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TNO report

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On-road NO_x and CO_2 investigations of Euro 5 Light Commercial Vehicles

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Samenvatting

De uitstoot van NO_x door voertuigen draagt bij aan de concentratie van NO_2 in de lucht. Om een indruk te verkrijgen van de uitstoot van NO_x door voertuigen meet TNO in opdracht van het Ministerie van Infrastructuur en Milieu op regelmatige basis de emissies van voertuigen in de praktijk. De resultaten van deze metingen worden verwerkt in emissiefactoren, die worden gebruikt voor het modelleren van de luchtkwaliteit ten behoeve van het Nationaal Samenwerkingsprogramma Luchtkwaliteit (NSL). De aandacht gaat daarbij vooral uit naar de NO_x-praktijkemissies van voertuigen met een dieselmotor, omdat deze veel hoger zijn dan de NO_x-praktijkemissies van voertuigen met benzinemotoren.

In dit rapport wordt verslag gedaan van een meetprogramma voor screening van de NO_x-praktijkemissies van tien Euro 5 diesel bedrijfswagens. De voertuigen zijn uitgerust met mobiele emissiemeetapparatuur, het zogenaamde Smart Emission Measurement Systeem (SEMS), en getest tijdens praktijkritten op de openbare weg. Eén voertuig is bovendien onderworpen aan een meer gedetailleerd onderzoek op een rollenbank in het laboratorium.

De op de weg geteste voertuigen stoten in de praktijk gemiddeld vijf tot zes maal meer NO_x uit dan de Euro 5 limietwaarde van 280 mg/km; de NO_x-emissies van de geteste Euro 5 voertuigen variëren in de praktijk tussen de 1421 en 1670 mg/km. Deze meetresultaten zijn vergelijkbaar met resultaten van een ander Europees instituut, IIASA uit Oostenrijk, dat door middel van metingen met een zogenaamd Remote Emission Sensing (RES) meetsysteem in Zürich, Zwitserland, NO_x-praktijkemissies vond van rond de 1300 mg/km.

Het voertuig dat ook op de rollenbank in het laboratorium is getest, had tijdens een typekeuringstest een NO_x-emissie van 287 mg/km en voldeed daarmee grosso modo aan de Euro-5 NO_x-norm van 280 mg/km. Als, echter, op de rollenbank de typekeuringstest wordt uitgevoerd met een al opgewarmde motor, of als de rollenbanktest wordt uitgevoerd met een zwaardere motorbelasting, die meer lijkt op de praktijk dan tijdens de naar verhouding ‘rustige’ typekeuringstest, dan neemt de NO_x-uitstoot met een factor drie à vier toe.

Tijdens emissietesten met een vergelijkbaar voertuig op de openbare weg, waarbij het voertuig werd beladen, lag de NO_x-uitstoot een factor zes à acht hoger dan de typekeuringsnorm. Het voertuig dat op de weg is getest was iets groter en zwaarder dan het voertuig dat op de rollenbank werd getest; de motor was echter identiek. Bovendien lieten de overige negen op de weg geteste voertuigen in de praktijk ook een dergelijke hoge NO_x-uitstoot zien.

Het onderzoek aan dit voertuig bevestigt resultaten gevonden in eerdere studies: dieselauto’s kunnen in het laboratorium aan de typekeuringsnorm voldoen; in de praktijk ligt de NO_x-uitstoot vaak, echter, fors hoger. De oorzaken hiervoor zijn niet onderzocht; dit vraagt een ander type onderzoek. Wel lijkt hiermee de trend van een groeiend verschil tussen norm- en praktijkemissies te worden voortgezet.

Al jaren moet TNO concluderen dat de beoogde reducties van NO_x-emissies van dieselpersonenauto’s en dieselbestelauto’s, op basis van de aanscherping van de emissielimieten, in de praktijk niet worden gehaald. Het verschil tussen de typekeuringswaarde en de praktijk groeit.

Voorheen waren de verschillen tussen de typekeuringswaarde en de praktijk deels te verklaren uit rijgedrag en rijomstandigheden. De uitgevoerde testen laten nu echter zien dat voor rijgedrag en gevraagd motorvermogen vergelijkbaar met de typekeurtest de NO_x-emissie in de praktijk veel hoger is. Een hogere NO_x-emissie treedt bijvoorbeeld op als een typekeuringstest met een al opgewarmde motor wordt begonnen. Deze hogere uitstoot kan niet worden verklaard door het gebruik van de marges van de testmethode door fabrikanten, waardoor het hogere brandstofverbruik en de hogere emissies van CO_2 dan de norm wel kunnen worden verklaard.

De verwachting is daarom dat een aanpassing van de testcyclus, zoals de nieuwe WLTP-testprocedure, weinig soelaas biedt voor dit probleem. Het op de weg meten en monitoren van voertuigen met mobiele meetapparatuur is mogelijk een oplossing om de praktijkemissies onder controle te brengen. Het op de weg meten van emissies tijdens typekeurtests is onderdeel van de nieuwe RDE (Real Driving Emissions) wetgeving, die momenteel in Brussel wordt ontwikkeld. De Europese Commissie heeft in het vooruitzicht gesteld dat de RDE-testprocedure per 1 september 2017 voor nieuwe typen voertuigen en in 2018 voor alle nieuwe voertuigen verplicht wordt. De Europese auto-industrie heeft echter voorkeur voor invoering van RDE-wetgeving in 2020. Het is dus onwaarschijnlijk dat deze kan bijdragen aan oplossingen voor de NO_2-luchtkwaliteitsproblemen op korte termijn.

TNO heeft naar aanleiding van deze meetresultaten de emissiefactoren voor bestelwagens naar boven bijgesteld. Een emissiefactor is een op basis van meetgegevens berekende gemiddelde emissie voor de vloot en wordt gebruikt voor luchtkwaliteitsberekeningen in Nederland. Afhankelijk van de inzet van het voertuig zijn de emissiefactoren voor de NO_x-uitstoot van bestelwagens met 33% tot 85% toegenomen; de nieuwe NO_2-emissiefactoren liggen 23% tot 83% hoger. Op basis van deze meetresultaten van Euro 5 bestelwagens zijn de emissiefactoren voor Euro 6 voertuigen niet aangepast. De huidige meetresultaten geven, echter, ook aanleiding voor zorgen met betrekking tot toekomstige emissiefactoren van Euro 6 bestelwagens.

Summary

NO_x emissions of vehicles contribute to the ambient NO_2 concentration. To gain insight into those NO_x emissions, TNO, commissioned by the Dutch Ministry of Infrastructure and the Environment, regularly performs real-world emission measurements on vehicles. The measurements mainly focus on vehicles with diesel engines as their real-world NO_x emissions are higher than those of petrol engines.

This report describes real-world emission test results of ten Euro 5 compliant diesel commercial N1 class III vehicles. The vehicles were equipped with TNO's Smart Emission Measurement System and their emission performance was subsequently screened while driving representative routes on the public road. One vehicle was tested in greater detail on a chassis dynamometer in a test laboratory.

The tested vehicles showed NO_x emission levels that are five to six times higher than the type approval emission limit vale of 280 mg/km: Their average NO_x emissions ranged from 1421 to 1670 mg/km. These measurement results confirm findings in another study of another European research institute , IIASA from Austria, which found comparable real-world NO_x emissions of 1300 mg/km in a Remote Emission Sensing experiment.

