Urbanisation
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 R11307

NOx and PM emissions of a Mercedes Citaro Euro VI bus in urban operation

Date	30 September 2014
Author(s)	Jordy Spreen Willar Vonk Robin Vermeulen
Copy no	2014-TM-RAP-0100169903
Number of pages	35
Sponsor	Mr. L.Z. Zuidgeest and Mr. H.L. Baarbé 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	060.10012

Samenvatting

In opdracht van het Ministerie van Infrastructuur en Milieu brengt TNO de praktijkemissies van vrachtwagens en bussen in Nederland in kaart door op regelmatige basis emissiemetingen uit te voeren. De nadruk bij deze metingen ligt op het vaststellen van de uitstoot van stikstofoxiden (NO_x). De verkregen meetgegevens en inzichten worden door het Ministerie en lokale overheden gebruikt bij de ontwikkeling van lokaal, nationaal en internationaal beleid voor het realiseren van doelstellingen op het gebied van klimaat en luchtkwaliteit.

Dit rapport doet verslag van een serie emissiemetingen die TNO in 2014 heeft uitgevoerd aan een Euro VI Mercedes Citaro stadsbus in Utrecht. De meetserie is medegefinancierd door de gemeente Utrecht. Behalve informatie over de NO_x-uitstoot van de stadsbussen, zijn ook inzichten in de praktijkuitstoot van fijnstof (PM) door stadsbussen voor de gemeente Utrecht van groot belang. Het doel van dit onderzoek was het vaststellen van de uitstoot van stikstofoxiden (NO_x) én fijnstof (PM) door de Mercedes Citaro onder omstandigheden die representatief zijn voor Utrechts busvervoer.

De uitstoot van uitlaatgassen is gemeten met een Portable Emission Measurement System, kortweg PEMS genoemd. Voor het bepalen van de *praktijk*uitstoot zijn de emissies gemeten op twee buslijnen in de stad Utrecht. Daarnaast heeft TNO de Citaro onderworpen aan een *“in-service conformity”* test: een test om te beoordelen of de bus voldoet aan de Euro VI emissie-eisen. Om het voertuig te kunnen vergelijken met eerder geteste voertuigen, is de Mercedes Citaro tot slot getest op TNO’s eigen referentieroute. In samenwerking met Daimler, de fabrikant van de Mercedes Citaro, heeft TNO tevens mogelijkheden onderzocht voor het verder reduceren van de NO_x-emissies onder stedelijke rijomstandigheden. Daarbij is gekeken naar twee alternatieve software-instellingen van het voertuig.

Over de emissieprestaties van de Mercedes Citaro trekt TNO de volgende conclusies:

1. De Euro VI Mercedes Citaro voldoet aan de Euro VI emissie-eisen.
2. De NO_x-emissies van de Mercedes Citaro zijn onder praktijkomstandigheden gemiddeld erg laag. Wel zijn de NO_x-emissies van de Mercedes Citaro erg gevoelig voor rijomstandigheden met een lage gemiddelde motorbelasting.
3. Verdere reductie van de NO_x-emissies van de Mercedes Citaro is mogelijk, maar heeft vrijwel zeker een hoger brandstofverbruik en bijbehorende hogere CO_2-emissies tot gevolg. De emissielimieten zijn met Euro VI zo ver teruggebracht dat voertuigfabrikanten bij het ontwerp van hun voertuigen zorgvuldig moeten balanceren tussen lage schadelijke emissies enerzijds en optimaal brandstofverbruik en CO_2-emissies anderzijds. Toepassing van nieuwe technologieën om de NO_x-uitstoot verder te verlagen vereist een nieuwe typegoedkeuring van het voertuig en de motor.

4 Bij het meten van de uitstoot van fijnstof massa (PM) en het aantal fijnstof deeltjes (PN) van de Mercedes Citaro blijkt dat de uitstoot van PM en PN onder alle rijomstandigheden zo laag is, dat zij nauwelijks te meten zijn. De PM-uitstoot die kon worden vastgesteld, ligt gemiddeld rond de zeer lage waarde van 6 mg/km.

Voor de gemeente Utrecht hebben de emissieprestaties van de Mercedes Citaro de volgende implicaties:

5 De Euro VI Mercedes Citaro voldoet aan de prognoses voor de uitstoot van NO_x- en NO_2 die de gemeente Utrecht heeft gebruikt in haar luchtkwaliteitsprojecties in 2012. Daarom mag worden aangenomen dat de introductie van de Euro VI bussen in het openbaarvervoerssysteem van Utrecht minimaal zo effectief zal zijn als in 2012 werd aangenomen.
6 Dit is in lijn met de NO_2-concentratiedata van het Luchtmeetnet, waarmee de gemeente Utrecht sinds 2011 de luchtkwaliteit monitort. Sinds de introductie van Euro VI bussen in Utrecht is een duidelijke daling van de NO_2-concentratie waarneembaar.
7 Het vervangen van de Euro III bussen door de Euro VI Citaro's heeft de PM- en NO_x-uitstoot van de Utrechtse stadsbusvloot aanzienlijk verlaagd; een Euro VI Mercedes Citaro stoot ongeveer 95% minder PM en 85% minder NO_x uit dan een gemiddelde Euro III stadsbus.
8 Het vervangen van de Utrechtse Euro V EEV stadsbussen zal de NO_x- en PM-uitstoot van de Utrechtse busvloot verder verlagen. In 2010 heeft TNO de emissies van zo'n Euro V EEV gemeten. Daaruit bleek dat deze bus, in vergelijking met andere gemeten vrachtwagens en bussen, één van de best presterende Euro V EEV-voertuigen is als het gaat om de uitstoot van NO_x. De NO_x-uitstoot van de Mercedes Citaro is ongeveer 38% lager dan de NO_x-uitstoot van de Euro V EEV stadsbus, de NO_2-uitstoot ligt zo'n 69% lager. De PM-uitstoot van de Mercedes Citaro is ongeveer 85% lager dan die van de Euro V EEV stadsbus.

Ten aanzien van de Europese emissiewetgeving concludeert TNO:

9 De huidige Euro VI wetgeving schiet te kort als het gaat om het zeker stellen van een zeer lage uitstoot van NOx onder stedelijke rijomstandigheden. Emissiemetingen aan meerdere Euro VI voertuigen hebben duidelijk aangetoond dat een voertuig dat voldoet aan de Euro VI emissie-eisen, niet per definitie onder alle representatieve omstandigheden een stabiele lage NOx-uitstoot laat zien. Verbeteringen van de Euro VI regelgeving is mogelijk door invoering van een realistische Real Driving Emission (RDE) testprocedure voor voertuigen die in de stad rijden. Dit stelt fabrikanten voor de technische uitdaging om een zeer lage NOx-uitstoot realiseren onder alle rijomstandigheden, met een minimale negatieve invloed op brandstofverbruik en de uitstoot van CO2. Naast voertuig gerelateerde maatregelen zal een integrale aanpak, inclusief bijvoorbeeld infrastructurele en logistieke maatregelen, een grote rol spelen in het verder reduceren van brandstofverbruik en de emissie van CO2 in de toekomst.

Al met al zorgt de introductie van de Euro VI Mercedes Citaro in de busvloot van Utrecht voor een aanzienlijke verbetering van de Utrechtse luchtkwaliteit. De uitstoot van NO_x en PM van de Mercedes Citaro is, in vergelijking met eerdere generaties stadsbussen, erg laag.

Summary

TNO regularly performs emission measurements to determine the in-use emission performance of heavy-duty vehicles in the Netherlands. Regular emission measurements are commissioned by the Dutch Ministry of Infrastructure and the Environment and mainly focus on nitrogen oxide, or NO_x, emissions of trucks and buses. The Ministry and local governments also use the insights and data from these measurements to develop local, national and international policies for the realisation of the environmental targets in the field of air-quality and climate. The measurements that are described in this report are co-sponsored by the City of Utrecht, as they were long looking for an opportunity to obtain real-world information on the particle matter (PM) and NO_x emissions by city buses.

TNO performed emission measurements on a Euro VI Mercedes Citaro city bus in Utrecht. The exhaust gas emissions were measured by means of a so-called Portable Emission Measurement System, or PEMS. As one of the most important goals of these emission measurements is to assess the *real-world* NO_x and PM emissions of vehicle, the Citaro was tested on two city bus routes that are representative for its typical use. For these specific driving conditions TNO, in cooperation with Daimler, also investigated if improvement of the NO_x emissions are possible by applying alternative vehicle software settings. In addition, TNO subjected the vehicle to an in-service conformity test to assess if the vehicle complies with the Euro VI emission legislation and tested it on TNO's reference route.

As regards the emission performance of the Mercedes Citaro, TNO concludes that:

1. The Euro VI Mercedes Citaro fulfils the legislative emission requirements laid down in the Euro VI emission legislation.
2. On average, the NO_x emissions of the Mercedes Citaro city buses in real operation are very low. The NO_x emissions of the Mercedes Citaro are however very sensitive to driving conditions with low average engine load.
3. Further decrease of the NO_x emission of the Citaro is considered possible in the context of future technology developments, but are likely to come with a CO_2 emission and fuel consumption penalty. Application of new technologies would require a new type approval for the vehicle and the engine.
4. Accurately measuring the PM emissions and Particle Number emission of the Mercedes Citaro is not easy, which is due to its very low PM emissions under all driving conditions. In fact, it is precisely the low particulate emission that cause the results to become imprecise. The PM emissions that could be established lies on average around 6 mg/km, which is considered to be very low.

