred mainly under the urban driving conditions characteristic for city bus operation, which differ from the typical driving conditions of long-haulage vehicles and from test conditions within the Euro VI legislation.

This clearly shows that the EU pass-fail method for in-service conformity excludes data that, in fact, was obtained during normal, representative operation of a city bus. This data exclusion leads to lower in-service conformity NO_x emissions that are not necessarily representative for the real-world emissions of this specific vehicle.

Note
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 was tested and therefore the results are indicative only.

Contents

1 Introduction

1.1 Background

Commissioned by the Dutch Ministry of Infrastructure and the Environment, TNO's research group Sustainable Transport and Logistics regularly performs measurements to determine the in-use emission performance and durability thereof of vehicles in the Netherlands. The main goal of this measurement programme is to gain insight into trends in real-world emissions of heavy-duty vehicles under conditions relevant for the Dutch situation. Secondly, the programme aims to better understand the correlation between emissions measured during the type approval test on an engine test bed, the in-service Conformity Factor established using PEMS and the real-world emissions under typical Dutch driving conditions. These insights are used to assist the European Commission in developing effective real-driving provisions.

The measurements and the evaluation presented in this report are performed under the above-mentioned national programme. The report gives an overview of the results from on-road emission tests performed with PEMS on a Euro VI M3 Class I heavy-duty vehicle. The focus of the measurements and the evaluation lies on the NO_x and NO_2 emissions[2], as in the Netherlands the air-quality limits for these compounds are locally still exceeded and the contribution from local (heavy-duty) traffic to these compounds is substantial. Furthermore, the level of the tailpipe emissions may be very dependent on the use of the vehicle and the quality of the exhaust gas reduction system used on the vehicle.

PEMS (Portable Emission Measurement System) can measure the regulated gaseous emissions (with the exception of NH_3, PM and PN) under a wide range of real-world conditions. PEMS is also used for the current procedure to evaluate the in-service conformity of Euro V and Euro VI heavy-duty vehicles. This procedure uses the data evaluation method EMROAD to calculate the Conformity Factor for a regulated emission component of a given engine type in a vehicle by means of a specially-developed pass-fail method.

1.2 Aim and approach

The aim of the research is to gain insight into the emission performance of trucks and buses in real-world operation. Using these insights, the overall aim of the programme is:

- to assess the real-world emission performance with a focus on the NO_x and NO_2 emissions, in particular at urban or low load, during low-speed driving conditions and with different payloads.
- to collect information to establish emission factors, in particular at urban or low-speed driving conditions and with different payloads.
- to evaluate the in-service conformity procedure for the type of truck using Euro-VI emission technology.

[2] The emission compound NO_x is composed of NO and NO_2. In EU vehicle emission regulation the tail-pipe NO_x emission is regulated whereas in EU air-quality regulation the ambient concentration of NO_2 is regulated. NO_2 is more harmful, but NO also contributes to the formation of NO_2.

- to extend the knowledge needed for the development of methods to effectively regulate real-world emissions.

Measurements on the road were performed with one category-M3 vehicle using PEMS.

The PEMS output data was analysed in three ways:

1. using EMROAD to determine the in-service Conformity Factors.
2. using EMROAD to determine distance-specific and mass-distance-specific emissions.
3. using EMROAD in combination with a binning method in order to obtain real-world NO_x emissions as a function of vehicle speed.

1.3 Structure of the report

This report is structured as follows. Chapter 2 describes the research method. The research results obtained for each test are presented in Chapter 3. Chapter 4 states the conclusions regarding the emission performance of the tested vehicle.

This document only reports results of the measurements with this specific vehicle. The results of this vehicle and other vehicles tested in 2013 and 2014 will be collectively reported in a separate report, which will also contain overall conclusions and recommendations drawn from the combined measurement programmes.

2 Emission measurement programme

The exhaust gas emissions of the bus were measured with a Portable Emission Measurement System (PEMS) on the road. After providing some general background on performing PEMS measurements in section 2.1 the specifications of the tested Mercedes Citaro are given in section 2.2. In order to assess the effect of vehicle weight on emission performance, the payloads at which the vehicle was tested are described in section. Section 2.3 then describes the selection of on-road trips that were used to test the vehicle. Finally, the methods to process and analyse the test data are explained in section 2.4.

2.1 Measuring real-world emissions with PEMS

European type approval for emissions of Euro VI heavy-duty engines is based on tests performed on prescribed engine cycles on an engine test bed under laboratory conditions. For the determination of real-driving emissions of in-use vehicles, execution of engine tests on an engine test bed may not be representative. With the introduction of PEMS it has become possible to regulate emissions of vehicles in-service in the real world.
In 2011 the EU regulation 582/2011/EC and amendments were introduced which describe on-road emission tests using PEMS for checking the in-service conformity of vehicles for Euro V (not mandatory, Annex II) and Euro VI (mandatory, Annex XII).

PEMS is a system to measure exhaust gas emissions of a vehicle. The measurements can take place on the road in normal traffic and thus yields estimates for real-driving emissions performance of the investigated vehicle.

For this investigation TNO used a PEMS Sensors Semtech DS for the determination of the real-world emissions. The system is widely used and accepted for real-world emission testing on heavy-duty vehicles, light-duty vehicles and non-road mobile machinery. The measured exhaust gas components are NO_x, NO_2, CO_2, CO and HC. The fuel consumption is calculated from the emissions using the carbon balance method.

2.2 The test vehicle; a category-M3 bus

In the In-Service Testing Programme the ministry and TNO each year define a selection of vehicles to be tested. Selection criteria include relevance for the Dutch vehicle fleet, the type of emission reduction technology and/or after treatment systems the vehicle is equipped with and relevance for air quality problems.

In 2013 and 2014 Euro VI vehicles formed the centre of attention in the testing programme. Euro VI is the latest European emission standard that sets new, stringent limits on emissions of heavy-duty vehicles, entering into force January 2014.

Compared to the limits set in the previous emission standard, Euro V, for example NO_x limits in Euro VI are lowered from 2.0 to 0.46 g/kWh.

Furthermore, large improvements have been made by the introduction of:
- a new, more representative test cycle for heavy-duty engines (WHTC),
- in-service conformity with PEMS,
- a new procedure with limits for the particle number emission, and
- improved requirements for on-board diagnostics.

Euro VI vehicles could therefore potentially prove to be an effective instrument in helping the Netherlands fulfil European air quality requirements set for 2015. The ministry of Infrastructure and the Environment therefore incentivised the purchase of Euro VI heavy-duty vehicles already in 2013.

The first Euro VI vehicles, mostly long-haulage trucks, appeared on the market early 2013. TNO has thus far tested six of those Euro-VI trucks and the results have been promising. The NO_x emissions of the tested trucks stayed well below the Euro VI emission limits.

Buses significantly contribute to local NO_x emissions. In a typical Dutch city they are responsible for over 10% of the total city traffic NO_2 emissions while buses only represent approximately 1% of the total city fleet [Eijk, 2012]. Here again, Euro VI buses potentially could be of great help in improving local air quality.

