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Variations of Real World NOx Emissions of Diesel Euro 5 and 6 Light-duty Vehicles

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Abstract

In order to gain insight into trends in real-world emissions of light-duty diesel vehicles under conditions relevant for the Dutch and European situations, eighteen Euro 6 passenger cars and ten Euro 5 light commercial vehicles (LCV's) were extensively tested in the laboratory and on the road. These measurements also form a basis for the annual update of Dutch emission factors. The majority of the vehicles comply in type approval emission tests but on the road real-world NO_x emissions are on average 5 to 6 times higher than the type approval limit value. Euro 6 passenger cars emit in the range of 50-2000 mg/km. The average NOx emissions of the N1 class III Euro 5 commercial vehicles range from 1421 to 1670 mg/km. In general the difference between real-world emissions and type approval emissions has been growing over the years. Improvement of real world NO_x emissions of future diesel vehicles is possible with Real Driving Emission legislation. Currently the relative expensive PEMS is foreseen as the type approval standard for on-road testing. TNO applies also a NO_x-O_2 sensor based system with data logger (SEMS) as a NOx screening tool. In the RDE legislation it is prescribed to normalize the measured data of RDE test trips. The current normalization tools (EMROAD and CLEAR) show a variation in the results.

Keywords: Real-world NOx emissions, light-duty vehicles, RDE, PEMS, SEMS.

1 Introduction

Commissioned by the Dutch Ministry of Infrastructure and the Environment, TNO regularly performs test programmes to determine real-world emission performance of vehicles in the Netherlands (Kadijk 2015 a,b,c & 2016a). The main goal of the programs is to gain insight into trends in real-world emissions of light-duty vehicles under conditions relevant for the Dutch and European situations. Between 2013 and 2015 in total eighteen Euro 6 passenger cars and ten Euro 5 light commercial vehicles (LCV's) were extensively tested. These measurements also form a basis for determining the annual update of the Dutch emission factors, used in national emission inventories and air-quality

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models
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 for real-world conditions. Dutch emission factors are based on these tests. The emission factors are one of the few independent sources of information on the growing difference between legislative emission limits and real-world emission performance of cars.

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. Since September 2014 all new type approved light-duty vehicles must comply with Euro 6 regulations and from September 2015 onwards all registered vehicles needs to comply with the Euro 6 limits, therefore the tested vehicles are relatively early models. The focus of the test program were compression ignition (diesel) vehicles. 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), NOx (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 NOx emissions of vehicles are an important measure 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.

TNO regularly performs emission measurements within the “in-use compliance program for light-duty vehicles”. Whereas in the early years, i.e. in 1987 to 2000, many standard type approval tests were executed, in recent years the emphasis has shifted towards the gathering of real-world emission data. Real-world emission data is collected by means of:

1. Performing emission measurements on a chassis dynamometer using various non-standard driving cycles, for example driving cycles that better reflect real-world driving conditions, and;
2. Equipping vehicle with an on-board emission measurement system and subsequently measuring the emissions of the vehicles while driving on the public road.

2 Objective

The objective of this research is to assess the real-world emission performance of Euro 6 passenger cars and Euro 5 light commercial vehicles (mainly N1 class III) and to assess the NOx reduction performance of Euro 5 and 6 diesel technologies.

3 Methods

Emission tests were performed on the chassis dynamometer and on the road.

Chassis dynamometer tests: The Type Approval (TA) value for NOx emissions of light-duty vehicles is based on a chassis dynamometer test in a laboratory. TNO tested most of the Euro 6 passenger cars in chassis dynamometer tests with a total number of approximately 130 tests. All vehicles were tested according to the official test procedure (UNECE Reg 83) and they nearly all comply with the NOx limit value of 80 mg/km. Also different driving cycles were conducted, such as the CADC and WLTC.

On-road testing: TNO performs real-world tests on the road with a Portable Emission Measurement System (PEMS) and/or a Smart Emission Measurement System (SEMS). PEMS equipment measures CO, CO_2, HC, NO and NO_2 emissions. SEMS is an emission screening tool which contains a data logger and a NO_x – O_2 sensor. Moreover, with SEMS NH_3 emissions are monitored.