The vehicle that was tested on the chassis dynamometer had a NO_x emission of 287 mg/km when subjected to a type approval test, which is near the type approval limit value of 280 mg/km. Tests on the chassis dynamometer under different conditions, e.g. with a hot engine, with a real-world road load or on a different test cycle, caused NO_x emissions that were three to four times higher than the type approval limit. Testing the same type of vehicle with an identical engine on the road at different vehicle payloads has shown NO_x emissions of 1928 mg/km to as high as 2302 mg/km; values that are approximately six to eight times higher than type approval results. The other nine light commercial vehicles tested on the road showed comparable, high real-world NO_x emissions.

These test results confirm the results of former studies: diesel vehicles comply with type approval requirements in the emission laboratory, however, real-world NO_x emissions of diesel vehicles are far higher. In this project, the causes for this difference in NO_x emissions have not been investigated as this would require another type of research. However, the results seem to indicate that the trend of a growing difference between type-approval and real-world emissions continues. This and previous studies have shown that although vehicles perform well during a type approval test, their real-world NO_x emissions generally and almost with no exception deviate substantially from the type approval limits. On top of this, the difference between real-world emissions and type approval emissions has grown over the years. In the past, this difference could be partly linked to a difference in driving behaviour and conditions between the real world and the type approval tests. Nowadays, the real-world NO_x emissions are much higher, even when a vehicle is driven under conditions that are comparable to the type approval test conditions. For example, higher NO_x emissions are observed when starting a type approval test with a hot engine.

These increased NO_x emissions cannot be explained by the utilization of test margins, as is the case for fuel consumption and CO_2 emissions whose real-world values are known to be higher than type approval values.

Therefore it is expected that a modification of the test cycle, like the World Harmonized Test Cycle (WLTP), will not solve the issue of high real-world NO_x emissions. The upcoming Real Driving Emission (RDE) legislation, which prescribes testing emissions under normal on-road driving, may be the means for closing the gap between the type-approval emission limits and the real-world values. The European Commission announced it plans to introduce RDE legislation by 1 September 2017 for new vehicle types and by 2018 for all new vehicles. Vehicle manufacturers however prefer the RDE legislation to enter into force in 2020. It is thus unlikely that it will solve the NO_2 air quality problems in a number of Dutch cities in the near future.

The new emission data stemming from this research have been used by TNO to update the current Dutch emission factors for light commercial vehicles. Except for the emission factor for congested motorway operation, NO_x emission factors increase with 33% to 85%. The NO_2 emission factors increase with 23% to 83%. Based on the results for Euro 5 light commercial vehicles presented in this report, emission factors for Euro 6 vehicles have not been adapted. Currently, it is assumed the light commercial vehicle still follow the optimistic trend in real-world emissions expected for diesel passenger cars, based on upcoming legislation. This would mean an 50% to 75% reduction from the current Euro 5 emission factors to Euro 6. The current measurements do, however, raise a concern for Euro 6 vehicles as well.

Contents

1 Introduction

1.1 Background

To minimize air pollutant emissions of light-duty vehicles, in 1992 the European Commission introduced the Euro emission standards. In the course of time, these standards have become more stringent. Currently-produced light-duty commercial vehicles of category N1 class III must comply with the Euro 5B+ standard.
The Euro 6 standard, that further limits the emissions of light-duty vehicles, will become mandatory in 2015.

The standards apply to vehicles with spark ignition engines and to vehicles with compression ignition engines and cover the following gaseous and particulate emissions:

- CO (carbon monoxide);
- THC (total hydrocarbons);
- NO_x (nitrogen oxides);
- PM (particulate mass), and;
- PN (particulate number).

As a result of the Euro emission standards, the pollutant emissions of light-duty vehicles as observed in type approval tests have been reduced significantly over the past decade. However, under real driving conditions some emissions substantially deviate from their type approval equivalents. The real driving nitrogen oxides, or NO_x, emissions of diesel vehicles are currently the largest issue with regard to pollutant emissions. As NO_x represents the sum of NO and NO_2 emitted, reducing NO_x emissions of vehicles is important in bringing down the ambient NO_2 concentration. In the Netherlands, the ambient NO_2 concentration still exceeds European limits at numerous road-side locations.

Commissioned by the Dutch Ministry of Infrastructure and the Environment, TNO regularly performs emission measurements within the “in-use compliance program for light-duty vehicles”. Whereas in the early years, i.e. in 1989 to 2000, many standard type approval tests were executed, in recent years the emphasis has shifted towards the gathering of real-world emission data on various non-standard driving cycles.

TNO has performed real-world tests on multiple Euro 4 and 5 diesel commercial vehicles over the years. However, the data was until now insufficient to determine separate emission factors for light commercial vehicles, and the emission factors were therefore based on passenger cars test data. All real-world investigations considered, urban emission factors for NO_x emissions of Euro 3, 4 and 5 diesel commercial vehicles were a lot higher than expected, as Table 1 shows. Urban emissions are of particular relevance for local air quality.

Table 1: Emission limits and real-world emission factors for N1 class III diesel commercial vehicles.

Emission standard	**Type approval emission limit NO_x [g/km]**	**Urban emission factor NO_x [g/km]**
Euro-0		0.91
Euro-1 (1994)	1.7*	1.2
Euro-2 (1997)	1.2*	1.51
Euro 3 (2001)	0.78	1.24
Euro 4 (2006)	0.39	1.43^x
Euro 5 (2010)	0.28	1.43^x
Euro 6 (2015)	0.125	0.37

*NO_x + HC, ^{x} this study

In this report the test results of ten Euro 5 diesel light commercial vehicles are discussed. Estimates based on passenger car tests for Euro 4 and 5 NO_x emission factors, used for prognoses in previous years are in between 0.65 g/km (rural) and 1.66 g/km (urban congestion).

Based on the performed emission measurements, TNO develops and annually updates vehicle emission factors that represent real-world emission data for various vehicle types and different driving conditions. Vehicle emission factors are used for emission inventory and air quality monitoring. TNO is one of the few institutes in Europe who perform independent emission tests. Dutch emission factors are based on these tests. The emission factors are one of the few independent sources of the growing difference between legislative emission limits and real-world emission performance of cars.

1.2 Aim and approach

The aim of this research is to assess the real-world emission performance of Euro 5 N1 class III diesel commercial vehicles and to provide emission factors for this category. This was done by performing emission measurements on the road with TNO’s Smart Emission Measurement System, or SEMS. Although less accurate than laboratory measurements on a chassis dynamometer or measurements with well-known Portable Emission Measurement Systems (PEMS), SEMS allows for a quick and low-cost assessment, or screening, of the emission performance of vehicles and is able to determine large deviations in emission performance. For the sizeable effects under consideration, with increases in emission factors up to 60% and variations between vehicles of 20%, the accuracy of the SEMS equipment suffices.

This study involves SEMS measurements on ten Euro 5 light commercial vehicles. This relatively large number of vehicles provides a sufficient basis to observe trends in their emission behaviour. Moreover, to validate the on-road measurements against laboratory measurements, one light commercial vehicle was tested on a chassis dynamometer as well. This vehicle was similar to one of the ten SEMS-tested vehicles, albeit that it had a slightly higher gross vehicle weight and somewhat larger dimensions. Its engine, however, was identical to the similar vehicle that was tested on the road using SEMS.

The study does not analyse the causes for possible deviations between real-world emissions and type approval emissions.

In order to obtain a more comprehensive understanding of the emission performance, the measurements are evaluated and compared against the available public data.