The ministry of Infrastructure and the Environment and TNO were therefore keen on testing Euro VI buses as part of the testing programme. Qbuzz, a public transport organization in Utrecht, the Netherlands, recently acquired a total of 138 Euro VI Mercedes Citaro city buses and was the first in the Netherlands to launch such a large-scale Euro VI city bus fleet. TNO asked Qbuzz to participate in the testing programme and Qbuzz responded positively. It kindly made available one of their Euro VI 12-meter Mercedes Citaro city buses to TNO for PEMS testing in week 5 and 6 of 2014.

The bus and its specifications are shown in Figure 1 and Table 1 respectively.

Figure 1: The test vehicle: a Euro-VI 12-meter Mercedes Citaro kindly provided by Qbuzz.

Table 1: Test vehicle specifications.

Vehicle brand	Mercedes-Benz
Type	Citaro
Legislative emission class	Euro VI
2007/46/EC Vehicle category	M3 Class I, diesel
Vehicle type approval number	e1*2007/46*0087*08
Vehicle type, axle config.	12m city bus, 4x2
VIN	WEB62803313703491
TNO test code	MB128
Engine make and model	Daimler OM936 hLA 6-2
Engine code	936980C0003061
Emission type approval number	e1*595/2009*64/2012A*0008*00
Engine # cylinders / displacement [liter]	6 / 7.698
Engine power [kW]	222.1 @ 2200 rpm
After treatment, emission reduction	EGR, DOC, DPF, SCR, NH_3 clean-up catalyst
Odometer at start of PEMS test [km]	11,500

2.3 The test programme

2.3.1 *Vehicle payloads*

Table 2 specifies the maximum and empty vehicle mass and, derived from that, the vehicle's maximum payload of 7,245 kg.

Table 2: Specification of vehicle maximum mass, empty mass and maximum payload.

Vehicle mass	[kg]
Max vehicle mass	18,745
Empty mass	11,500
Max payload	7,245

In order to assess the effect of vehicle weight on emission performance, the Mercedes Citaro was tested at three different payloads, as shown in Table 3.

Table 3: The payloads at which the Mercedes Citaro was tested and its subsequent total mass during the tests.

Payload		Vehicle total mass during test
[%]	[kg]	[kg]
10	720	12,220
(SORT) 41	2,960	14,460
100	7,240	18,740

The 10% and 100% payload tests are used to identify the emission performance at the lower and higher end of the vehicle mass range. The intermediate payload is usually chosen to represent a typical, average payload the vehicle is presented with over its life span. For in-service conformity this is defined to be between 50 and 60 % of the maximum vehicle payload. Selection of another representative value is permitted if a substantiation is provided.

In this case TNO set the intermediate payload at 41% of the maximum payload, based on discussions with the operator and the vehicle test mass prescribed as part of the Standardised On-Road Test Cycles (SORT) for buses Reference [UITP, 2009]. 41% of the maximum payload corresponds to 3,100 kg payload.

2.3.2 *Test trips*

The vehicle was equipped with PEMS and then tested by driving three types of test trips.

1. A **Euro VI trip** (section 2.3.2.1) according to the EU in-service conformity legislation to check whether the vehicle does not exceed the Euro VI emission limits;
2. **bus routes** (section 2.3.2.2) typical for the vehicle at hand to assess the emission performance of the vehicle in everyday operation, and;
3. a **reference route** (section 2.3.2.3) in order to be able to compare this Mercedes Citaro with other vehicles tested and yet to be tested in the in-service conformity programme.

The vehicle's emission performance per trip will be analysed. Furthermore, TNO will make a comparison between the emission performance on the Euro VI trip and the emission performance on the bus routes. This allows for an assessment of the effectiveness and robustness of the procedures that currently apply for in-service conformity legislation, and it can form input to the ongoing development of future Real-Driving Emissions legislation.

The trips are further detailed in the sections below.

2.3.2.1 *Euro VI trip*

As of 2011, Commission Regulation (EU) No 582/2011 prescribes the use of PEMS as a means of determining the 'in-service conformity' of heavy-duty vehicles. This regulation also gives directions for the trip that should be performed when executing the PEMS measurements. The trip requirements defined in regulation 582/2011 differ per class of vehicle, i.e. trips for testing N3-category vehicles differ from trips for testing M3-category vehicles.

Based on these directions, TNO also designed its own so-called Euro VI trips, that are located in the surroundings of TNO's vehicle laboratory in Helmond.

According to directive 2001/85/EC the Mercedes Citaro tested here is an M3 Class I vehicle. regulation [EU582/2011] states that such vehicles *'shall be tested in approximately 70% urban and 30% rural operation'.* To this end, TNO designed a Euro VI trip for this M3 Class I vehicle, consisting of approximately 70% urban and 30% rural operation in the surrounding of TNO's vehicle laboratory in Helmond, the Netherlands (Figure 2).

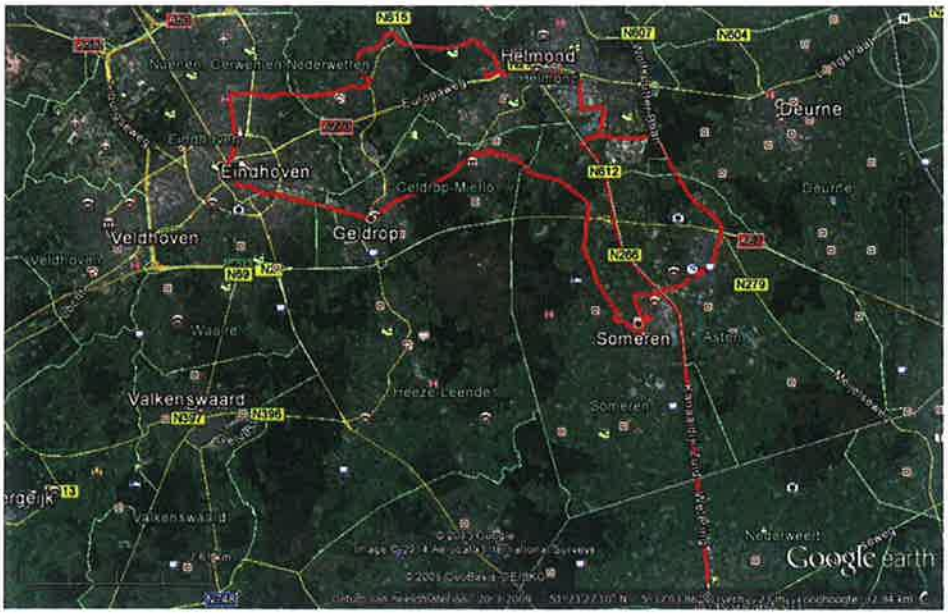

Figure 2: Euro VI M3 Class I trip consisting of 70 % urban and 30% rural operation, as prescribed by regulation 582/2011.

Table 4 shows the different trips regulation [EU582/2011] prescribes and highlights the trip used for the emission measurements of the Mercedes Citaro.

Table 4: Overview of trip requirements for various vehicle categories as stated in [EU582/2011]. The trip used for the emission measurements of the current vehicle is highlighted.

Vehicle category	Sub 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 of Class I, II or Class A	**70**	**30**	**0**

A speed trace of the M3 trip is shown in Figure 3.