For the city of Utrecht, this emission performance of the Mercedes Citaro has the following implications:

5. The Euro VI Mercedes Citaro meets the forecasted NO_x and NO_2 emission levels Utrecht used in its air quality projections in 2012. It is therefore safe to conclude that the introduction of Euro VI city buses in the public transport system of Utrecht is minimally as effective as forecasted in improving the air quality.

6 This is in line with the NO_2 concentration monitoring the city of Utrecht performs since 2011. Since the introduction of Euro VI buses in the public transport system of Utrecht a clear drop in NO_2 concentration in Utrecht is observed.
7 The replacement of Euro III buses with the Euro VI Mercedes Citaro's substantially reduces the PM and NO_x emissions of the Utrecht bus fleet; a Euro VI Mercedes Citaro emits approximately 95% less PM and 85% less NO_x than an average Euro III city bus.
8 Replacing the Euro V EEV city buses that are still part of the Utrecht bus fleet would further decrease the NO_x and PM emissions. The PM emissions are approximately 85% lower than the Euro V EEV city bus. The NO_x emissions of the Mercedes Citaro are approximately 38% lower than the NO_x emissions of the Euro V EEV city bus tested by TNO, the NO_2 emissions are approximately 69% lower. This city bus, that is still in the Utrecht city bus fleet, is compared to other vehicles one of the best performing Euro V EEV vehicles when it comes to emissions of NO_x.

As far as emission legislation is concerned, TNO concludes that:

9 The current Euro VI legislation lacks when it comes to assuring very low emission of NOx under urban driving conditions. The measurements have clearly shown that, although a vehicle fulfils the Euro VI emission requirements, this does not mean they have a stable low NOx emission under all representative circumstances. This was also the conclusion of other measurements TNO has performed lately. Improvement of the Euro VI legislation is possible by introducing a Real Driving Emission (RDE) test procedure for vehicles that are operated in urban areas. This faces the manufacturers with the challenge to assure a very low emission of NOx under all circumstances with a minimal negative influence on fuel consumption and CO2 emissions. Next to vehicle related measures, an integrated approach including for example infrastructural and logistical measures will play a large role in further reduction of fuel consumption and CO2 emission in the future.

All in all, TNO concludes that the air quality in Utrecht substantially benefits from the introduction of the Euro VI city buses in the city bus fleet, as the emission of NO_x and PM is very low compared to earlier generations of vehicles.

Contents

Samenvatting ... 2

Summary ... 5

1 Introduction ... 8
1.1 Background ... 8
1.2 Aim and approach ... 8
1.3 Structure of the report ... 9

2 Emission measurement test method ... 10
2.1 The test programme ... 10
2.2 The test vehicle ... 11
2.3 The measurement equipment ... 12
2.4 Matching the Mercedes Citaro's everyday use ... 13
2.5 Tested options for optimizing NO_x emissions ... 15
2.6 Data processing and evaluation methods ... 16

3 Test results ... 19
3.1 CO_2, NO_x and PM emissions over all test trips ... 19
3.2 Real-world test trips are difficult to reproduce ... 20
3.3 CO_2 emission tends to increase when alternative settings are applied ... 21
3.4 NO_x emissions are low but show some variations ... 22
3.5 PM emissions are very low ... 24

4 Discussion on test results ... 25
4.1 Euro VI buses substantially reduce NO_x and PM emissions of Utrecht bus fleet ... 25
4.2 Euro VI buses have a positive effect on the NO_2 concentration in Utrecht ... 28
4.3 Euro VI city buses in Utrecht meet forecasted NO_x and NO_2 emission levels ... 29
4.4 Further reduction of NO_x emissions is possible, but comes at a price ... 31
4.5 Euro VI legislation does not assure low NO_x emission under urban driving conditions ... 31

5 Conclusions ... 32

6 References ... 34

7 Signature ... 35

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 emission measurements to determine the in-use emission performance of heavy-duty vehicles in the Netherlands. The main goal of these measurements is to gain insight into trends in real-world emissions of heavy-duty vehicles under conditions relevant for the Dutch situation.

In 2013 and 2014 Euro VI vehicles formed the centre of attention in the emission testing programme. Euro VI is the latest European emission standard that sets new, stringent limits on emissions of heavy-duty vehicles, and entered into force in January 2014. The first Euro VI vehicles TNO tested were mostly long-haulage trucks. Staying well below the Euro VI emission limits, these vehicles showed promising results.

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]. Given the low real-world emissions of Euro VI long-haulage trucks, Euro VI city buses could prove to be an important instrument in improving local air quality.

The Ministry of Infrastructure and the Environment and TNO were therefore keen on testing a Euro VI bus as part of the testing programme. Qbuzz, a public transport organization in Utrecht, the Netherlands, introduced a total of 138 Euro VI Mercedes Citaro city buses in December 2013 and was the first in the Netherlands to launch such a large-scale Euro VI city bus fleet. Upon TNO's request to participate in the measurement programme, Qbuzz kindly made available one of their Euro VI 12-meter Mercedes Citaro city buses for emission tests.

The City of Utrecht, long looking for an opportunity to obtain real-world information on the PM emissions of city buses, co-financed part of the measurement series to fill this knowledge loophole.

1.2 Aim and approach

This measurement series aims to determine the NO_x and PM emissions of the Euro VI Mercedes Citaro in urban operation. To this end, TNO fitted a Mercedes Citaro with a so-called Portable Emission Measurement System, or PEMS. Subsequently, TNO performed several test trips at representative vehicle payloads and on representative routes, i.e. two bus routes that Qbuzz operates in Utrecht. The routes were driven according to the Qbuzz timetable.

In so doing, the emissions of the Mercedes Citaro were measured under conditions that are relevant to the vehicle's everyday operation and its *real-world* emission performance can be properly assessed.

1.3 Structure of the report

Firstly, chapter 2 details the method TNO used to perform the emission measurements. Next, chapter 3 describes the test results briefly and in a factual manner. Chapter 4 subsequently elaborates on the implications of the test results and places the outcomes in perspective. The main conclusions follow in chapter 5.

2 Emission measurement test method

This chapter describes the test programme, the tested vehicle and the measurement equipment in sections 2.1, 2.2 and 2.3 respectively. In order to properly assess the Mercedes Citaro's *real-world* emission performance, the test conditions were matched to the real-world city bus operation conditions as much as possible. Section 2.4 will elaborate on that. Real-world city bus operation faces vehicle manufacturers with challenges in finding a balance between low pollutant emissions on the one hand and low CO_2 emissions and thus fuel consumption on the other. As part of the tests, TNO and Daimler assessed the effects of two different vehicle settings on NO_x and CO_2 emissions, which are described in section 2.5. To conclude, section 2.6 briefly describes the data processing and evaluation methods that were used to analyse the test results.

2.1 The test programme

Two emission measurement series were performed: one in February of 2014 and one in June of 2014. This report describes main results and conclusions of both measurement series.

2.1.1 February measurement series

The February measurement series was the first investigation of the gaseous, mainly NO_x, emissions of the vehicle under various conditions. It was tested by driving three types of test trips.

1. A **Euro VI trip** according to the EU in-service conformity (ISC) legislation to verify that the vehicle does not exceed the Euro VI emission limits. The Euro VI trip is also referred to as 'Euro VI M3 ISC trip';
2. **two bus routes** typical for the vehicle at hand to assess the emission performance of the vehicle in everyday operation, and;
3. a **reference route** 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 results of February measurement series gave rise to follow-up measurements in June of 2014 to further investigate possible improvements of the NO_x emissions of the Mercedes Citaro under heavy urban conditions, as well as to assess the real-world PM emissions of the vehicle.

2.1.2 June measurement series

The June testing programme consisted of emission measurements on bus routes 8 and 77 only.

2.1.3 Overview of the test programme

Table 1 gives an overview of the complete test programme.

Table 1: Overview of the test programme of the Mercedes Citaro PEMS tests.

date	morning	afternoon	vehicle configuration	payload	PM measurement
February measurement series first investigation of NO_x emissions under various conditions, including in-service conformity test					
31 January 2014	Euro VI		standard	10%	n/a
5 February 2014	Route 77	Route 8	standard	41%	n/a
6 February 2014	Euro VI	TNO Reference	standard	41%	n/a
7 February 2014	Euro VI		standard	100%	n/a
June measurement series investigation of potential improvements in NO_x emissions and assessing PM emissions					
17 June 2014	Route 77	Route 8	standard	41%	mass
18 June 2014	Route 77	Route 8	setting A: adapted gear shifting strategy	41%	mass
19 June 2014	Route 77	Route 8	setting B: adapted fuel injection strategy	41%	mass
20 June 2014	Route 77	Route 8	standard*	41%	numbers

*this measurement was performed to check if periodic settings A and/or B did not cause a permanent change in the emission performance of the bus.