1.3 Structure of the report

Chapter 2 first describes the characteristics of the commercial vehicle fleet. Then, in Chapter 3, the tested vehicles and the test methodologies are described. A short literature review on the emissions of light-duty commercial vehicles is reported in Chapter 4. Chapter 5 gives an overview of the test results, which are the topic of the discussion in Chapter 6. Finally, Chapter 7 presents the conclusions.

2 Light Commercial Vehicles – definition and usage

Light Commercial Vehicles, also referred to as LCV's or vans, are light-duty goods vehicles below a gross vehicle weight (GVW) of 3,500 kg. In the European emission legislation they are designated "N1" (Table 2). This does not fully correspond with the Dutch definition of "bedrijfswagens", however, "bedrijfswagens" cover a similar group. LCV's exist in a variety of weight classes and cabins and chassis types.

Table 2: The vehicle categories designated in emission legislation. This report deals with N1 Class III vehicles mainly. Reference mass is typically 100 kg above the kerb weight.

Category	Description	Category	Gross Vehicle Weight	Subcategory
Passenger cars and buses				Persons
M	Passenger transport with 4 wheels or more	M1	≤3500 kg	Up to 9
		M2	≤5000 kg	10 or more
		M3	>5000 kg	
Vans and trucks				Reference mass
N	Goods transport with 4 wheels or more	**N1**	**≤3500 kg**	Class I: 1305 kg
				Class II: 1305 – 1760 kg
				Class III: > 1760 kg
		N2	3500 - 12000 kg	NA
		N3	> 12000 kg	

The three weight classes I, II, and III have different emission standards and introduction dates of new legislation. The heavy vans, class III, have a reference mass above 1760 kg. Class III is the majority of the vans sold in the Netherlands. Light vans, class I and class II are more alike the diesel passenger cars, with similar weight, size, and engines. However, in almost all cases the fuel is diesel, with only a small portion of the smaller vans on petrol, LPG and CNG fuel. The number of light-duty commercial vehicles (LCV), or vans, has grown in the last decades. Only in recent years the numbers have levelled off to a stable fraction of the light-duty fleet. Combined with the annual mileage, which is lower than that of diesel passenger cars, vans travel about 17 billion kilometres annually in the Netherlands, compared to 100 billion kilometres travelled with Dutch passenger cars. This is quite a high fraction, which is probably related to the tax benefits for vans in business use.

Consequently, on urban streets the average fraction of LCV's of the total light-duty fleet[1] is 15%, as used in the national emission factors. This varies greatly from city to city and with the time of the day. Even between one location in a city and another large variations exist. However, compared to passengers cars, the vans are relatively new, as Figure 1 shows.

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[1] Light-duty vehicles: all vehicles up to 3,500 kg gross vehicle weight (GVW).

The relevance of LCV’s for the pollutant emissions is threefold:

1. Most of these vehicles are diesel-fuelled;
2. The emission legislation of heavy LCV’s lags one year behind the emission legislation of passenger cars, and;
3. The heavy LCV’s have less strict emission limits.

Consequently, despite their limited numbers, the LCV’s are a major contributor to the traffic-related emissions. Heavy LCV’s are particularly important, because of the later date of less strict regulation compared to passenger cars. They comprise about two-third of the total LCV sales; on the road the situation is similar.

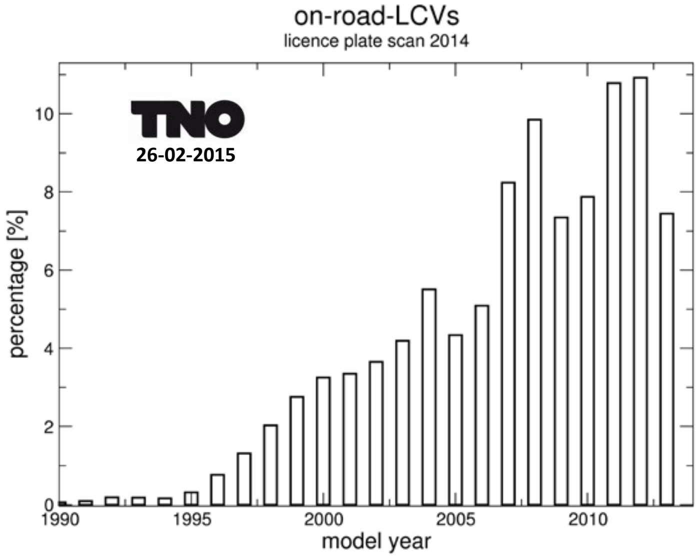

Figure 1: The age distribution of vans on urban roads in the Netherlands. More than half of the vehicles are under 8 years old and thus are Euro 4 and Euro 5 vehicles.

Small LCV’s (Class I and Class II) are a second group of LCV’s. In many cases they are sold as a passenger car, and they are not part of the LCV fleet. However, a number of them is sold as real commercial vehicles: these are typically the two-seater models with a larger cargo space, examples of which are models like the Peugeot Partner, Volkswagen Caddy, Citroen Berlingo, Renault Kangoo and the Mercedes Benz Citan. Originally designated Class I, the empty weight below 1205 kg is nowadays often exceeded, and most such vehicles are in the Class II category. Figure 2 shows the weight distribution of LCV’s, clearly indicating the three groups of LCV’s: mainly older Class I, the newer Class II and the majority in Class III.

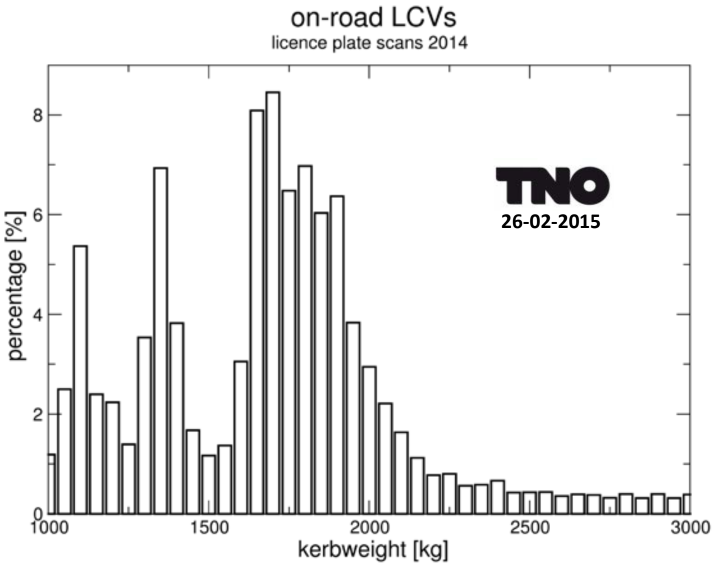

Figure 2: The distribution of kerb weight of vans on an urban road. The majority of vehicles have a kerb weight above 1660 kg and belong therefore to the Class III.

The test programme reported here focusses on modern Class III vehicles. It is expected that Class II vehicle will have similar emissions as diesel passenger cars.

3 Method

3.1 Tested vehicles

The tested vehicles are commercial Euro 5 vehicles of eight different manufacturers. Nine N1 class III vehicles are tested and one N1 class II vehicle. Only vehicles with a compression ignition engine, i.e. a diesel engine, are tested. It is expected that NO_x emissions of vehicles using spark ignition, or gasoline, engines comply with legislative limits and are well-controlled.

The 10 tested Euro 5 vehicles are provided by rental companies. In all cases the vehicles have exceeded the minimum requirement of 3.000 driven kilometres. Table 3 shows the specific data of the 10 tested vehicles.