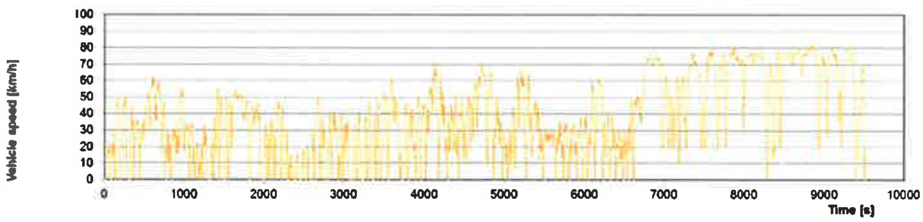

Figure 3: Speed trace of the M3 Class I trip TNO designed according to Euro VI specifications and that was used for the measurements.

2.3.2.2 *Bus routes*

To assess the emission performance of the Mercedes Citaro in everyday operation, testing included PEMS tests on two of Qbuzz's bus routes: route 77 and route 8 in

Utrecht. Route 77 consists of rural and urban roads; route 8 predominantly consists of urban operation.

The Mercedes Citaro subject to the test trailed another Qbuzz bus that at that moment was operating the bus route under investigation. The test bus therefore also halted at bus stops when the 'chased' bus stopped to embark or disembark passengers. The test bus did not board passengers. Besides the practical aspect of following a bus operating the Qbuzz timetable, it also guarantees the bus was driven in a representative fashion.

Route 77

Route 77, shown in Figure 4, connects the towns 'Nieuwegein' and 'Bilthoven' and crosses the city center of Utrecht. It therefore contains rural as well as urban roads. Route 77 was driven vice versa once, in the morning of the testing day in Utrecht. Mild traffic conditions prevailed during the test. Figure 5 shows a speed trace of the route 77 test on 5 February 2014.

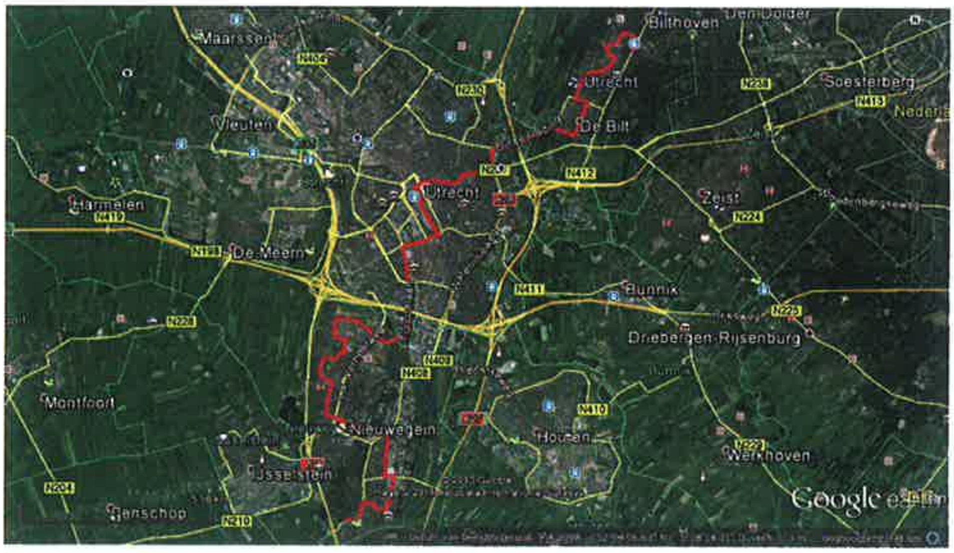

Figure 4: GPS plot of bus route 77, connecting 'Nieuwegein' and 'Bilthoven' while crossing the city center of Utrecht.

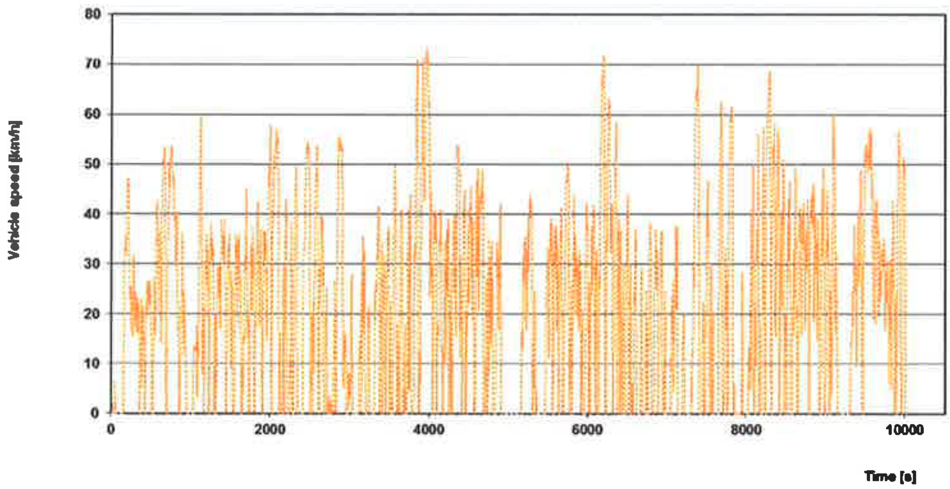

Figure 5: Speed trace of bus route 77 from Nieuwegein to Bilthoven. Route 77 was driven vice versa once, taking approximately 2h47m.

In 2010, TNO performed PEMS measurements on a Euro V VDL Ambassador city bus Connexxion operated in Utrecht at that time. The VDL Ambassador was tested on route 77. As the route did not change since 2010, it was decided to also test the Euro VI Mercedes Citaro on route 77 as well. The results of the current measurements on the Euro VI Mercedes Citaro will be compared with the 2010 results of the Euro V VDL Ambassador in Chapter 3.

Route 8

As can be seen in Figure 6, route 8 is an urban bus route leading from the suburb 'Oudwijk' to the suburb 'Lunetten'. Buses servicing route 8 predominantly encounter busy city-center roads. Route 8 was driven in the afternoon of the testing day in Utrecht, with rush hour coming up to speed as the test trip progressed. Traffic, therefore, was quite heavy. Route 8 was driven from Oudwijk to Lunetten and back, and then forth once more.

Figure 6: GPS plot of bus route 8, an urban bus route leading from the suburb 'Oudwijk' to the suburb 'Lunetten'.