2.2 The test vehicle

The test vehicle is a Qbuzz-owned Euro VI Mercedes Citaro, which, according to directive 2001/85/EC is an M3 Class I vehicle. The bus and its specifications are shown in Figure 1 and Table 2 respectively.

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

Table 2: 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 (first test series), MB133 (second test series)
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 (first test series) / 36,648 (second test series)

2.3 The measurement equipment

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

Figure 2: PEMS installed on the exhaust of the Mercedes Citaro.

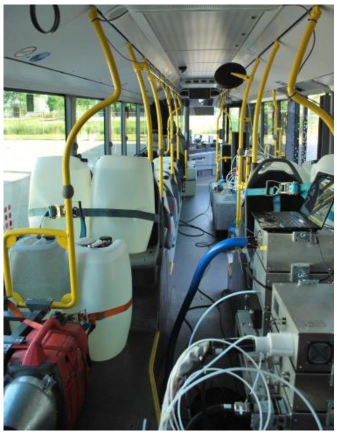

Figure 3: PEMS analyzers, additional equipment and payload inside the bus.

For the first measurements in February, TNO used its own Semtech PEMS system. Existing, off-the-shelf PEMS systems are typically capable of measuring exhaust gas components NO_x, NO_2, CO_2, CO and HC. Systems for measuring real-world PM emissions have, thus far, not been available. This is mainly due to the fact that measuring PM emissions is very difficult and requires laboratory equipment that was not available in a portable fashion until recently.

Anticipating on future PM emission requirements in Euro VI in-service conformity legislation, over the last years PEMS manufacturers have been developing PEMS equipment capable of measuring PM. For the second measurements in June, TNO therefore contacted Sensors, a PEMS manufacturer that currently has available a prototype PEMS suitable for PM measurements. Sensors agreed to make its prototype available for the purpose of measuring the PM emissions of the Mercedes Citaro, and kindly provided its assistance to TNO in installing and handling the prototype equipment.

2.4 Matching the Mercedes Citaro's everyday use

One the most important goals of the emission measurements TNO performs for the Ministry of Infrastructure and the Environment, is to assess the ***real-world* emissions** of vehicles. Every measurement therefore includes one or more tests that are performed under conditions that are representative for a vehicle's normal operation. This means the test route, the way of operating the vehicle and the vehicle payload are brought in agreement with reality as much as possible.

One of the challenges in real-world testing is to make sure test conditions resemble real-world operation as much as possible, while at the same time enabling mutual comparison of test results.

2.4.1 Test routes

To assess the emission performance of the Mercedes Citaro in everyday operation, it was tested on two bus routes that are representative for its typical use: route 77 and route 8 of Qbuzz's timetable in Utrecht. Route 77 consists of rural and urban roads; route 8 predominantly consists of urban operation. Route 77 and route 8 are further detailed in sections 2.4.1.1 and 2.4.1.2 respectively.

2.4.1.1 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 days.

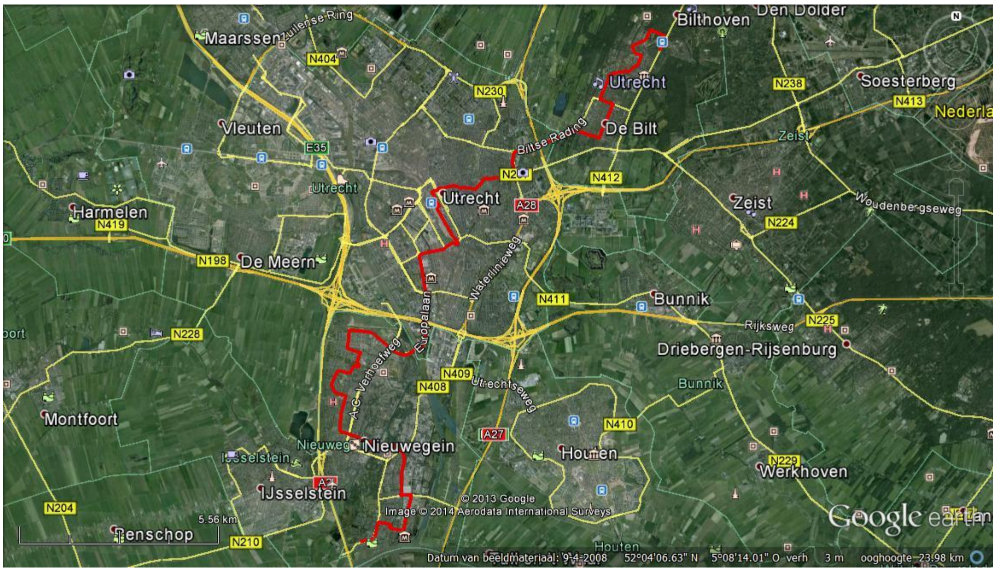

Figure 4: GPS plot of bus route 77, connecting 'Nieuwegein' and 'Bilthoven' while crossing the city center of Utrecht.

2.4.1.2 Route 8

As can be seen in Figure 5, 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 is one of the busiest Qbuzz routes passing a number of air-quality-critical locations in Utrecht. In February, it was driven forth and back and forth once more in the afternoon of the Utrecht testing day. In June, it was driven vice versa once in the afternoon of each testing day.

Figure 5: GPS plot of bus route 8, an urban bus route leading from the suburb ‘Oudwijk’ to the suburb ‘Lunetten’.

2.4.2 Vehicle operation

The Mercedes Citaro was driven by a TNO certified test driver who operated the bus in a moderate driving style.

In February, the Mercedes Citaro 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.

The June measurements comprised four testing days of city bus operation. As bus routes are operated by many different bus drivers, trailing other buses during the four testing days would be likely to introduce a considerable variation in driving behavior. Driving behavior in turn has a significant effect on vehicle emissions. The goal of the June measurements was to assess the effects of changed vehicle settings on the NO_x emissions of the vehicle. Driving behavior as an additional variable would make it impossible to distinguish driving behavior effects from effects of changed vehicle settings.

Therefore, in order to be able to draw conclusions on the effects of changed vehicle settings, a professional Qbuzz bus driver instructor accompanied TNO’s test driver on all June testing days, giving the TNO test driver bus route directions. The test bus also halted at each bus stop when in the city center, and halted at every other bus stop when outside the city center. The test bus did not board passengers.

During all test trips, accessories such as air conditioning and the like were switched off.

This way of operating the vehicle during the tests makes sure the real-world city bus operation is copied as much as possible, while at the same time the test results can be well compared.

While testing in the real world, a number of parameters obviously cannot be controlled. Traffic density of course differs from day to day and week to week and varies during one day as well. In order to take this variable out of the equation as much as possible, each testing day was driven according to a fixed day schedule whenever possible. Moreover, certain events like for instance an open bridge, which happened during one of the testing days, cannot be avoided.

2.4.3 *Vehicle payload*

Table 3 specifies the maximum and empty vehicle mass and, derived from that, the vehicle's maximum payload of 7,245 kg.

Table 3: 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

Based on a combination of 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] a payload at 41% of the maximum payload was selected. 41% of the maximum payload corresponds to 3,100 kg payload and a subsequent total vehicle weight of 14,460 kg.

2.5 Tested options for optimizing NO_x emissions

During the measurements in February, the bus did not exceed the Euro VI in-service conformity limits. This means that Mercedes Citaro fulfils the requirements laid down in the Euro VI emission regulation. The measurements did however also show the vehicle's NO_x emissions were sensitive to driving conditions with low average engine load. Those conditions are typical for the demanding city-center bus route 8.

The Dutch Ministry of Infrastructure and the Environment asked Daimler and TNO to together review the test results and to investigate if the NO_x emissions under heavy urban conditions can be improved. Daimler provided its full cooperation and two possible solutions were soon identified:

1 **Adapted gear shifting strategy ('setting A'):** An adaptation of the gear shifting programme of the vehicle, aiming to increase the exhaust gas temperatures under low-load conditions. This would lead to a better functioning SCR catalyst, resulting in lower NO_x emissions. The higher exhaust gas

temperatures are realized by letting the engine run at higher engine speeds. This inevitably causes a higher fuel consumption. In other words: further decreasing the NO_x emissions of the vehicle would come at the penalty of higher CO_2 emissions. The vehicle was tested with this setting on one of the June testing days, as shown in Table 1.

2 **Adapted fuel injection (‘setting B’):** An adaptation of the engine’s fuel injection strategy. This option also aims to increase the exhaust gas temperatures under low-load conditions resulting in the SCR to function better. In this case, the higher exhaust gas temperatures are realized by ‘post’-injecting extra fuel, which also increases fuel consumption. Thus, here also, a CO_2 penalty is expected. Moreover, according to the Type Approval legislation, changing the fuel injection strategy is a change in the vehicle configuration. Applying this option therefore, would require a new Type Approval procedure. The vehicle was tested with this setting on one of the June testing days.

2.6 Data processing and evaluation methods

Before conclusion can be drawn, the output of the PEMS equipment needs to be processed and analyzed. This section briefly describes how this is done for NO_x emissions in section 2.6.1 and for PM emissions in 2.6.2.