PEMS testing: Emission tests with different vehicles were performed on the road under real-world conditions. During the PEMS tests, the vehicle was loaded with a test driver, a test engineer and the test equipment (including a battery and a generator), amounting to a total test weight of approximately 200 kg.

SEMS testing: In recent years, TNO has developed the so-called Smart Emission Measurement System or SEMS (Vermeulen et al. 2012 & 2014). Most vehicles in this testing program were also tested using SEMS. SEMS is an emission screening tool which contains a data logger, a NO_x – O_2 sensor (Continental, UniNOx) and a thermocouple, the latter two of which are installed in the tailpipe of the vehicle. It measures the exhaust gas temperature and the O_2 and NO_x volume concentrations in vol% or ppm. SEMS also measures geographical data and logs the CAN data of the vehicle 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, the CO_2 concentrations are calculated. In former projects, the accuracy and the reliability of the SEMS equipment and method has been proved (2012), (2014b). However, the absolute emission results are calculated with data from the CAN bus of the vehicle and these can deviate which may lead to deviations in the end results. In this project, the air mass rate of the vehicle CAN bus has been applied for calculations of the NOx and CO_2 mass flow rates [mg/km]. The quality of the air mass rate signal has a large influence on the accuracy of the NO_x and CO_2 mass emissions. Moreover, the NO_x – O_2 sensor is sensitive for temperature and pressure which may have an effect on the accuracy.

The test and data processing procedure contains the following steps:
1. The CO_2 volume concentration is determined from the measured O_2 volume concentration and the fuel C:H ratio.
2. The exhaust mass flow rate is determined from the vehicle Mass Air Flow signal, augmented with combustion products CO_2 and H_2O using the fuel C:H ratio and the normal air density
3. The CO_2 and NOx mass flow rates are determined from the measured volume concentrations and the exhaust mass flow rate.

This analysis requires three input parameters:

- the C:H ratio of the fuel, which is assumed to be 1.95 for modern market-fuel diesel, and;
- the ambient oxygen content of air at 20.8% for on-road conditions;
- Normal air density of 1.29 kg/m^3 at standard conditions to calculate the exhaust gas density

Test routes:

PEMS and SEMS register real-world conditions and real-world emissions. In order to be able to compare the individual real-world vehicle emissions, the TNO-designed ‘reference trip’ is always part of the investigation. The reference trip consists of urban, rural and highway driving. Additionally, some other trips are driven: a constant speed trip, a trip mainly containing urban driving and a trip consisting mainly of highway driving. Table 1 shows the main characteristics of the test trips. All trips are started in Helmond, the Netherlands. For the LCV’s tests are carried out with different payloads.

Table 1: Specifications of PEMS and 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 (excluding idle time)	55 km/h (excluding idle time)	93 km/h (total route)*
Load [-]	Driver** + test equipment	Driver** + test equipment	Driver** + test equipment

*Constant speed measurements are part of this route; constant speed tests have duration of approximately 300 to 600 seconds.

**For PEMS trips a driver and a test engineer run the test.

Driving styles in on-road measurements:

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

Test vehicles:

Table 2,

Table 3 and Table 4 show the sixteen tested Euro 6 vehicles per phase in the measurement programme. The three phases in the measurement programme are defined as follows:

- Phase 1: Euro 6 prototype vehicles, tested in 2010;
- Phase 2: First Euro 6 production models, tested in 2012 and 2013
- Phase 3: Selection of Euro 6 vehicles with an SCR system, tested in 2014 and 2015.

In Table 5 the types of test per passenger vehicle are specified.

In Table 6 the tested diesel light commercial Euro 5 vehicles are specified.

Table 2: Phase 1: Tested Euro 6 prototype vehicles in 2010.