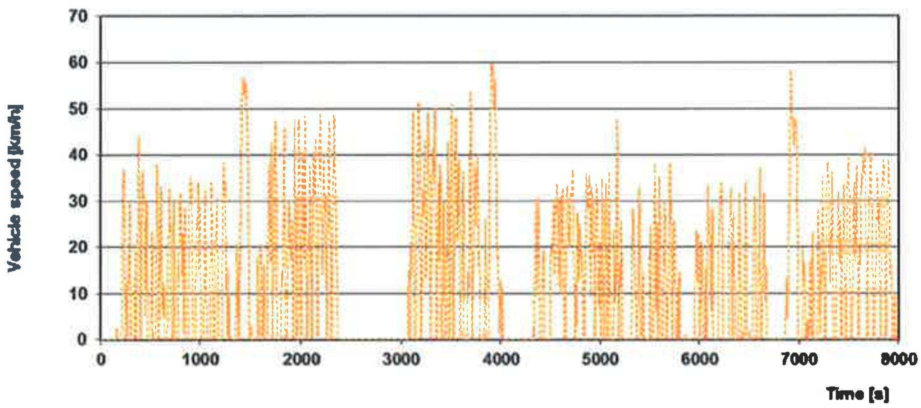

Figure 7: Speed trace of bus route 8 from 'Oudwijk' to 'Lunetten'. Route 8 was driven from Oudwijk to Lunetten and back, and then forth once more, taking approximately 2h13m.

It was selected in consultation with Qbuzz: route 8 is one of the busiest Qbuzz routes passing a number of air-quality-critical locations in Utrecht. It is for this kind of bus routes Euro VI could help in mitigating air quality issues.

Route 8 was not part of the 2010 test programme. Emission results will therefore only be presented as is, i.e. no comparison with other vehicles can be made here.

2.3.2.3 *TNO reference trip*

The so-called 'TNO reference trip' is designed by TNO and is normally performed with each vehicle that is tested in this programme. Its main goal is to yield trip data that allow for easy comparison between vehicles.

2.3.3 *Overview of test programme*

Table 5 gives an overview of the complete test programme.

Table 5: Overview of the test programme of the Mercedes Citaro PEMS tests

Date	Test #	Type of trip	Payload [%]	Weather, traffic, remarks
31 January 2014	1	Euro VI M3 warm start	10 %	regeneration of the DPF occurred
5 February 2014	3+4	bus route 77 warm start	41 %	cloudy, 8 °C, calm traffic
5 February 2014	5+6	bus route 8 warm start	41 %	cloudy, 8 °C, partly heavy traffic
6 February 2014	7	Euro VI M3 cold start	41 %	-
6 February 2014	8	TNO reference warm start	41 %	cloudy, 11 °C
7 February 2014	9	Euro VI M3 warm start	100 %	9 °C, heavy wind from west

2.4 Data processing with EMROAD and the binning method

For analyzing the PEMS data two processing methods have been applied. Both methods will be briefly explained here. Section 2.4.1 discusses the **binning method**: the **in-service conformity pass-fail evaluation methodology** using EMROAD is explained in section 2.4.2.

2.4.1 Method using Vehicle Emission Speed Binning (VESBIN)

The primary purpose of the binning method is to facilitate the use of large amounts of PEMS data as input for calculating 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 the vehicle.

As preparation for the binning method PEMS data of the trips was pre-processed with EMROAD. EMROAD performs a data-quality check and aligns the test signals.

Vehicle speed bins with a width of 5 km per hour were selected to easily distinguish emission data for low, intermediate and high vehicle speeds. 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 calculate brake-specific emissions in gram per kilowatt-hour.

Below, the formula is given, together with an example of how the CO_2-specific emission can be compared with the work-specific emission limit.

$$gNO_x\ per\ kgCO_2 = \frac{\sum_{v=v_i}^{v=v_i+5} NO_x[g/s]}{\sum_{v=v_i}^{v=v_i+5} CO_2[kg/s]}$$

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 BSFC of 210 g/kWh and a $BSCO_2$ of 666 g/kWh, the g/kg CO_2 results can be multiplied with 0.666 to get a corresponding g/kWh result. Lower average engine efficiencies lower this factor and would thus increase the brake specific results accordingly. For comparison, the Euro VI NO_x emission limit of 0.46 g/kWh would amount to 0.69 g/kg CO_2. When the ISC Conformity Factor of 1.5 is taken into account, this would amount to 1.0 g/kg CO_2.

2.4.2 *Method used for in-service conformity*

The pass-fail evaluation method has been applied, using the EMROAD tool (version 5.10). 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 WHTC limit value. A CF of 1.5 for NO_x of a Euro VI vehicle means that an equivalent of 1.5 times 0.46 g/kWh = 0.69 g/kWh is calculated by the tool. Vehicles are not allowed to emit more than 1.5 times the emission limit value under the conditions and data-evaluation rules prescribed for the in-service conformity procedure.

Table 6 shows the settings that are used for the pass-fail data evaluation with EMROAD. The CO_2-based averaging window method was used for the data evaluation. This method is an alternative to the work-based method and calculates the average emissions over windows as large as the CO_2 mass that would have been emitted during an WHTC test. As shown in Table 6, criteria are defined to exclude windows from the dataset. Cold engine operation and high altitudes (>1500m) are excluded from the pass-fail analysis. Furthermore, windows with a very long duration are excluded. A maximum for the window duration excludes windows with a very low average engine power because at a low average power it takes a long time before the CO_2 reference mass is reached.

After exclusion of data a set of 'valid windows' remains. The single window with the largest value of 90 percentile of the data is taken to calculate the CF for each emission component.

Note

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. <u>In this programme only one vehicle was tested and therefore the results are indicative only</u>.

Table 6: EMROAD data evaluation settings for the calculation of the Conformity Factor according to the applicable pass-fail method.

EMROAD version	5.10
Reference quantity	CO_2
Reference cycle	WHTC
Cycle work (WHTC hot) / CO_2 mass	Estimated at 18 kWh / 12,8 kg
Data exclusion	Engine coolant temperature < 70 °C, altitudes > 1500 m, 10th percentile of the maximum values of the valid windows Power threshold 15-20%
Time-alignment	On
Fuel density	0.84 kg/litre, (EN590 market fuel)
Vehicle speed	GPS vehicle speed
Conformity Factor	1.5

3 Results

In this chapter the results of the test programme are presented.
The results are presented as:

- emissions per component per trip, in g/km;
- CO_2-specific NO_x emissions, binned in speed intervals;
- Conformity Factors calculated by EMROAD, according to the in-service conformity pass-fail method.

3.1 The test conditions

During the data analysis the test conditions must be taken into account. Table 7 shows the test conditions that prevailed during the test trips.

Table 7: Overview of the test conditions.

Test date	6-12-2013 to 12-12-2013
Ambient conditions	Mostly calm weather, mild winter temperatures (8-11 °C), heavy western winds during one Euro VI trip
Traffic	Varying per trip, mostly calm in reference trip and Euro VI trip, mostly calm on route 77, but busy to dense traffic on route 8 during city testing in Utrecht
Driver	TNO experienced test driver with regular driving style, who in Utrecht copied driving pattern of bus drivers. The driving pattern varied per bus driver.

3.2 Distance-specific emissions and CO_2-specific emissions

Table 8: Trip characteristics.