2.6.1 Processing and evaluating NO_x emissions

2.6.1.1 Method used for in-service conformity

For assessing if the vehicle complies with the European emission legislation, 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. This means that the CF limit is 1.5.

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>.

2.6.1.2 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.

2.6.2 Processing and evaluating PM emissions

Until recently systems for real-world measurement of PM emissions have not been available (also refer to section 2.3). Furthermore, in-service conformity legislation which would allow PM emission testing with PEMS is under development but has not yet been established. It is expected however that this will be part of the next stages of Euro VI. In that case, legislation will also prescribe the methods manufacturers should use for measuring PM emissions in their Type Approval testing procedures.

For now, this means that in measuring and evaluating the PM emissions of the Mercedes Citaro, no judgment can be made on whether the vehicle fulfils Euro VI legislation. The PM emission results will therefore only be expressed only in mg/km.

On three of the testing days, particle mass (PM) was measured; on the last testing day the particle numbers (PN) were measured (Table 1). This was done as PM and PN cannot be measured simultaneously.

3 Test results

This chapter starts with an overview of the CO_2, NO_x and PM emissions per test trip in section 3.1. Section 0 then deals with the reproducibility of real-world test trips such as bus routes. Sections 0, 3.4 and 0 respectively discuss the CO_2, NO_x and PM emissions in detail and on a graphical basis.

3.1 CO_2, NO_x and PM emissions over all test trips

Table 4 shows the results of all measurements performed. The results are grouped by type of test trip. Based on this table, the next sections will mainly focus on the emission test results on route 77 and route 8 and will, in a more graphical sense, further elaborate on them. The emissions measured on the Euro VI trip and the TNO reference trip are given for reference purposes.

Table 4: Results of the February and June measurements performed on the Mercedes Citaro.

date	test trip	setting	CO_2	NO_x	NO_2	NO_x/CO_2	NO_x Conformity Factor CF [-]	PM
			[g/km]	[g/km]	[g/km]	[g/kg]	[-]	[mg/km]
6 February 2014	Euro VI	standard	915	0,41	0,08	0,45	1,01[3]	-
6 February 2014	TNO reference	standard	817	0,21	0,04	0,26	-	-
5 February 2014	route 77	standard	1224	1,65	0,60	1,35	-	-
17 June 2014	route 77	standard	979	1,67	0,45	1,70	-	5,80
18 June 2014	route 77	setting A	1055	1,35	0,20	1,28	-	3,30[1]
19 June 2014	route 77	setting B	959	0,66	0,04	0,68	-	2,50[1]
20 June 2014	route 77	standard	941	1,38	0,04	1,46	-	-
5 February 2014	route 8	standard	1371	4,02	1,14	2,93	-	-
17 June 2014	route 8	standard	1180	1,78	0,28	1,51	-	14,80[2]
18 June 2014	route 8	setting A	1271	2,89	0,52	2,27	-	3,30[1]
19 June 2014	route 8	setting B	1223	0,77	0,01	0,63	-	2,50[1]
20 June 2014	route 8	standard	1095	2,28	0,08	2,08	-	-

[1] in the setting A measurement and the setting B measurement, the PM emissions over route 8 and route 77 were summed
[2] considered as outlier caused by the variance in the measurement equipment that measures PM
[3] the conformity factor limit is 1,5

3.2 Real-world test trips are difficult to reproduce

Reproducing route 77 and route 8 in the real-world tests has proven to be difficult, as can be seen when comparing the CO_2 emissions on those routes in Table 4. On both routes, the average g/km CO_2 emissions varies significantly between the different executed trips. The average CO_2 emissions on a trip are a good indicator of reproducibility, as it is a measure for the amount of fuel consumed. Significantly varying CO_2 emissions on one specific test trip indicate that the conditions must have varied, as the distance driven is largely the same.

Looking at the average speed on every test trip reconfirms the non-reproducing character of the bus routes. The average speed over the test trips is not included in Table 4, but shown in Figure 6.

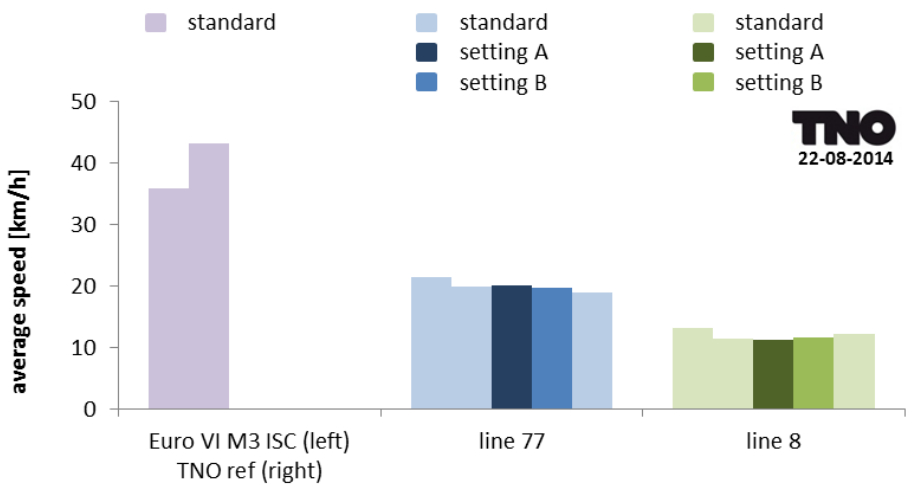

Figure 6: Average speed during the different tests. The measurements of the Euro VI M3 In-Service Conformity trip, the TNO reference trip and the first standard trips for line 77 and line 8 were performed in February 2014, the other measurements in June 2014.

As said in section 2.4.2 this in part is inherent to testing on the public road where not all variables influencing the vehicle's emissions can be controlled. It does however show that urban driving poses vehicles with large circumstantial variations, which also makes a direct comparison of the test results more difficult.

3.3 CO_2 emission tends to increase when alternative settings are applied

Figure 7 shows the CO_2 emissions on all test trips performed.

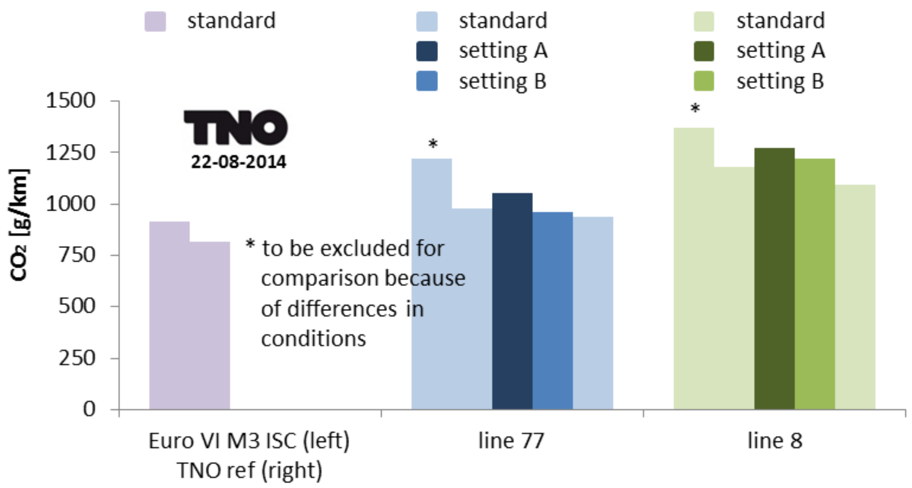

Figure 7: CO_2 emission results over the different trips. The measurements of the Euro VI M3 ISC trip, the TNO reference trip and the first standard trips for line 77 and line 8 were performed in February 2014, the other measurements in June 2014. For comparison the February measurements should be excluded, because the environmental conditions and the measurement equipment were both different, which significantly influences the results.

The following observations can be made:

1 **Different PEMS systems may output different CO_2 emissions.** The bus was tested in its standard settings three times: once in February and twice in June. The CO_2 emissions of the two June measurements in standard vehicle setting are approximately comparable. Comparing the standard setting CO_2 emissions measured in June with those measured in February reveals an approximate 10% difference. As stated in section 2.3, for the two measurement series different PEMS systems were used. This is likely to be the main reason for the difference between the CO_2 emissions obtained during February and June. Also the reproducibility of the CO_2 emission results with PEMS typically lies around 10%, even when using the same equipment For other emission components this effect is likely to be lower to negligible.

2 **Seasonal effects influence the CO_2 emissions of the vehicle.** The difference between the February and June measurement results can partially also be explained by seasonal effects: in February, outside temperatures were around 5-10 degrees Celsius whereas in June temperatures were more in the range of 15-20 degrees Celsius. Also, in June, the traffic conditions were a little bit milder than in February. This combined would partially explain the higher CO_2 emissions in February.

3 **Lower average speeds increase the kilometer specific CO_2 emissions of the vehicle.** CO_2 emissions on route 77 and route 8 are higher than on the Euro VI and the TNO reference trips. This is due to the lower average velocity on route 77 and route 8, when compared to the Euro VI and TNO reference trips. The same goes when comparing route 8 and route 77: CO_2 emissions on

route 8 are high than those of route 77, caused by the low average speed on route 8.