Table 3: TNO tested diesel commercial Euro 5 vehicles.

Vehicle ID	[-]	1	2	3	4	5	6	7	8	9	10
Engine Power class	[kW]	65-70	50-55	60-65	60-65	95-100	70-75	90-95	65-70	75-80	95-100
Engine capacity class	[dm^3]	1.6	1.6	2.2	2.0	2.1	2.1	2.0	2.0	2.3	2.2
Odometer	[km]	18.500	42.000	41.700	23.400	91.000	52.200	12.800	99.000	99.000	10.000
Empty vehicle mass	[kg]	1.700	1.400	1.850	1.750	2.300	1.900	2.100	2.000	2.200	1875
Emission class	[-]	Euro 5	Euro 5	Euro 5	Euro 5	unknown	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5
Type	[-]	Van	Van	Van	Van	Van	Van	Van	Van	Van	Van
Category	[-]	N1 cl III	N1 cl II	N1 cl III	N1 cl III	N1 cl III	N1 cl III	N1 cl III	N1 cl III	N1 cl III	N1 cl III
Date of production	[-]	11-2012	03-2013	01-2013	02-2014	05-2011	02-2013	08-2014	02-2012	01-2012	04-2014
CO_2 Type approval	[g/km]	177	136	183	176	223	195	211	Not declared	Not declared	199

3.2 Test methods and test routes

On-road tests with a Smart Emissions Measurement System, or SEMS for short, are performed in various test cycles with all vehicles of Table 3. Furthermore, one chassis dynamometer program is executed with another model of ‘vehicle 5’ with the same engine.

3.2.1 Description of the Smart Emission Measurement System

SEMS contains an NO_x – O_2 sensor (Continental, UniNOx) and a thermocouple which are installed in the vehicle’s tailpipe. It measures the exhaust temperature, and the O_2 and NO_x emissions in vol% or ppm. An on-board data logger measures geographical data and the CAN data with a measuring frequency of 1 Hz. On the basis of the measured O_2 readings and the carbon and hydrogen content of the fuel, CO_2 concentrations are calculated. In former projects the accuracy and the reliability of the SEMS equipment and method has been proved [TNO2012, TNO2014].

In this project, the air mass rate of the vehicle CAN bus has been applied for calculation of the NO_x and CO_2 mass rates [mg/km].
The quality of the air mass rate signal determines the accuracy of the NO_x mass emissions. In Appendix A the calibration data of the applied NO_x sensor is reported.

Figure 3, Figure 4 and Figure 5 show an example of a SEMS-instrumented vehicle.

Figure 3: NO_x sensor and thermocouple mounted in the vehicle's tailpipe.

Figure 4: Load packages (black box) and data logger of the SEMS (blue cradle).

Figure 5: The laptop used to monitor and control the SEMS equipment.

3.2.2 Test routes

The SEMS registers real-world conditions and emissions. In order to be able to compare vehicle emissions, the TNO-designed 'reference trip' always forms part of the investigation. The reference trip consists of urban, rural and highway driving. Additionally, some other trips are driven: constant speed, urban driving and highway driving. Table 4 shows the main characteristics of the test trips. All trips are started in Helmond, the Netherlands, and are carried out with 28% and 100% payload.

Table 4: SEMS test trips.

	TNO City route Helmond	**TNO reference route**	**Constant speed route Germany**
Type	City	City, rural and highway	Highway
Cold/Hot start	Hot start	Cold and hot start	Hot start
Distance [km]	25.6 km	73.5 km	189 km
Duration [min]	57 min	89 min	119 min*
Av. speed [km/h]	32 km/h (excl. idle time)	55 km/h (excl. idle time)	93 km/h (total route)*
Load [%]	28 and 100	28 and 100	28 and 100

*Constant speed measurements are part of this route.

3.2.3 Driving styles

The test driver is given instructions for the required driving style. This can be 'economic' or 'dynamic'. Some vehicles are tested with both driving styles. After every trip the fuel tank of the vehicle is filled off at the same pump of the same filling station.

3.3 Calculation of the NO_x and CO_2 emissions

The SEMS equipment does not provide the overall flow, or absolute numbers. Therefore the air flow signal available from the On-Board Diagnostic system is used. Together with the concentrations of oxygen (O_2) and NO_x from the SEMS equipment the flow rates of CO_2 and NO_x are determined.

This procedure contains the following steps:

1. The CO_2 concentration is determined from the remaining O_2 concentration compared to the ambient O_2 concentration.
2. The total combustion gas flow (CO_2 and H_2O) is determined from the CO_2 rate.
3. The exhaust rate flow [kg/s] is constructed from the air flow signal and the combustion gas flow, ensuring the combusted oxygen is not double counted.
4. The concentrations of CO_2 and NO_x are converted to flow rates using the exhaust rate flow.

This analysis requires two input parameters:

- the C:H ratio of the fuel, which is assumed to be $CH_{1.95}$ for modern market-fuel diesel, and;
- the ambient oxygen content of air at 20.8% for on-road conditions. This is determined via calibration measurements.

The SEMS equipment is calibrated. The quality of the OBD air-flow signal is not known. Hence, independent verification with fuelling data was used to determine the quality of the air flow signal of the different vehicles. The total CO_2 between fuelling, as determined from the fuel and from the air flow signal was equal for all vehicles, within a 5% range. No systematic deviation for this 5% variation was found.

It is noted that at very low concentrations of NO_x, the SEMS sensor is less accurate for transient signals. However, in the range of concentrations of the current measurements the correlation and calibration tests carried out in the last four years provide a good evidence for accurate measurements.

4 Investigations of public data on emissions of light commercial vehicles

An external presentation of real-world emissions of Euro 5 commercial vehicles [IIASA2014] was found and investigated.

The city of Zürich in Switzerland regularly collects emission data of vehicles by means of Remote Emission Sensing or RES equipment. These RES-data are processed by the International Institute for Applied Systems Analysis (IIASA) in Austria. From discussions with Mr. Borken-Kleefeld and personal briefings it is clear that modern commercial diesel vehicles have typical emissions of 20 g NO_x/kg fuel.

In case of a vehicle CO_2 emission of 200 g/km, the NO_x emission is 1300 mg/km[2], which is approximately 60% higher than the 800 mg/km NO_x emission of diesel passenger cars.

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[2] For diesel, 1 kg of fuel burnt produces 3,15 kg CO_2.

5 Experimental results

In this chapter the test results of the emission measurements of TNO are shown.

5.1 TNO SEMS test results of 10 Euro 5 commercial vehicles

Figure 6 and Table 5 show the NO_x emission test results of the on-road test trips of 10 Euro 5 commercial vehicles. In the three trips with two different payloads the average NO_x emissions range from 1421 – 1670 mg/km. These emission levels are 5-6 times higher than the type approval emission limit vale of 280 mg/km and are in line with the Zürich test results described in chapter 4. Vehicle 2 has relatively low NO_x emissions, which is mainly due to the fact that it is an N1 class II vehicle with a lower weight than the nine N1 class III vehicles. An increase of the payload from 28 to 100% in city and reference trips results in an average increase of NO_x emissions of 11-15%.