Trip	**Payload**	**Start**	**Distance**	**Average Speed**	**Hours**	**Fraction trip**
			[km]	[km/h]	[h]	[%]
Reference	**41%**	**Warm**	**73,1**	**43,2**	**1,7**	**n/a**
Euro VI M3*	**10%**	**Warm**	**60,5**	**28,3**	**2,1**	**100%**
Urban			*48,2*	*25,8*	*1,9*	*87%*
Rural			*12,3*	*45,3*	*0,3*	*13%*
Euro VI M3*	**41%**	**Cold**	**95,9**	**35,4**	**2,7**	**100%**
Urban			*49,2*	*27,9*	*1,8*	*65%*
Rural			*46,7*	*49,4*	*0,9*	*35%*
Euro VI M3*	**100%**	**Warm**	**96,5**	**36,5**	**2,6**	**100%**
Urban			*48,2*	*26,2*	*1,8*	*69%*
Rural			*48,4*	*59,8*	*0,8*	*31%*
Bus route 77	**41%**	**Warm**	**58,9**	**21,2**	**2,8**	**n/a**
Bus route 8	**41%**	**Warm**	**29,0**	**13,1**	**2,2**	**n/a**

* The Euro VI M3 trip was designed during the experiments and was fine-tuned as the experiments advanced. Based on the first Euro VI M3 trip, more urban roads were added to the trip to finally arrive at a 69%-31% urban-rural distribution (see Figure 2).

Table 9: Distance-specific emissions. NO_2 percentage and CO_2-specific NO_x emissions over all trips and trip parts.

Trip name	Payload	CO_2	NO_x	NO_2	NO	Perc NO_2	NO_x per CO_2	CO	HC
		[g/km]	[g/km]	[g/km]	[g/km]	[%]	[g/kg]	[g/km]	[g/km]
Reference	**41%**	**817**	**0,21**	**0,04**	**0,17**	**20**	**0,26**	**0,68**	**0,02**
Euro VI M3*	**10%**	**1028**	**1,19**	**0,30**	**0,89**	**25**	**1,16**	**0,79**	**0,13**
Urban		*1017*	*1,33*	*0,36*	*0,97*	*27*	*1,31*	*0,80*	*0,17*
Rural		*1069*	*0,66*	*0,07*	*0,58*	*11*	*0,62*	*0,75*	*0,00*
Euro VI M3*	**41%**	**949**	**1,02**	**0,24**	**0,79**	**23**	**1,08**	**0,72**	**0,03**
Urban		*1080*	*1,85*	*0,43*	*1,42*	*23*	*1,71*	*0,86*	*0,00*
Rural		*812*	*0,16*	*0,04*	*0,12*	*23*	*0,19*	*0,57*	*0,06*
Euro VI M3*	**100%**	**1117**	**0,39**	**0,13**	**0,27**	**32**	**0,35**	**0,79**	**0,11**
Urban		*1251*	*0,69*	*0,21*	*0,48*	*30*	*0,55*	*0,88*	*0,04*
Rural		*983*	*0,10*	*0,05*	*0,05*	*46*	*0,10*	*0,69*	*0,18*
Bus route 77	**41%**	**1223**	**1,73**	**0,58**	**1,15**	**33**	**1,42**	**1,04**	**0,18**
Bus route 8	**41%**	**1372**	**4,04**	**1,14**	**2,90**	**28**	**2,95**	**1,43**	**0,09**

Compared to other Euro VI vehicles TNO tested, the Mercedes Citaro's NO_x emissions vary significantly per trip. Its NO_2 fraction is relatively low. NO_x emissions during bus route 8 are very high compared to NO_x emission levels encountered with other Euro VI vehicles. It must be noted however that all other tested Euro VI vehicles are long-haulage trucks and that, therefore, those vehicles have not been tested on a trip with the urban character and driving style of a bus on route 8.

3.3 Binned CO_2-specific emissions

In this section, the CO_2-specific NO_x emissions of the tested vehicle are presented. First section 3.3.1 presents the emissions of the Mercedes Citaro 'as is'; secondly, section 3.3.2 compares them with emissions of other vehicles.

3.3.1 CO_2-specific NO_x emissions of the Mercedes Citaro

Figure 8 shows the CO_2-specific NO_x emissions of the Mercedes Citaro, for all test trips, including the bus routes 77 and 8.

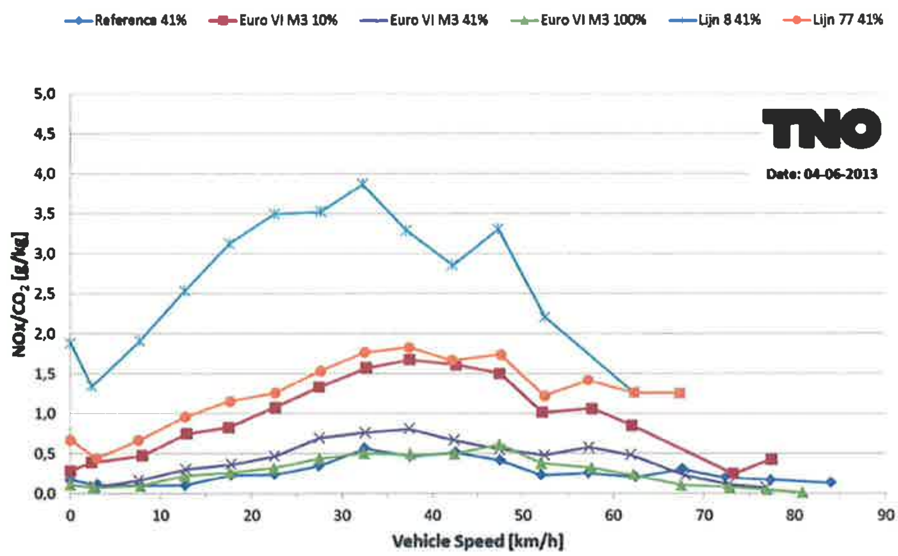

Figure 8: CO_2-specific NO_x emissions of the Mercedes Citaro averaged per speed interval of 5 km/h over the speed range for all measured trips.

NO_x emissions on Euro VI trips

1 During the Euro VI trip at 41% and 100% payload the CO_2-specific NO_x emissions stay below 1 g/kg.
2 At 10% payload, the CO_2-specific NO_x emissions of the Euro VI trip increase up to about 1.7 g/kg.

NO_x emissions on bus routes

3 The vehicle's CO_2-specific NO_x emissions for bus route 8 are significantly higher at all speeds, compared to the other trips. The values range between 1.3 to almost 4 g/kg.
4 CO_2-specific NO_x emissions for bus route 77 are lower than those of bus route 8. This is mainly due to the fact that route 77 has larger fractions of rural operation, leading to a somewhat higher average speed.

NO_x emissions on TNO's reference route

5 CO_2-specific NO_x emissions on TNO's reference route stay below 0.6 g/kg.

General observation regarding the vehicle's CO_2-specific NO_x emissions
The tested vehicle is very sensitive to driving conditions with an average low engine load. Driving the vehicle at low payload or at low speeds has a significant adverse effect on this vehicle's NO_x emissions. Under these circumstances, the NO_x emissions of the vehicle are high compared to the NO_x emissions of all other Euro VI vehicles tested in this programme.

Again, it must be noted that all other tested Euro VI vehicles were long-haulage trucks and that, therefore, those vehicles have not been tested on a trip with the urban, dynamic character of bus route 8.