4 **CO_2 emissions seem to increase when alternative settings are applied.** Comparing the CO_2 emissions of the alternative settings and the standard vehicle settings on route 8 and route 77 seems to indicate that setting A gives rise to a higher CO_2 emission when compared to the standard vehicle settings. For setting B on route 77 the CO_2 emission is equal to that of the standard vehicle setting; on route 8 it is a little higher. The differences fall within the uncertainty margins however, so no solid conclusions can be drawn on the effect of setting B on the CO_2 emissions. However, given the strategy of both setting A and B, as explained in section 2.5, an increase in CO_2 emission was expected.

3.4 NO_x emissions are low but show some variations

Figure 8 shows the NO_x emissions on all test trips performed.

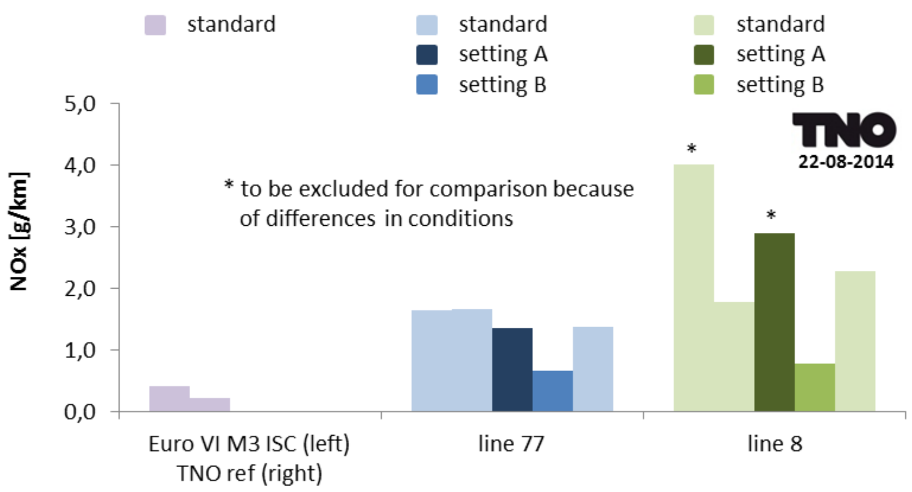

Figure 8: NO_x emission results over the different trips. The measurements of the Euro VI M3 ISC trip, the TNO reference trip and the first standard trips for line 77 and line 8 were performed in February 2014, the other measurements in June 2014. For direct comparison, the 1st standard test and setting A test on line 8 are excluded, as the differences in external and traffic conditions have a very high influence, as further elaborated below.

The following observations can be made:

1 **The NO_x emissions of the Mercedes Citaro are very sensitive to driving conditions with low average engine load.** The NO_x emissions of the Mercedes Citaro are very low on the Euro VI trip and the TNO reference trip, and at the same level as those of other Euro VI heavy-duty vehicles. Those test trips contain large shares of high-speed segments, leading to high or higher engine loads with accordingly higher exhaust gas temperatures and, subsequently, a well-functioning SCR. NO_x emissions in urban operation, i.e. on route 77 and route 8, reach values that are approximately up to 8 times higher than those in the Euro VI trip and the TNO reference trip. Figure 8 clearly shows the NO_x emissions are highest for the most demanding bus route: route 8. In other words: driving the vehicle at low payload or at low speeds has a

significant adverse effect on this vehicle's NO_x emissions while the NO_x emissions are overall on a low level.

2 **NO_x emissions on route 77 reproduce well and setting B has a positive effect on route 77 NO_x emissions.** For setting A, an effect on the NO_x emissions could not be measured.

3 Comparing NO_x emissions of the different test drives on route 8 reconfirms the finding that the Mercedes Citaro shows varying emissions at low engine loads. **Setting B considerably decreases the NO_x emissions** on route 8. The data and the manually observed traffic and external conditions clearly indicate that the test conditions with setting A on route 8 differ too much from those during the other route 8 tests performed in June. Therefore the setting A test results on line 8 are excluded for comparison and lower NO_x emissions on route 8 due to Setting A cannot be confirmed.

Figure 9 shows the NO_2 emissions on all test trips performed. The Citaro's NO_2 emissions and NO_2 fractions are very low. Further, the conclusions regarding NO_x emissions therefore can be equally drawn for NO_2 emissions.

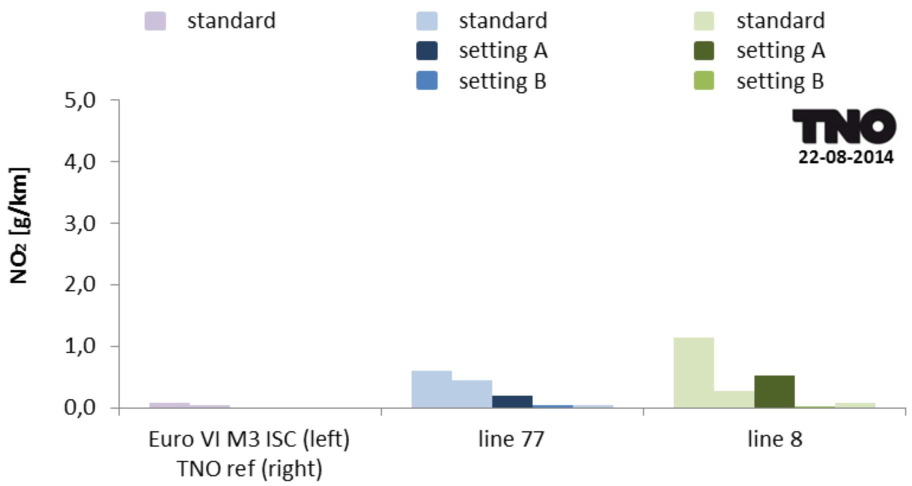

Figure 9: NO_2 emission results over the different trips. The measurements of the Euro VI M3 ISC trip, the TNO reference trip and the first standard trips for line 77 and line 8 were performed in February 2014, the other measurements in June 2014. For direct comparison, the 1st standard test and setting A test on line 8 are excluded, as the differences in external and traffic conditions have a very high influence.

3.5 PM emissions are very low

Figure 10 shows the PM emissions for all test trips on which PM measurements were performed. As stated in section 2.3, the PM measurements were performed using experimental measurement equipment. As procedures for measuring PM emissions using PEMS equipment have not yet been established, this assessment should be regarded as indicative. The PM measurement on the Mercedes Citaro is one of the first real-world assessment of the emission of PM of a Euro VI vehicle.

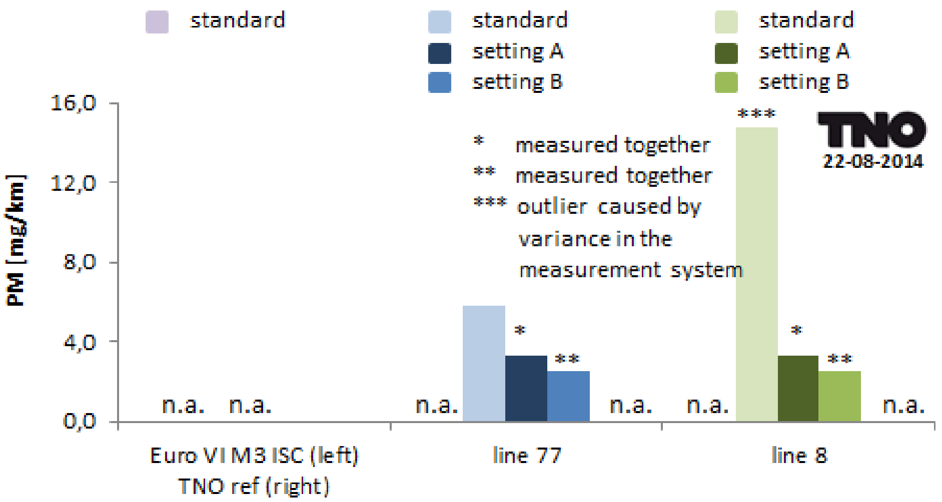

Figure 10: PM emission results over the different trips measured with experimental measurement equipment. For the measurements performed in February no results are available as no PM measurement equipment was installed at that time. The measurements of route 77 and route 8 were combined for the measurements with setting A and setting B to improve accuracy, as the emission levels are very low and almost undetectable. The first standard measurement on route 8 is considered as outlier caused the by the variance in the measurement system.

As Table 1 shows, the June testing programme contained four days of PM (particle matter) measurements. On three of those days, particle mass (PM) was measured; on the last testing day the particle numbers (PN) were measured.

The PN measurements results revealed no valid data. The number of particles is too low to enable assessment of the measurement data, which, in fact is sufficient evidence for concluding that the Mercedes Citaro emits very low particulate numbers.

The measurements of particle mass confirm this finding: the measured PM emissions are very low, ranging from approximately 2 to 7 mg/km with one outlier of approximately 15 mg/km on route 8 which cannot be explained by events that occurred during the measurement. The measurement system has a high variance, certainly at these low emission levels, which explains this outlier. The average PM emission of the vehicle lies around 6 mg/km, which is considered to be very low.