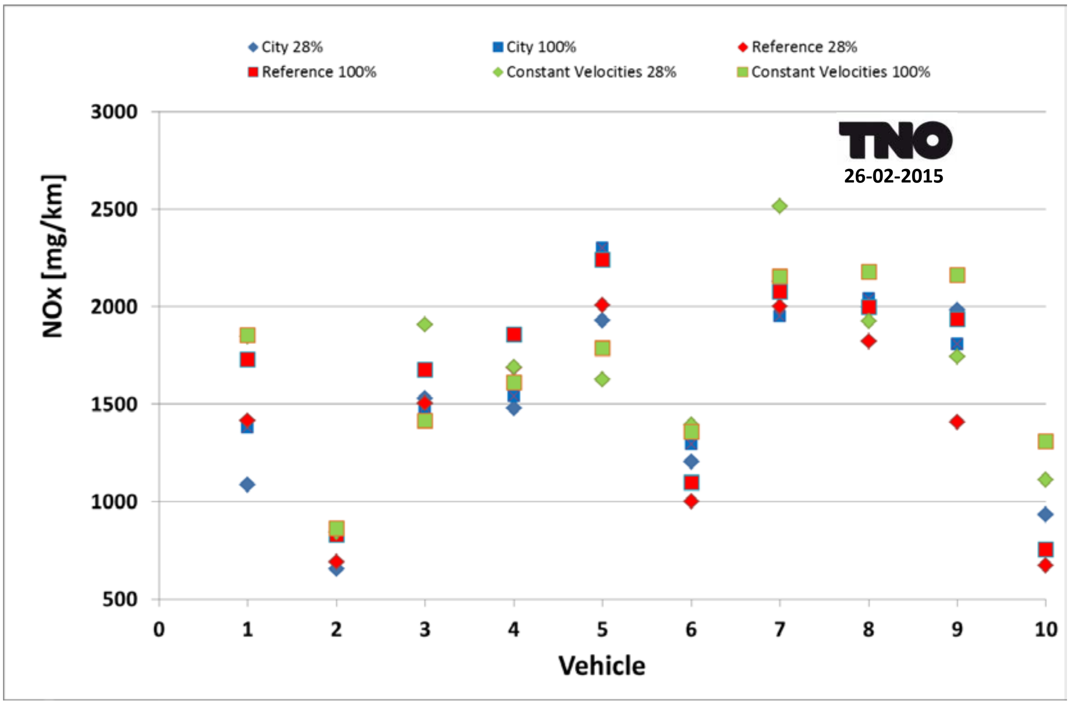

Figure 6: NO_x emission test results of 10 Euro 5 commercial vehicles.

Table 5: NO_x emission test results per trip of 10 Euro 5 commercial vehicles.

[mg/km]	**28% Payload**			**100% Payload**		
	City	**Reference**	**Constant Velocities**	**City**	**Reference**	**Constant Velocities**
Vehicle						
1	1089	1416	1848	1380	1731	1854
2	655	692	843	830	832	862
3	1531	1504	1907	1484	1678	1415
4	1480	1686	1690	1541	1859	1612
5	1928	2009	1625	2302	2242	1787
6	1204	1002	1393	1295	1098	1360
7	2131	2002	2515	1952	2077	2156
8	1999	1822	1925	2039	1998	2181
9	1984	1408	1745	1810	1938	2161
10	935	673	1111	1309	756	1309
Average	1493	1421	1660	1594	1621	1670

The CO_2 emission test results of the on-road test trips are shown in Figure 9 and Table 7. In real-world tests the CO_2 emissions per kilometre are 7% to 52% higher than the CO_2 emissions in the type approval tests.

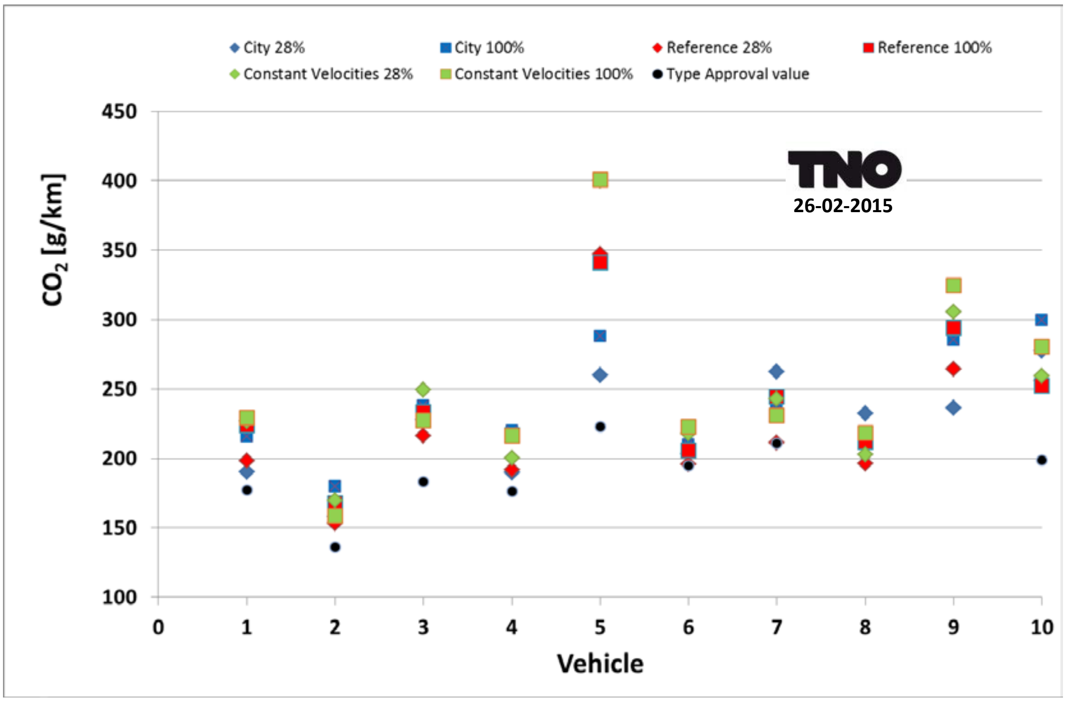

Figure 7: CO_2 emission test results per trip of 10 Euro 5 commercial vehicles

Table 6: CO_2 emission test results per trip of 10 Euro 5 commercial vehicles.

[g/km]	**28% Payload**			**100% Payload**		
	City	**Reference**	**Constant Velocities**	**City**	**Reference**	**Constant Velocities**
Vehicle						
1	190	198	227	216	224	230
2	158	153	170	180	168	158
3	228	216	250	238	233	227
4	190	192	200	220	217	216
5	260	347	400	288	341	401
6	204	196	218	210	206	223
7	263	211	243	239	244	231
8	232	196	203	217	212	218
9	236	265	306	285	294	325
10	277	256	259	300	253	280
Average	224	223	248	239	239	251

Table 7: Type approval and on road CO_2 emissions of 10 Euro 5 commercial vehicles

	Type Approval	**On road average**	**Ratio [%]**
Vehicle			
1	177	214	121%
2	136	165	121%
3	183	232	127%
4	176	206	117%
5	223	339	152%
6	195	209	107%
7	211	239	113%
8	?	213	-
9	?	285	-
10	199	271	136%
Average	194	237	123%

5.2 Chassis dynamometer and SEMS test results of a commercial Euro 5 vehicle

In order to be able to compare different test results, one vehicle make and model was tested more extensively by testing it on the road as well as on the chassis dynamometer. The vehicle on the road, equipped with SEMS, was heavier and larger than the vehicle tested on the chassis dynamometer in the laboratory, but both vehicles were equipped with the exact same engine. NO_x and CO_2 results are shown in Table 8.