Vehicle ID	**-**	**veh: H2**	**veh: H3**	**veh: A2**	**veh:E4***
Engine Power class	[kW]	>150	>150	>150	100 - 125
Engine capacity class	[cm3]	>2000	>2000	>2000	1750 - 2000
Odometer	[km]	2.354	16.634	9.466	9.400
Fuel	-	Diesel	Diesel	Diesel	Diesel
Inertia	[kg]	1700	1930	2040	1590
Emission class	-	Euro 6	Euro 6	Euro 6	Euro 6
Type	-	Sedan	Sedan	Sedan	Sedan
Applied system for NO_x reduction	-	LNT	LNT	SCR	SCR

*Three vehicles

Table 3: Phase 2: First Euro 6 production models, tested in 2012 and 2013.

Vehicle ID	**-**	**veh: H4**	**veh: H6**	**veh: H7**	**Veh: E6**	**Veh: J1**	**Veh: J2**
Engine Power class	[kW]	125 - 150	100 - 125	100 - 125	100 - 125	100 - 125	100 - 125
Engine capacity class	[cm3]	1750 - 2000	1750 - 2000	1750 - 2000	1750 - 2000	1750 - 2000	1750 - 2000
Odometer	[km]	10.965	28.376	3.000	26.200	20.100	11.616
Fuel	-	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Inertia	[kg]	1590	1470	1810	1590	1590	1590
Emission class	-	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6
Type	-	Wagon	Sedan	Sedan	Sedan	MPV	MPV
Applied system for NOx reduction	-	LNT	LNT	LNT	SCR	EGR	EGR

Table 4: Phase 3: Selection of Euro 6 vehicles with SCR system, tested in 2014 and 2015.

Vehicle ID	**-**	**Veh. K1**	**Veh. K2**	**Veh. L1**	**Veh. M1**	**Veh. N1**	**Veh. O1**
Engine Power class	[kW]	100 - 125	100 - 125	75 - 100	100 - 125	>150	>150
Engine capacity class	[cm3]	1500 - 1750	1500 - 1750	1500 - 1750	>2000	>2000	>2000
Odometer	[km]	3.500	15.000	10.125	20.000	19.500	11.400
Fuel	-	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Inertia	[kg]	1700	1700	1250	1590	2270	1930
Emission class	-	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6
Type	-	MPV	MPV	Wagon	Sedan	MPV	Sedan
Applied system for NOx reduction		SCR	SCR	SCR	SCR	SCR	LNT+SCR

Table 5: Types of tests per vehicle.

Phase of measurement programme	**Type of vehicle**	**Vehicle ID**	**Chassis dynamometer tests**	**PEMS tests**	**SEMS tests**
[-]	[-]	[-]	[#]	[#]	[#]
Phase 1	Prototype models	Veh: H2	6	-	-
		Veh: H3	3	-	-
		Veh: A2	3	-	-
		Veh:E4	6	-	-
Phase 2	First Euro 6 production models	Veh: H4	7	-	-
		Veh: H6	9	-	-
		Veh: H7	0	14	-
		Veh: E6	8	15	-
		Veh: J1	8	-	-
		Veh: J2	10	-	
Phase 3	Selection of Euro 6 SCR models	Veh. K1	19	-	-
		Veh. K2	7	16	
		Veh. L1	12	11	16
		Veh. M1	7	14	37
		Veh. N1	7	-	55
		Veh. O1	7	-	20
Total			**119**	**70**	**128**

Table 6: 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

4 Results

Most vehicles were tested on a chassis dynamometer. Between 2013 and 2015 five Euro 6 vehicles were tested using PEMS with a total of approximately 70 tests. Fifteen vehicles were tested with SEMS (four Euro 6 passenger cars and eleven Euro 5 LCV's), approximately 220 SEMS tests were performed.

Chassis dynamometer test results Euro 6 vehicles:

CO emissions: In chassis dynamometer tests the CO emissions of most vehicles are well below the type approval limit value of 500 mg/km.

THC emissions: The combined type approval limit value of THC+NO_x is 170 mg/km. As already shown, the NO_x emissions exceed their limit value of 80 mg/km. In most tests the THC emission is well below 90 mg/km.

PM emissions: The PM emissions of most vehicles are well below the type approval limit value of 4.5 mg/km. This is caused by the diesel particulate filters which have high filter conversion rates.