3.3.2 *CO_2-specific NO_x emissions compared to other vehicles*

Figure 9 and Figure 10 show CO_2-specific NO_x emissions averaged per speed interval of 0-50, 50-75 and >75 km/h. Figure 9 contains data of vehicles of different legislative emission stages; Figure 10 only contains data of Euro VI vehicles. Vehicle AJ represents the Mercedes Citaro tested in this measurement.

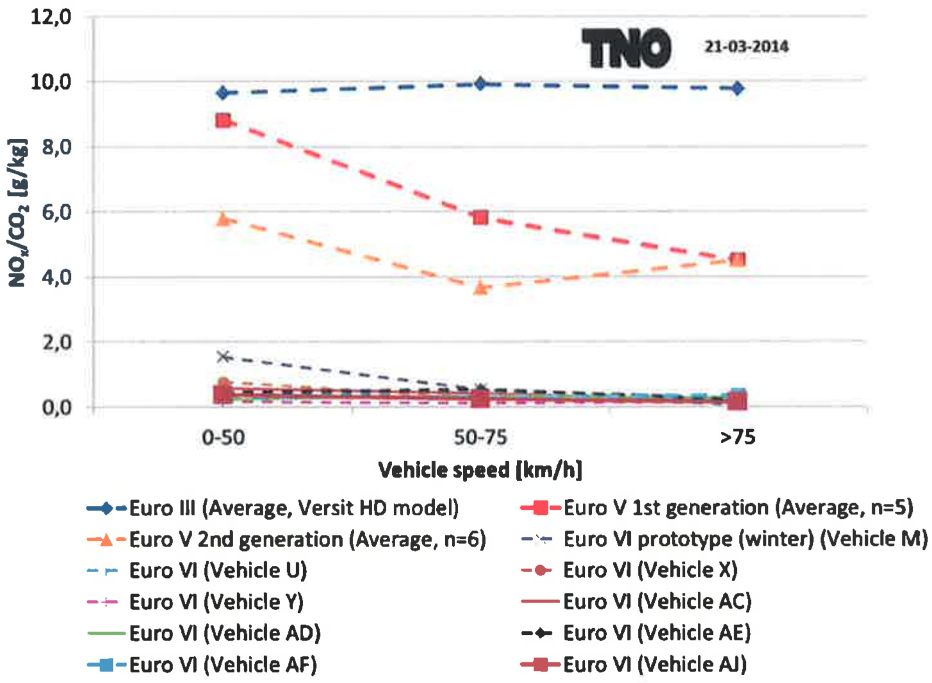

Figure 9: CO_2-specific NO_x emissions averaged per speed interval of 0-50, 50-75 and >75 km/h for legislative emission stages Euro III to Euro VI. The results are from reference trips with ~55% payload. The Euro III and V results are averages over the emission stage. The tested Euro VI vehicles are presented individually. **Vehicle AJ represents the vehicle discussed in this report. As stated, vehicle AJ was tested at 41% of maximum payload and is the only bus in this figure.**

Figure 9 shows that compared to the average NO_x emissions of previous emission stages, the CO_2-specific NO_x emissions of the tested vehicle are at a low level.

Zooming in on Euro VI NO_x emissions of vehicles TNO tested thus far (Figure 10) shows that for the TNO reference trip the Mercedes Citaro performs well at vehicle speeds between 50 and 75 km/hr and above 75 km/hr and is a medium performer in the 0-50 km/hr speed range.

It must be noted that the vehicle comparison is based on the emission performance on the TNO reference trip. The TNO reference trip thus far does not discriminate between the type of vehicle, i.e. trucks as well as buses are driven on the same reference trip. Therefore, emission results on the reference trip are purely for the purpose of comparing vehicles and do not necessarily represent the emissions that can be encountered in everyday operation of a specific vehicle. In case of the tested Mercedes Citaro, this phenomena has clearly presented itself.

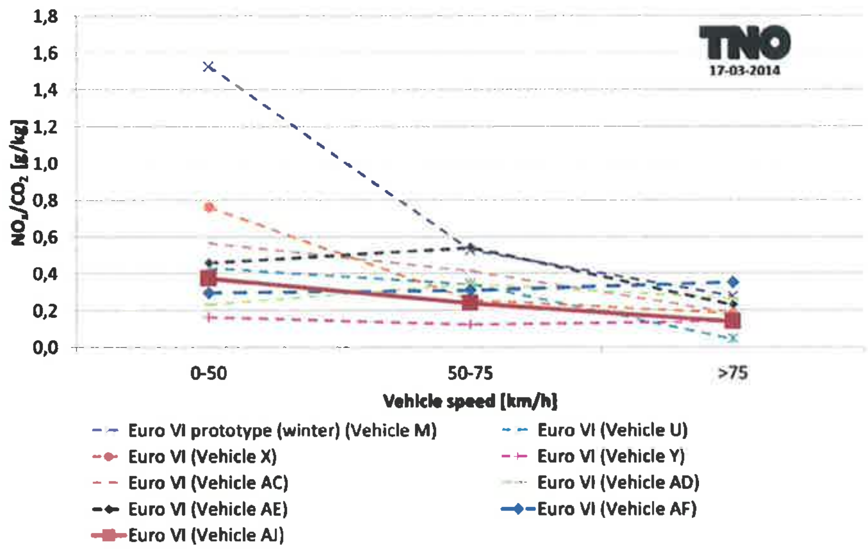

Figure 10: CO_2-specific NO_x emissions averaged per speed interval of 0-50, 50-75 and >75 km/h, showing only Euro VI vehicles. **Vehicle AJ represents the vehicle discussed in this report. It is the only bus in this figure; all other vehicles are long-haulage trucks.**

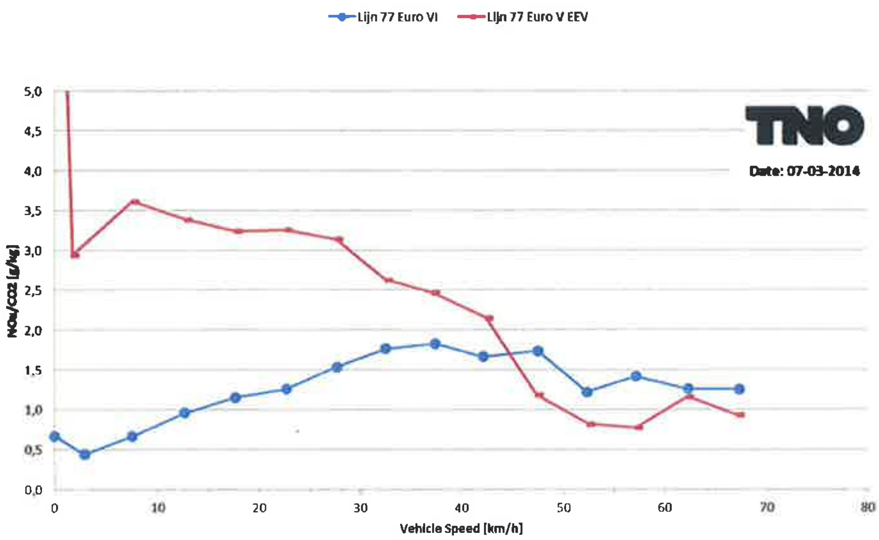

Figure 11: CO_2-specific NO_x emissions of a Euro V EEV city bus tested in 2010 and the Euro VI city bus of this report, measured over bus route 77. The emissions are averaged per speed interval of 5 km/h over the speed range.