All in all, accurately measuring PM and PN emissions is not easy: it's precisely the particulate emission that cause the results to become imprecise. Except from concluding the emissions are very low, it is hard to put an exact number on them.

4 Discussion on test results

This chapter puts the emission results of the Mercedes Citaro in perspective. It does so by comparing the Euro VI Mercedes Citaro with other vehicles in section 4.1. Section 4.2 shows the results of air quality measurements in Utrecht. Section 4.3 makes a note on how in earlier years Euro VI bus NO_x emission factors were estimated for future air quality projections. Finally, sections 4.4 and 4.5 show that further improvement of the NO_x emissions is possible and that although Euro VI has significantly improved the emission performance of heavy-duty vehicles, the emission legislation still leaves room for improvement for urban area operation.

4.1 Euro VI buses substantially reduce NO_x and PM emissions of Utrecht bus fleet

4.1.1 Comparing NO_x and NO_2 emissions of several vehicles

To assess the effect of the introduction of the Mercedes Citaro on the NO_x emissions of the Utrecht bus fleet, Figure 11 compares the NO_x emissions of the Citaro with those of several other vehicles:

1. Euro III buses that are replaced by the Euro VI Mercedes Citaro city buses (magenta);
2. a Euro V EEV city bus TNO tested in 2010 and which is still part of the Utrecht bus fleet (blue);
3. the Euro VI Mercedes Citaro part of this testing programme (green – all Euro VI vehicles in Figure 11 are printed in green);
4. another Euro VI city bus TNO tested in 2014 which was a demonstration vehicle retrieved directly from the manufacturer and not part of a city bus fleet (green);
5. the average of 6 Euro VI long-haulage trucks TNO tested in 2012-2014 (green).

As can be seen, the replacement of Euro III buses with Euro VI buses substantially reduces the NO_x emissions of the Utrecht bus fleet; a Euro VI Mercedes Citaro emits approximately 85% less NO_x than an average Euro III city bus.

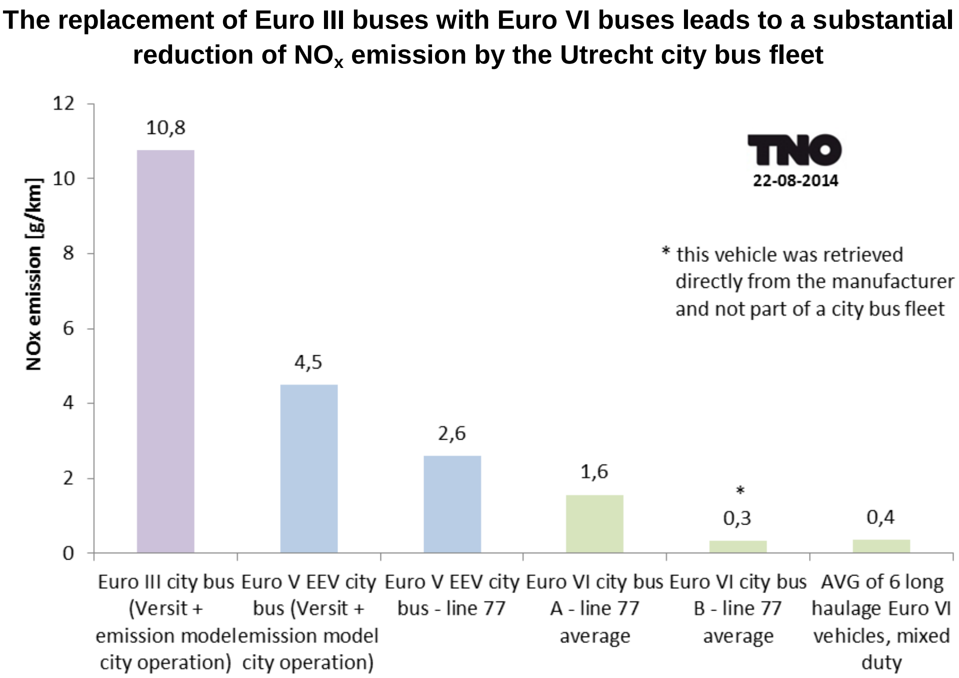

Figure 11: Comparison of the NO_x emissions of the Mercedes Citaro on line 77 (indicated as bus A) with the Euro III city buses it replaces (the emissions were not measured, the Versit+ emission factor [Hensema, 2013] for this bus is used for comparison), the average for Euro V EEV city buses (Versit+ emission factor), the Euro V EEV city bus that is still in the Utrecht bus fleet, another type Euro VI city bus driven in Utrecht on line 77 and the average of 6 long-haulage Euro VI vehicles during mixed operation.

In 2010, TNO tested a Euro V EEV city bus, which currently is still part of the Utrecht bus fleet. The bus was tested, amongst others, on route 77 and proved to be one of the cleanest Euro V and EEV diesel vehicles measured by TNO. Comparing the NO_x emissions of this Euro V EEV bus with those of the Euro VI Mercedes Citaro shows that the NO_x emissions of the Mercedes Citaro are approximately 38% lower. Replacement of these Euro V EEV city buses would therefore further decrease the NO_x emissions.

In 2013 and 2014, TNO tested a number of long-haulage trucks under driving conditions representative for these vehicles. Comparison of the NO_x emissions of the bus on route 77 with the long-haulage trucks is difficult, as the driving conditions are different. For a fair comparison, one could best look at the Citaro results on the TNO reference trip, during which the bus emits 0,21 g/km NO_x (chapter 3). In this comparison the bus performs slightly better than the average long-haulage trucks measured. It is likely that, if the long-haulage trucks were operated under urban conditions like route 8 or route 77 the vehicles would have emission behavior that is comparable to that of the Mercedes Citaro. This was recently confirmed by measurement results on a city distribution truck under representative conditions, which are not reported here [Vermeulen, 2014].

In 2014, TNO also tested a second Euro VI bus. This bus has a very stable and low emission performance during varying driving conditions. It has to be remarked that this bus was a demonstration vehicle retrieved directly from the manufacturer and not part of a city bus fleet and thus not in operation. Still, this bus shows the further

NO_x emission potential of Euro VI vehicles, on which sections 4.4 and 4.5 further elaborate.

As the direct NO_2 emission is important for the contribution to local air quality, a comparison of the NO_2 emission with other vehicles also has been made in Figure 12. As can be seen from this figure, the direct NO_2 emission increased from Euro III to Euro V EEV buses, while the total NO_x emission decreased. In other words, the portion of NO_2 in the NO_x emission increased. With the step from Euro V to Euro VI, in general the direct NO_2 emission decreases. In general, the direct NO_2 emission of Euro VI vehicles is very low and comparable between the different vehicles.

As can be seen, the replacement of Euro III buses with Euro VI buses reduces the direct NO_2 emissions of the Utrecht bus fleet; a Euro VI Mercedes Citaro emits approximately 50% less NO_2 than an average Euro III city bus. Comparing the Euro V EEV city bus, which currently is still part of the Utrecht bus fleet and tested by TNO in 2010, the NO_2 emissions of the Mercedes Citaro are approximately 69% lower. Replacement of these Euro V EEV city buses would therefore further decrease the NO_2 emissions and improve the local air quality.

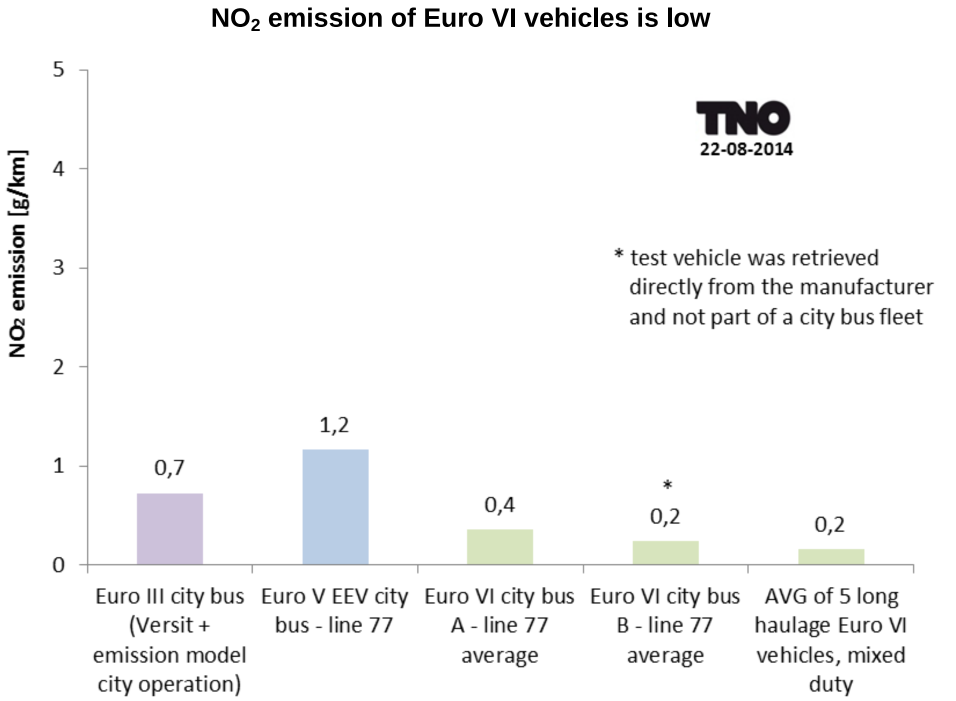

Figure 12: Comparison of the NO_2 emissions of the Mercedes Citaro on line 77 (indicated as bus A) with the Euro III city buses it replaces (the emissions were not measured, the Versit+ emission factor [Hensema, 2013] for this bus is used for comparison), the Euro V EEV city bus that is still in the Utrecht bus fleet, another type Euro VI city bus driven in Utrecht on line 77 and the average of 6 long-haulage Euro VI vehicles during mixed operation.