As Table 8 shows, the fuel consumption of the vehicle tested on the road was higher than that of the vehicle tested on the chassis dynamometer. The effect on NO_x emissions is even larger. The notable exception is the type approval test: in this case the NO_x emission is only a fraction of all other tests.

In this type approval test the vehicle has a NO_x emission of 287 mg/km, which is near the type approval limit value of 280 mg/km. Testing under different conditions, e.g. with a hot engine, a different road load or on a different test cycle, cause far higher NO_x emissions, ranging from 722 to 1944 mg/km.

Emission tests on the road with this vehicle, at ambient temperatures lower than 20 °C and at different vehicle payloads, have shown NO_x emissions of 1928 – 2302 mg/km, which are approximately 6 to 8 times higher than type approval results. These and former results [TNO2013] show that vehicles that perform well during a type approval test generally have significantly higher NO_x emissions under real-world conditions.

Table 8: NO_x emission test results of the same engine in two Euro 5 commercial vehicles, tested in the laboratory and on the road. The on-road vehicle body was larger and heavier.

	Test	**NO_x [mg/km]**	**CO_2 [g/km]**
Laboratory	NEDC (type-approval test)	287	203
	NEDC (hot start)	970	179
	NEDC (hot start, road load adapted)	1051	189
	WLTP	722	254
	WLTP (hot start)	1082	239
	CADC city	1944	295
	CADC rural	1108	202
	CADC motorway	859	307
On-road SEMS	Reference trip (28% load)	2009	347
	Reference trip (100% load)	2242	341
	City (28% load)	1928	260
	City (100% load)	2302	288

More detailed NO_x emissions of the vehicle that was tested on the chassis dynamometer are shown in the next figures. Figure 8 and Figure 9 show the real time and cumulative NO_x emissions of an NEDC test, whereas in Figure 10 and Figure 11 the real time and cumulative NO_x emissions of a WLTP test are shown. During the hot tests the NO_x emissions are significantly and continuously higher than the NO_x emissions in the cold test. Testing the vehicle on the NEDC using a hot start, the cumulative NO_x emission of the vehicle is approximately 11 gram; executing the NEDC with a cold start, as the type approval test procedures prescribe, leads to a cumulative NO_x emission of approximately 2 gram.
Test results on the WLTP show similar results, with a hot start cumulative NO_x emission of approximately 24 gram, against a cumulative NO_x emission of 12 gram in a cold-start cycle.

The hot start test and the cold start test are identical, except for the engine temperature at the start of the test. As can be seen in the figures there are no discernible differences in tailpipe temperature after approximately 6 and 10 minutes into the test. The NO_x emissions in the hot start tests however are significantly higher than those in the cold start tests. As neither the test cycle nor the engine and exhaust temperature can explain this large difference in NO_x emission in the second part of the test, it can be concluded that the vehicle shows a different emission behaviour in both tests. This seems to indicate that different emission control strategies are applied in cold and hot tests. So far, no explanation was found as to why this would be the case. Finding the exact cause for these elevated NO_x emissions during hot tests would require a detailed analysis and consultation with vehicle manufacturers.

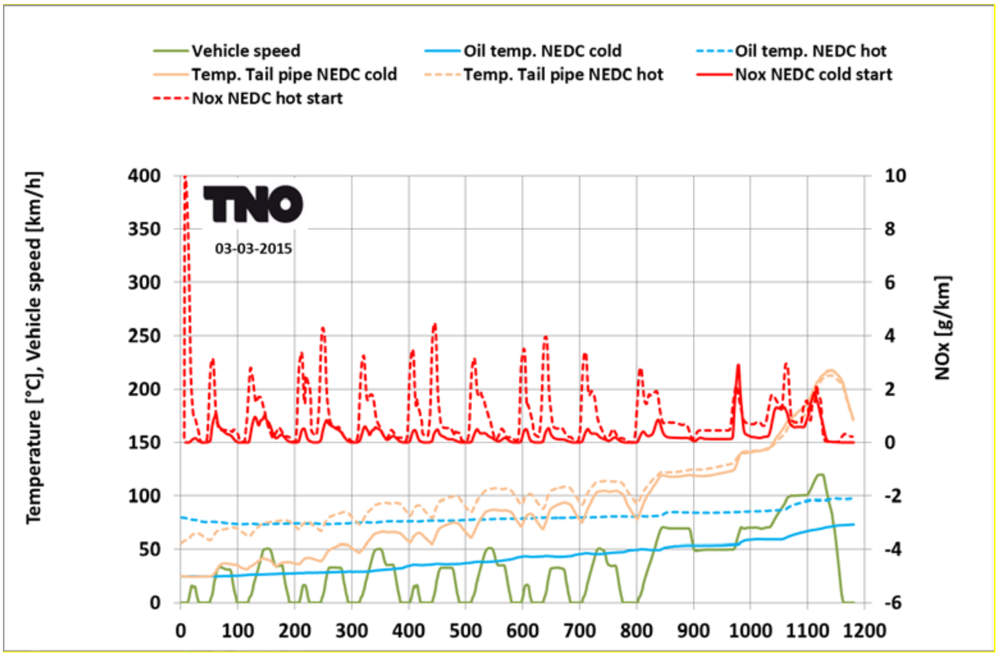

Figure 8: Real time NO_x emissions in an NEDC test with cold and hot start.

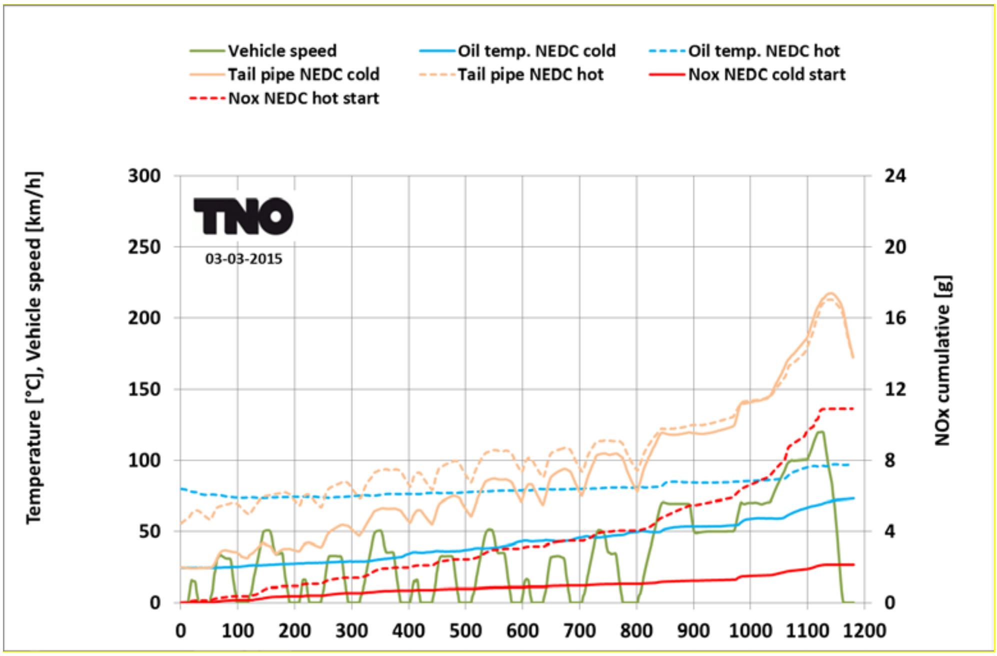

Figure 9: Cumulative NO_x emissions in an NEDC test with cold and hot start.