As stated in section 2.3.2.2, TNO in 2010 performed PEMS measurements on a Euro V EEV city bus. This type of bus was operated by Connexxion in Utrecht at that time. The bus was tested, amongst others, on bus route 77.

Figure 11 compares the CO_2-specific NO_x emissions of the Euro V EEV tested in 2010 with the emissions of the Euro VI Mercedes Citaro. They are comparable at speeds from approximately 40 – 70 km/hr. In the lower speed range however, the Euro VI Mercedes Citaro has significantly lower NO_x emissions on route 77.

3.4 In-service conformity

Figure 12 shows the CO_2-based Conformity Factors of the Mercedes Citaro over the different trips. Over the M3 Euro VI trip the NO_x Conformity Factor range from 0.69 at a payload of 100%, to 1.0 at a 41% payload and 1.35 at 10% of the maximum payload. On the reference trip the vehicle has a Conformity Factor of 0.18, which can be explained by the fact that the reference trip has a larger share of rural and motorway operation. The Conformity Factor over bus route 77 is 1.41, the highest value in the measurement. For bus route 8, no Conformity Factor could be calculated, due to the insufficient amount of valid windows available. The average power in the windows that were evaluated remained below the threshold of 15% and were therefore not marked as valid.

The values for the Conformity Factor for NO_x emissions of this vehicle are in the high end of the values encountered in Euro VI vehicles tested before, but are at a comparable level on the reference trip. The Conformity Factor for the Euro VI trip at 41% payload does stay below the 1.5 in-service conformity limit.

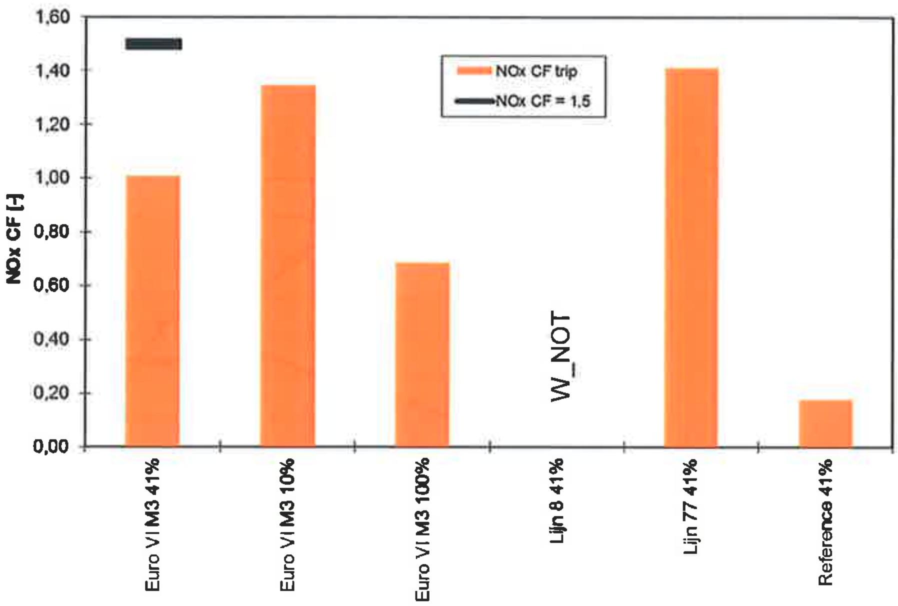

Figure 12: CO_2-based NO_x Conformity Factors calculated with EMROAD.

Table 10: Overview of NO_x Conformity Factors and EMROAD parameters qualifying the pass-fail evaluation, using the CO_2-based averaging window method. W_NOT in this case means that the average power in all windows was too low to find valid windows.

Trip	NO_x Conformity Factor CF (90%ile) [-]	NO_x maximum Conformity Factor CF (100%ile) [-]	Window maximum time [s]	Window minimum time [s]	Number of valid windows	Percentage of valid windows [%]	Data coverage index [%]	CF max
Euro VI M3 41%	1,01	1,37	1530	934	4651	62	79	1,5
Euro VI M3 10%	1,35	1,52	1536	919	4848	94	85	
Euro VI M3 100%	0,69	0,77	1524	632	6616	85	95	
Lijn 8 41%	W_NOT	W_NOT	W_NOT	W_NOT	W_NOT	W_NOT	W_NOT	
Lijn 77 41%	1,41	1,89	1621	1360	5097	74	63	
Reference 41%	0,18	0,19	1530	713	2006	52	70	

Figure 13 and Figure 14 show the Conformity Factors for CO and THC respectively. Conformity Factors for CO are low and steady (0.13 – 0.14) over all trips.

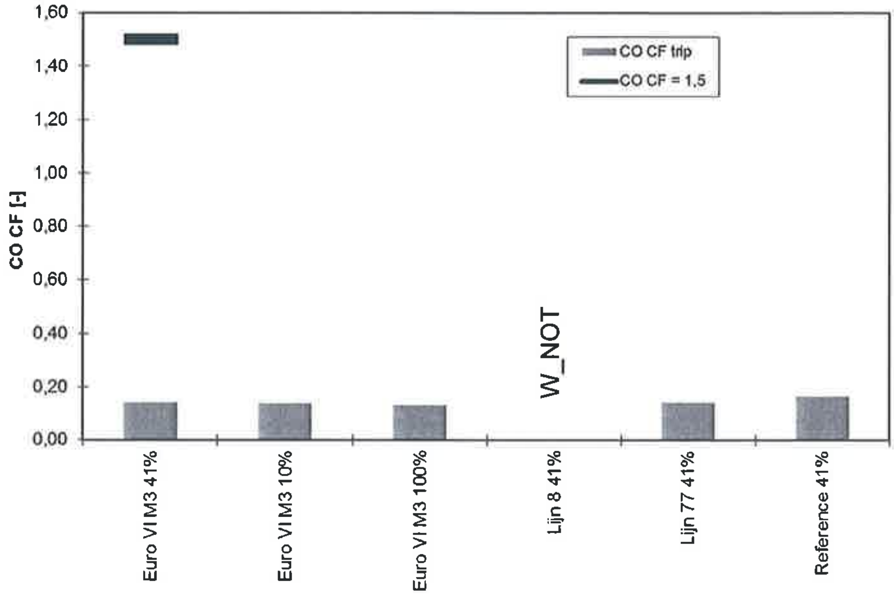

Figure 13: CO (carbon monoxide) Conformity Factors calculated with EMROAD. W_NOT in this case means that the average power in all windows was too low to find valid windows.

The Conformity Factors for HC on the other hand are very high and much higher than values encountered in tests with other Euro VI vehicles tested. The Conformity Factor for the Euro VI trip at 41% payload does, however, stay well below the in-service conformity limit of 1.5. It must be stated that the HC measurement is not accurate at given emission levels and results have to be analyzed taking account this accuracy.