4.1.2 Comparing PM emissions of several vehicles

Figure 13 shows the PM emissions of several generations of city buses. Compared to the Euro III city buses (magenta) the Euro VI Mercedes Citaro emits around 95% less PM.

Figure 13 also shows the effect of the installment of a Diesel Particulate Filter on an Euro V EEV city bus, which about more than halves PM emissions.

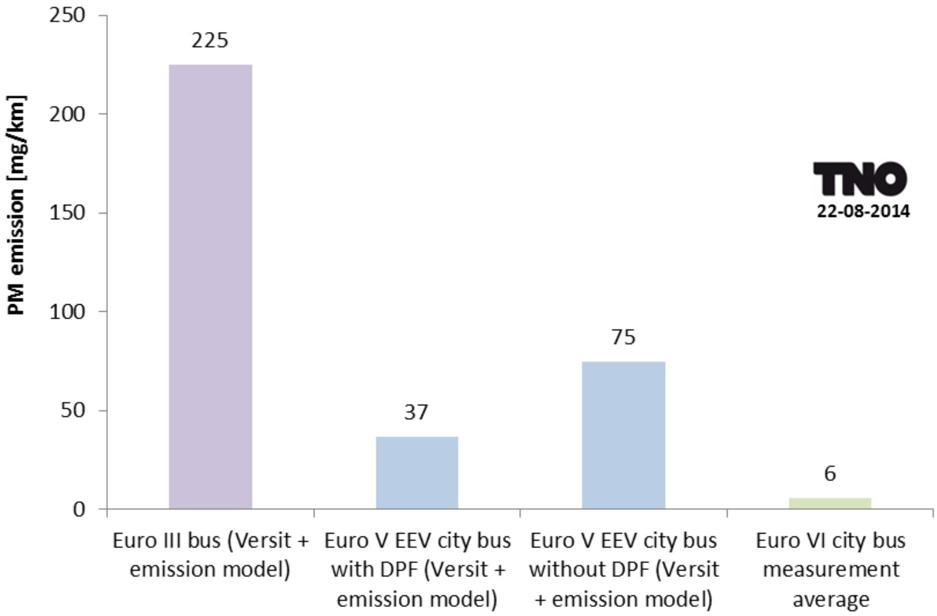

Figure 13: Comparison of the average PM emissions of the Mercedes Citaro with the emission factors for city operation, calculated by the Versit+ emission model [Hensema, 2013], for a Euro III city buses and a Euro V EEV city bus with and without Diesel Particulate Filter (DPF).

4.2 Euro VI buses have a positive effect on the NO_2 concentration in Utrecht

Since 2011 the city of Utrecht monitors the NO_2 concentration on several locations in the inner city. The uncalibrated results are publically available on the website of the city of Utrecht [Utrecht, 2014].

The latest results show that the NO_2 concentration in the city of Utrecht tends to drop over the long term. At measurement locations along intensively-used city bus lines, the NO_2 concentration seems to drop quicker when compared to concentrations at locations where no or a just relatively small number of city buses pass. More specifically, since the introduction of Euro VI buses in the city bus fleet of Utrecht at the end of 2013, the contribution of traffic to the NO_2 concentration along intensively-used bus routes has decreased substantially, as shown in Figure 14.

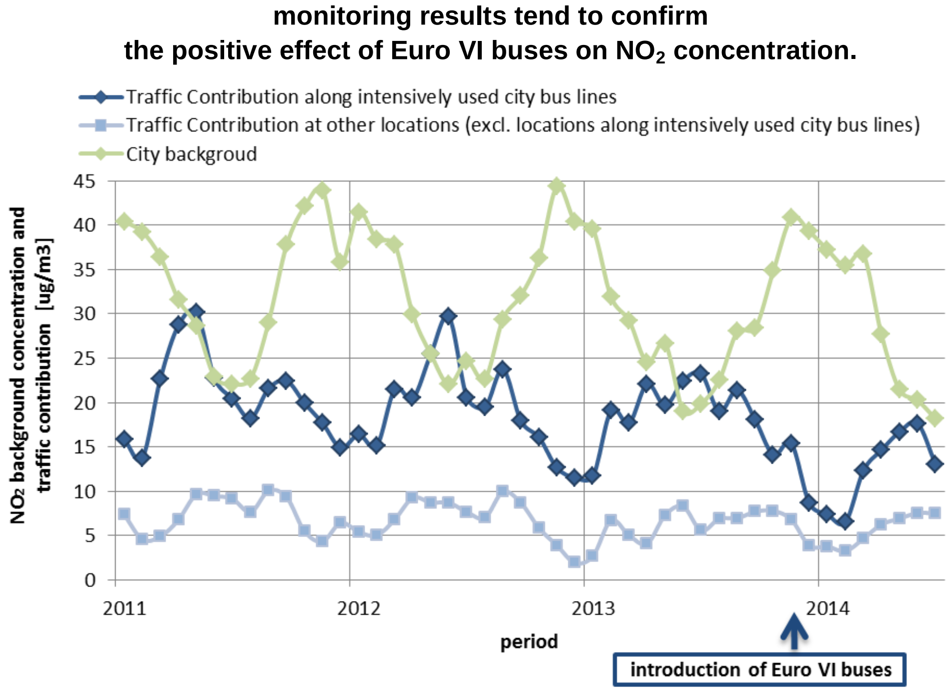

Figure 14: Uncalibrated NO_2 monitoring results in the city of Utrecht: background concentration and traffic contribution, source [Utrecht, 2014]

Although longer periods of monitoring are necessary to draw safe conclusions, the monitoring results tend to confirm that the introduction of the Mercedes Citaro Euro VI buses in the public transport system of Utrecht has a positive effect on urban air quality when it comes to NO_2 concentration.

4.3 Euro VI city buses in Utrecht meet forecasted NO_x and NO_2 emission levels

In order to make projections on future air quality in Utrecht, TNO in 2012 provided the city of Utrecht with a forecast on the emission factors for Euro VI diesel buses. These emission factors were input for the effect-assessment of different measures to be taken to improve the air quality in the city of Utrecht [Utrecht, 2013]. The introduction of Euro VI buses was one of the possible measures at hand at that time.

The preliminary estimates were based on the Euro VI emission limits, results of PEMS measurements TNO had already performed on Euro VI long-haulage trucks available at that time as well as on expert opinion. The preliminary estimates were presented for three scenarios: high, average and low.

The driving conditions of the different test trips described in this report vary from mild to severe. A comparison between the preliminary estimates of 2012 and the current 2014 test results can be made by:

- comparing the low scenario estimate of 2012 with 2014 test results of trips with mild rural and urban driving conditions, where average driving speeds are around 15-25 km/h for urban driving and typically higher than 25 km/h for mild rural driving, i.e. the TNO Reference trip and the Euro VI M3 trip;

- comparing the average scenario estimate of 2012 with the 2014 test results of an average trip with combined mild rural and urban and severe urban conditions, i.e. the average of all route 77 tests with the standard setting, where in addition a portion of severe urban driving is present with typical average speeds are 10-15 km/h and;
- comparing the high scenario estimate of 2012 with the 2014 test results of trips with only severe urban driving conditions (average of all route 8 tests with the standard setting).