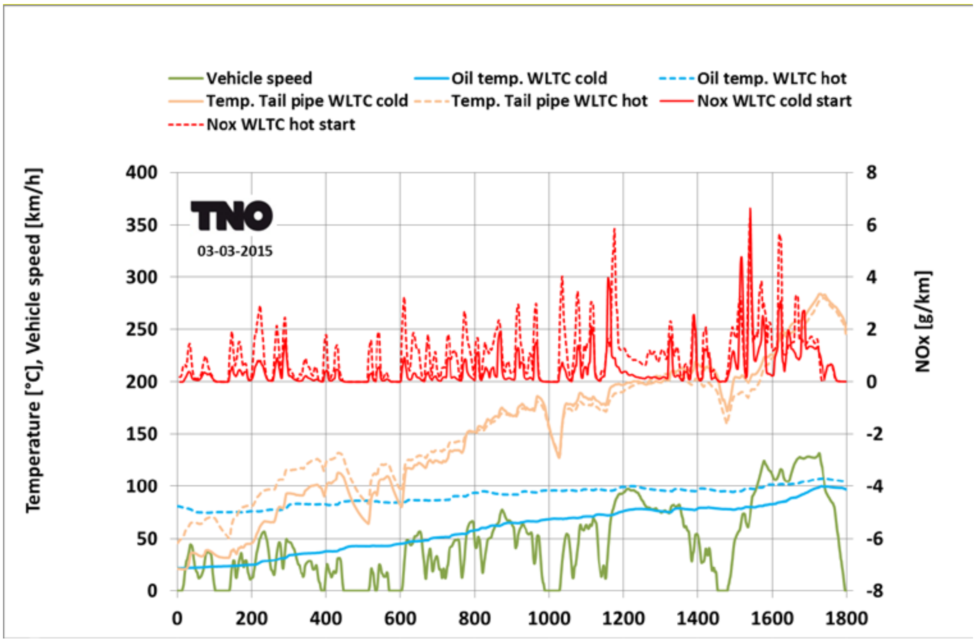

Figure 10: Real time NO_x emissions in a WLTP test with cold and hot start.

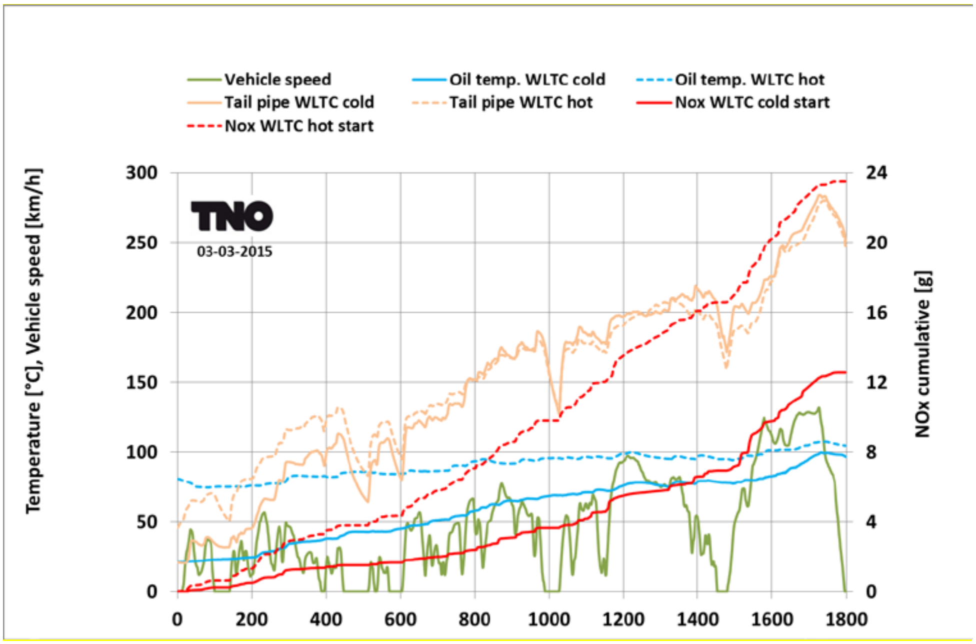

Figure 11: Cumulative NO_x emissions in a WLTP test with cold and hot start.

5.3 Vehicle emission factors

These new emission data are input for an upgrade of current emission factors. In Table 9 and Table 10 the old and newly proposed NO_x and NO_2 emission factors of Euro 4 and 5 N1 class III commercial vehicles are reported.
The Euro 4 are expected to perform similar to the Euro 5 vehicles.

Except from the emission factor of the motorway (congested), the NO_x emission factors increase with 33 to 85%. The NO_2 emission factors increase with 23 to 83%.

Table 9: Old and newly proposed NO_x emission factors of Euro 4 and 5 N1 class III commercial vehicles.

[g/km]	Emission estimate	NO_x Old	NO_x New	Increase
Urban	Congested	1.66	2.45	48%
	Normal	0.98	1.44	47%
	Free-flow	0.90	1.40	56%
Rural	Normal	0.54	0.86	59%
Motorway	Congested	1.57	1.53	-3%
	80 km/h strict	0.65	0.92	42%
	80 km/h	0.73	0.99	36%
	100 km/h strict	0.80	1.06	33%
	100 km/h	0.82	1.16	41%
	120 km/h	0.90	1.53	70%
	130 km/h	0.95	1.76	85%

Table 10: Old and newly proposed NO_2 emission factors of Euro 4 and 5 N1 class III commercial vehicles.

[g/km]	Emission estimate	NO_2 Old	NO_2 New	Increase
Urban	Congested	0.52	0.73	40%
	Normal	0.30	0.43	43%
	Free-flow	0.27	0.42	56%
Rural	Normal	0.16	0.26	63%
Motorway	Congested	0.52	0.46	-12%
	80 km/h strict	0.21	0.28	33%
	80 km/h	0.24	0.30	25%
	100 km/h strict	0.26	0.32	23%
	100 km/h	0.26	0.35	35%
	120 km/h	0.28	0.46	64%
	130 km/h	0.29	0.53	83%

6 Discussion

The selected and tested vehicles are mainstream commercial vehicles and cover a large part of the Dutch fleet of commercial vehicles. Due to a lack of accurate fleet data of the numbers of commercial vehicles it is not possible to determine the quantitative rate of representativeness.

In this project the NO_x and CO_2 emission mass rates are based on measured volume concentrations, fuel parameters, calculations and the measured air mass rates. Although the air mass rate signals of the vehicles might deviate (i.e. +/- 10%) it is clear that the on-road vehicle NO_x emissions are far higher than the type approval emissions. Independent comparison of the CO_2 emissions with the recorded fuel consumption, based on the same signals, yields typical deviations of less than 5% for the accumulated CO_2 over a few trips.

Type approval emission testing on light commercial vehicles is limited. Due to a large variation in vehicle bodies, transmission and engines, manufacturers have achieved a special status. Only a few vehicles are tested as representative vehicle for a large group. In particular, the rolling resistance and air drag of such vehicles is seldom determined but assumed to be low, according to table values in the regulation R83 of the UNECE, which is adopted in European legislation. Moreover, the vehicles are assumed and tested empty, which is rather unlikely for a light commercial goods vehicle. Together, this ensures the vehicle in the type approval test is not tested on engine loads and velocities common in normal driving. Very likely this is partly responsible for even higher deviations between type approval and real-world emissions of such vehicles compared to diesel passenger cars.