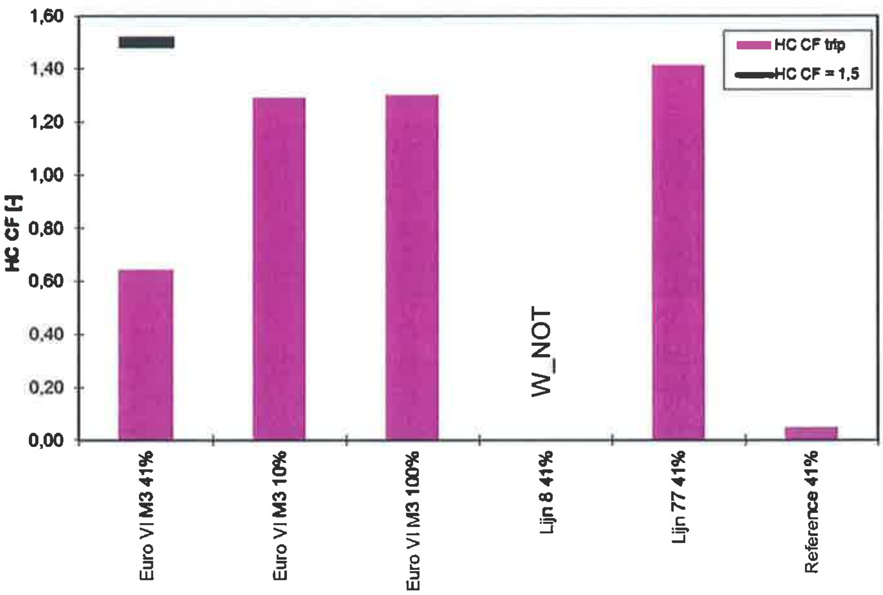

Figure 14: THC (Total Hydrocarbons) Conformity Factors calculated with EMROAD. Results are to be analyzed taking account of the low accuracy of the measurement equipment at given emission levels. W_NOT in this case means that the average power in all windows was too low to find valid windows.

Table 11 summarizes the CO and HC Conformity Factors over all trips.

Table 11: Overview of CO and HC Conformity Factors.

Trip	CO Conformity Factor 90-%	HC Conformity Factor 90-%	CF max
Euro VI M3 41%	0,1	0,6	1,5
Euro VI M3 10%	0,1	1,3	
Euro VI M3 100%	0,1	1,3	
Lijn 8 41%	W_NOT	W_NOT	
Lijn 77 41%	0,1	1,4	
Reference 41%	0,2	0,1	

4 Conclusions

The tested vehicle fulfils the requirements laid down in the Euro VI emission regulation, i.e. it does not exceed the Euro VI in-service conformity limits. Its emission performance has, however, shown to be very sensitive to driving conditions with low average engine load. On a demanding city-center bus route, TNO measured NO_x emissions that are high compared to NO_x emissions encountered in all other tested Euro VI heavy-duty vehicles. This indicates that the test trip as prescribed by the Euro VI emission legislation does not necessarily yield representative real-world emissions of this specific vehicle.

It has to be noted that all other tested Euro VI vehicles in the test programme so far were long-haulage trucks and that, therefore, those vehicles have not been tested on a trip with the urban character and driving style of a city-center bus route.

The findings are further detailed below.

4.1 Real-world emissions

Real-world NO_x and NO_2 emissions of the tested vehicle
Compared to the average NO_x emissions of previous emission stages, the CO_2-specific NO_x emissions of the tested vehicle are on average at a low level. The NO_2 fraction of the tested vehicle is relatively low as well. Compared to other Euro VI vehicles TNO tested so far, the Mercedes Citaro performs well at vehicle speeds between 50 and 75 km/hr and above 75 km/hr and is a medium performer in the 0-50 km/hr speed range.

The NO_x emission of the tested vehicle is however very sensitive to driving conditions with an average low engine load. Driving the vehicle at low payload or at low speeds has a significant adverse effect on this vehicle's NO_x emissions. Under these circumstances, the NO_x emissions of the vehicle are high compared to the NO_x emissions of all other Euro VI vehicles tested in this programme [Vermeulen, 2013].

Comparison with Euro V EEV city bus tested in 2010
In the lower speed range the Euro VI Mercedes Citaro has 20 to 80% lower NO_x emissions on bus route 77 compared to the CO_2-specific NO_x emissions of the Euro V EEV bus tested on that same route in 2010. At speeds from approximately 40 – 70 km/hr, the emissions of the Euro VI Mercedes Citaro are comparable to those of the Euro V EEV bus. It has to be noted that the Euro V EEV bus performed very well compared to the other Euro V vehicles tested.

Emission performance on a city-center bus route
The Mercedes Citaro was also tested on bus route 8, containing a much larger share of urban operation than route 77. Route 8 is a relatively short bus route serving the city center of Utrecht with many stops and a low average speed. Compared to the emissions in other test trips, the vehicle's CO_2-specific NO_x emissions for bus route 8 are high, reaching an average value of almost 3 g/kg and an average distance-related NO_x emission of 4 g/km. It should be noted that in the past no emission measurements on route 8 have been performed. This Euro VI

vehicle was the first vehicle to be tested on route 8. Route 8 was selected as it is representative for a significant number of routes the operator's timetable contains.

4.2 In-service conformity

NO_x

The Conformity Factor for NO_x over an M3 Class I Euro VI trip at a payload of 41% is 1.0 and thus below the legislative limit of 1.5. The Conformity Factors for NO_x over the Euro VI trip with alternative payloads is 0.7 at a payload of 100% and 1.4 at a payload of 10%.

The values for the Conformity Factor for NO_x emissions of this vehicle are higher than values encountered in most Euro VI heavy-duty long-haulage trucks tested before.

CO

The Conformity Factors for CO are low and steady (about 0.1) over all trips.

HC

The Conformity Factors for HC are below 1.5 but this measurement has a low accuracy.

4.3 General observation

Although the vehicle does not exceed Euro VI limits for in-service conformity, in many occasions the NO_x emissions of the tested vehicle are higher than those recently encountered when measuring Euro VI long-haulage vehicles under their typical driving conditions. The high NO_x emissions occurred mainly under the urban driving conditions characteristic for city bus operation, which differ from the typical driving conditions of long-haulage vehicles and from test conditions within the Euro VI legislation.

This clearly shows that the EU pass-fail method for in-service conformity excludes data that, in fact, was obtained during normal, representative operation of a city bus. This data exclusion leads to lower in-service conformity NO_x emissions that are not necessarily representative for the real-world emissions of this specific vehicle.

4.4 Note

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 was tested and therefore the results are indicative only.

5 References

[Eijk, 2012] Eijk, A. and Obdeijn, C., Samenstelling van het wagenpark op zes locaties in de gemeente Utrecht, 9 March 2012. TNO report TNO-060-DTM-2012-00825.

[UITP, 2009] Standardized on-road test cycles. New edition 2009. (Second edition).

[Vermeulen, 2013] Vermeulen et al., The Netherlands In-Service Testing Programme for Heavy-Duty Vehicle Emissions 2012, 20 November 2013, TNO report TNO 2013 R10960.

6 Signature

Delft, 28 March 2014

[redacted] [redacted]