Euro VI city buses in Utrecht meet the expected NO_x and NO_2 emission levels

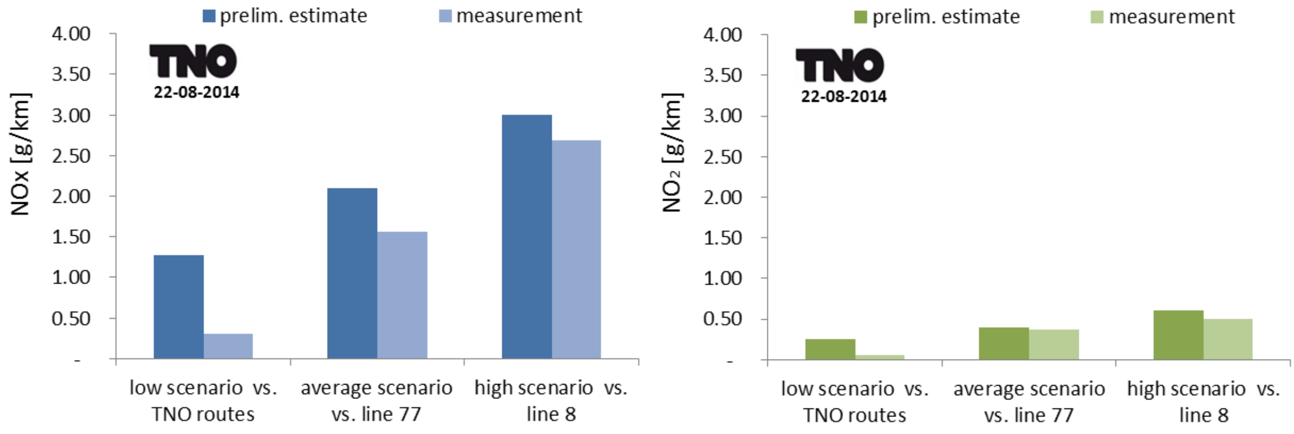

Figure 15: Comparison of the NO_x (left) and NO_2 (right) emission test results with the preliminary estimated emission level scenarios that were input for the projections on future air quality in Utrecht [Utrecht, 2013]

Figure 15 shows these comparisons. The final air quality projections were calculated with the preliminary estimates for the average scenario. Therefore a comparison of the average scenario with the average of all test results with standard settings could also be considered as valid, which is given in Figure 16.

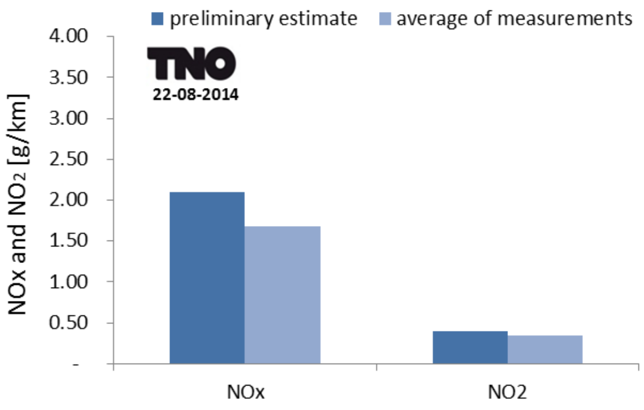

Figure 16: Comparison of the average NO_x (left) and NO_2 (right) emission test results with the preliminary estimated average emission level scenario that was input for the projections on future air quality in Utrecht [Utrecht, 2013]

From these two comparisons, as depicted in Figure 15 and Figure 16, it can be concluded that the NO_x and NO_2 emissions of the current Euro VI buses in the city of Utrecht bus fleet meet the expected emission levels of the 2012 preliminary estimates. Therefore the introduction of Euro VI city buses in the public transport system of Utrecht proves to be minimally as effective as forecasted in improving the air quality.

4.4 Further reduction of NO_x emissions is possible, but comes at a price

As noted in section 3.4 one of the alternative settings, i.e. setting B, was found to further decrease NO_x emissions of the Mercedes Citaro, likely with an increase in fuel consumption and CO_2 emission as a direct result. Also measurements with a second Euro VI bus demonstrate that further reduction of the NO_x emissions under severe urban conditions is possible.

As said earlier, real-world city bus operation faces vehicle manufacturers with challenges in finding a balance between low pollutant emissions on the one hand and low CO_2 emission fuel consumption on the other. The Euro VI Mercedes Citaro is one of the most fuel efficient vehicles in the field [IBC, 2014], meaning its CO_2 emissions and fuel consumption belong to the lowest in the field.

All in all it can be concluded that there is a balance between low NO_x emissions and low CO_2 emissions and fuel consumption, meaning that further reduction of the NO_x emissions is possible. The upcoming challenge for manufacturers is to limit the resulting increase in CO_2 emission and fuel consumption.

4.5 Euro VI legislation does not assure low NO_x emission under urban driving conditions

The Euro VI Mercedes Citaro fulfils the requirements laid down in the Euro VI emission regulation. That means it complies with the Euro VI in-service conformity limits during a trip that fulfils the requirements that are prescribed in the Euro-VI legislation for this vehicle type.

In severe urban operation however, NO_x emissions of the vehicle tend to increase. Although these are the circumstances that are utterly characteristic for city bus operation, it is exactly those heavy-urban operating conditions that are not explicitly regulated in the Euro VI emission legislation.

In other words, test conditions within the Euro VI legislation sufficiently cover the operating conditions of long-haulage trucks but are not capable of guaranteeing clean city-operated vehicles.

As a result, not all vehicles fulfilling the Euro VI emission requirements that are used in an urban environment, have as-low tail-pipe emission of NO_x under all representative circumstances. This was recently confirmed by measurements with other vehicles that were operated under urban conditions [Vermeulen, 2014].

5 Conclusions

TNO PEMS-tested the Euro VI Mercedes Citaro on real-world bus routes to establish its NO_x and PM emissions under urban conditions. Also, TNO subjected the vehicle to an in-service conformity test and tested it on TNO's reference route.

From the measurements, TNO concludes that:

1. **The Euro VI Mercedes Citaro fulfils the legislative emission requirements** laid down in the Euro VI emission legislation.
2. On average, the **NO_x emissions** of the Mercedes Citaro city buses in real operation are very low. The **NO_x emissions** of the Mercedes Citaro are however very sensitive to driving conditions with low average engine load.
3. **Further decrease of the NO_x emission** of the Citaro is considered possible in the context of future technology developments, but are likely to come with a CO_2 emission and fuel consumption penalty. Application of new technologies would require a new type approval for the vehicle and the engine.
4. Accurately measuring the **PM emissions and Particle Number emission** of the Mercedes Citaro is not easy, which is due to its very low PM emissions under all driving conditions. In fact, it is precisely the low particulate emission that cause the results to become imprecise. The PM emissions that could be established lies on average around 6 mg/km, which is considered to be very low.

For the city of Utrecht, this emission performance of the Mercedes Citaro has the following implications:

5. The **Euro VI Mercedes Citaro meets the forecasted NO_x and NO_2 emission levels** Utrecht used in its air quality projections in 2012. It is therefore safe to conclude that the introduction of Euro VI city buses in the public transport system of Utrecht is minimally as effective as forecasted in improving the air quality.
6. This is backed by the NO_2 concentration monitoring the city of Utrecht performs since 2011. Since the introduction of Euro VI buses in the public transport system of Utrecht **a clear drop in NO_2 concentration in Utrecht** is observed.
7. The **replacement of Euro III buses** with the Euro VI Mercedes Citaro's substantially reduces the PM and NO_x emissions of the Utrecht bus fleet; a Euro VI Mercedes Citaro emits approximately 95% less PM and 85% less NO_x than an average Euro III city bus.
8. **Replacing the Euro V EEV city buses** that are still part of the Utrecht bus fleet would further decrease the NO_x and PM emissions. The PM emissions are approximately 85% lower than the Euro V EEV city bus. The NO_x emissions of the Mercedes Citaro are approximately 38% lower than the NO_x emissions of the Euro V EEV city bus tested by TNO, the NO_2 emissions are approximately 69% lower. This city bus, that is still in the Utrecht city bus fleet, is compared to other vehicles one of the best performing Euro V EEV vehicles when it comes to emissions of NO_x.

As far as emission legislation is concerned, TNO concludes that:

9 The current Euro VI legislation lacks when it comes to assuring very low emission of NO_x under urban driving conditions. The measurements have clearly shown that, although a vehicle fulfils the Euro VI emission requirements, this does not mean they have a stable low NO_x emission under all representative circumstances. This was also the conclusion of other measurements TNO has performed lately. Improvement of the Euro VI legislation is possible by introducing a Real Driving Emission (RDE) test procedure for vehicles that are operated in urban areas. This faces the manufacturers with the challenge to assure a very low emission of NO_x under all circumstances with a minimal negative influence on fuel consumption and CO_2 emissions. Next to vehicle related measures, an integrated approach including for example infrastructural and logistical measures will play a large role in further reduction of fuel consumption and CO2 emission in the future.

6 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.

[Hensema, 2013] Hensema, A., Ligterink, N., Geilenkirchen, G., VERSIT+ Emissiefactoren voor Standaard rekenmethode 1 en 2 – 2013 update, juli 2013, TNO report TNO 2013 R11083.

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

[Utrecht, 2013] Gemeente Utrecht; Uitvoeringsprogramma 2013-2015, Gezonde lucht voor Utrecht, Naar een vernieuwd maatregelenpakket luchtkwaliteit; december 2013.

[Utrecht, 2014] http://www.utrechtmilieu.nl/meetnet/#data

[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.

[IBC, 2014] IBC 2014: Vergleichstest Niederflurbusse mit Euro 6-Motoren, Fachzeitschrift für Nahverkehr, Verkehrsindustrie und Stadtplanung, Nahverkehrs-praxis – Ausgabe 5-2014.

[Vermeulen, 2014] Vermeulen et al., The Netherlands In-Service Emissions Testing Programme for Heavy-Duty 2011-2013, 26 May 2014, TNO report TNO 2014 R10641 | 2.

7 Signature

Delft, 30 September 2014

Willar Vonk
Project manager

Jordy Spreen
Author