Despite of the continuous tightening of the NO_x type approval limit values from Euro 1 to Euro 5 real-world NO_x emission factors have stabilized at around 1430 mg/km in the last decade, as Figure 12 clearly shows. In other words: the difference between type approval NO_x emissions and real-world NO_x has grown significantly over the year. Compared to the current type approval limit value of 280 mg/km, the difference between type approval emissions and real-world is substantial.

This study concerns the measurements of NO_x on Euro-5 vehicles solely. However, it is untenable to retain the current low Euro-4 NO_x and NO_2 emission factors, which were still based on favorable extrapolations from passenger cars and reduction in emission limits. Hence, the emission factors for Euro-5 are also applied to Euro-4. The emission factors of Euro-1 to Euro-3 are based on measurements on these vehicles. Therefore, no reason exists to adapt these values. The fraction of NO_2 in NO_x, relevant for local NO_2 ambient air concentrations close to busy roads, is the result of the particular particulate matter emission control technology, i.e. oxidation catalysts. With the introduction of the particulate filter with Euro-5 the NO_2 fraction in NO_x is stabilized at 30%, from an increase from Euro-2 to Euro-4. The fraction of 30% direct NO_2 is also applied to Euro-4. However, there are no underlying measurements and the value of direct NO_2 can be in the range from the current 30% to the original 55% for Euro-4 light commercial diesel vehicles.

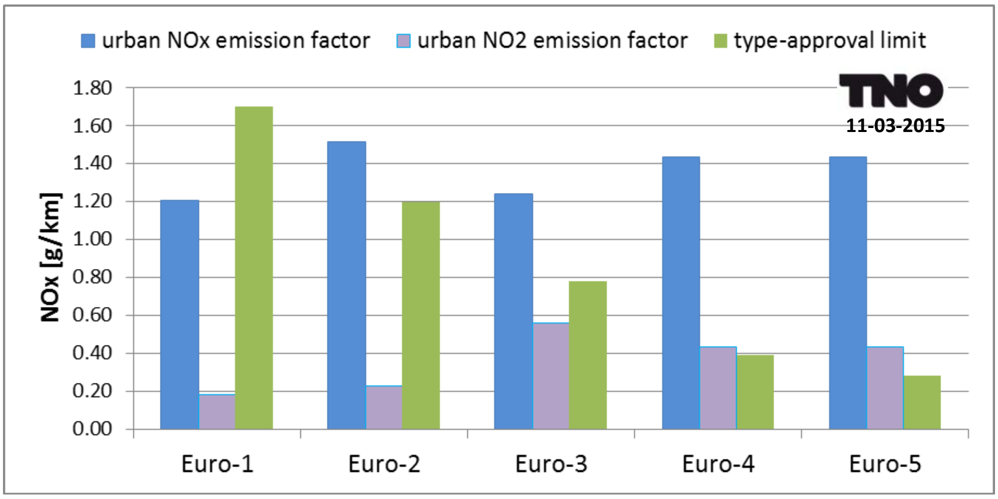

Figure 12: NO_x and NO_2 emission factors in the city and type approval limit values of NO_x of diesel commercial vehicles.

The test results of this study proved a limited effect of driving behaviour, engine load and external circumstances, causing typically less than 15% variation per vehicle between the extreme cases. To determine the actual cause of the difference between real-world emissions and type approval emissions, however, a different type of investigation is required. Euro-4 and older vehicles, the typical velocities and engine loads comparable with the type-approval test still led to comparable emissions with the type-approval values. With Euro-5 it is no longer the case: for the same velocities and engine loads as on the type-approval the real-world NO_x emissions are also factors higher than the type-approval value. Moreover, test execution and vehicle state may explain a few percent difference between one test and another, but not such magnitude. Concluding, emission tests were executed on the conservative side, not to produce high emissions due to special test circumstances, however, still they were high. Moreover, variations found among vehicles and among test circumstances were much smaller than the factor 5 to 6 difference between type-approval value and real-world emissions.

7 Conclusions

In this research project the real-world NO_x and CO_2 emission performance of Euro 5 compliant diesel commercial N1 class III vehicles has been determined on the road in several test trips. The emissions were measured by means of TNO's Smart Emission Measurement System, which contains an automotive O_2/NO_x sensor. Combined with CAN bus data of the vehicle and a dedicated emission calculation method, the mass emission rates were determined. One vehicle was tested in greater detail on a chassis dynamometer in a test laboratory.

The average NO_x emissions of the N1 class III commercial vehicles tested in this project range from 1421 to 1670 mg/km and are 5 to 6 times higher than the type approval emission limit value of 280 mg/km. The measurements confirm findings in another study, which found comparable real-world NO_x emissions of around 1300 mg/km in a Remote Emission Sensing experiment. The only vehicle showing relatively low NO_x emissions was an N1 class II vehicle, with a relatively low weight. The effect of payload on NO_x emissions is moderate. In city trips and reference trips an increase of the payload from 28% to 100% results in an average increase of NO_x emissions of 11-15%. The average CO_2 emissions per kilometre during the road tests are 7% to 52% higher than the CO_2 emissions in the type approval certificates.

The vehicle that was tested on the chassis dynamometer had a NO_x emission of 287 mg/km when subjected to a type approval test, which is near the type approval limit value of 280 mg/km. Tests on the dynamometer under different conditions, e.g. with a hot engine, with a different road load or on a different test cycle, cause far higher NO_x emissions, ranging from 722 to 1944 mg/km. Testing the same type of vehicle with an identical engine on the road at different vehicle payloads has shown NO_x emissions of 1928 to as much as 2302 mg/km. In other words, the vehicle's real-world NO_x emissions were approximately 6 to 8 times higher than type approval results.

The large and increasing difference between the NOx emission limit and the real world emissions of modern diesel vehicles is remarkable result. This, and previous studies, have shown that vehicles that perform well during a type approval test, generally and almost with no exception have far higher NO_x emissions under real-world conditions. Moreover, the difference between real-world emissions and type approval emissions has been growing over the years. Neither appropriate speed limits, nor driving behaviour, or reduced congestion can bring the emission down to an acceptable level.

The new emission data have been used to update the current emission factors for light commercial vehicles. Except for the emission factor for congested motorway operation, NO_x emission factors increase with 33% to 85%. The NO_2 emission factors increase with 23% to 83%. Based on the results for Euro 5 light commercial vehicles presented in this report, emission factors for Euro 6 vehicles have not been adapted. Currently, it is assumed the light commercial vehicle still follow the optimistic trend in real-world emissions expected for diesel passenger cars, based on upcoming legislation. This would mean an 50% to 75% reduction from the current Euro 5 emission factors to Euro 6. The current measurements do however raise a concern for Euro 6 vehicles as well.

8 References

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9 Signature

Delft, 9 March 2015	TNO
Jordy Spreen Project Leader	Gerrit Kadijk Author

A NO$_x$ sensor calibration

Serial number:	707130061
Date:	3-11-2014

Bottle NOx [ppm]	Sensor NOx [ppm]	Absolute Difference [ppm]	Difference [%]
9.98	9.28	-0.7	-7
48.16	49.03	0.9	2
193.7	199.71	6.0	3
960	968.09	8.1	1

Serial number:	707130061
Date:	27-1-2015

Bottle NOx [ppm]	Sensor NOx [ppm]	Absolute Difference [ppm]	Difference [%]
9.98	9.75	-0.2	-2
48.16	49.33	1.2	2
196	199.8	3.8	2
959	962.6	3.6	0