NOx emissions: In Figure 1 the NOx emissions of sixteen Euro 6 vehicles in various test cycles are shown. The range of NO_x emission results in chassis dynamometer tests is very broad; 40 – 800 mg/km. In the type approval test (NEDC) nearly all vehicles comply with the NO_x limit value of 80 mg/km, depicted as a red line in the figure.

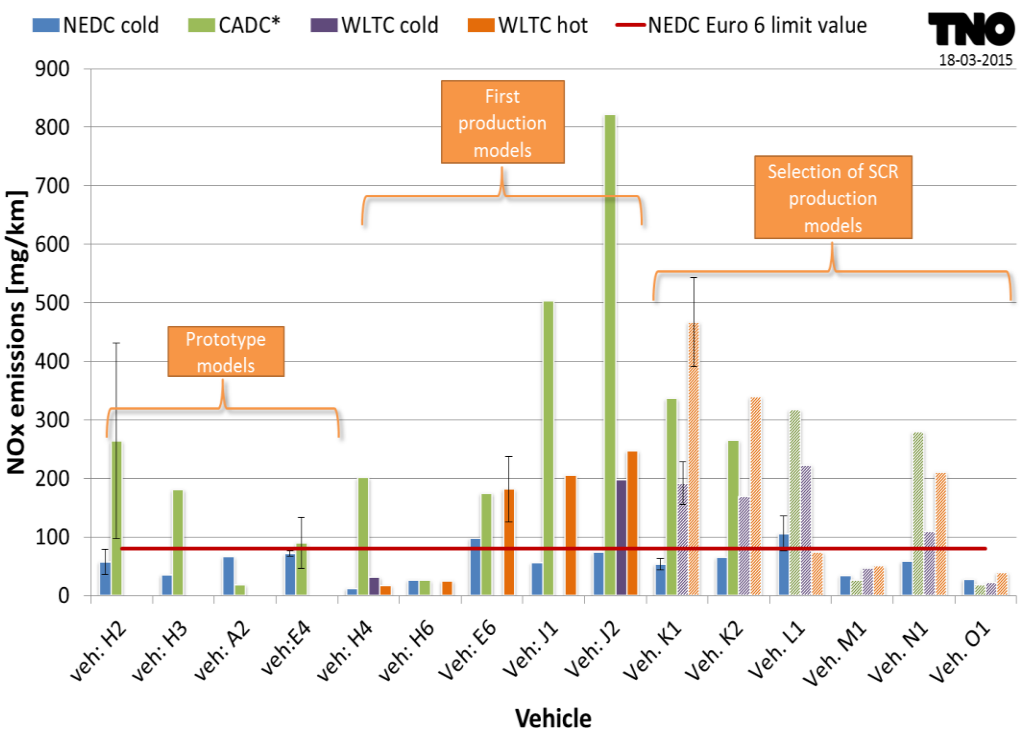

Figure 1: NOx emissions on the chassis dynamometer per driving cycle of Euro 6 diesel vehicles

- In CADC tests the NO_x emissions of the vehicles are 4 - 10 times higher (200-800 mg/km) than in NEDC tests. Especially vehicle J1 and J2 have extreme high NO_x emissions in the CADC test (up to 1150 mg/km). These vehicles are not equipped with a NO_x aftertreatment device but NO_x emissions are controlled with an engine with a lowered compression ratio and an EGR system.

- The NO_x emissions on WLTC tests are also often higher than the NEDC test results. Moreover the vehicles K1, K2 and N1 show significant higher NOx emissions in the WLTC with hot start compared to the WLTC with cold start. These results indicate that emission optimization is related to the applicable type approval test cycle.
- The vehicles A2, E4, M1 and O1 perform very well in all chassis dynamometer tests (< 80 mg/km). These vehicles are equipped with a SCR system, most likely in combination with EGR. But other SCR vehicles (K1, K2 and N1) have elevated emissions in test cycles that better represent real-world conditions (100-500 mg/km, or up to 6 times the type approval limit value).
- Vehicles H2, H3, H4, H6 are equipped with an LNT for NO_x reduction, most likely in combination with EGR. The vehicles H4 and H6 perform well below 80 mg/km but H2 and H3 emit 180-280 mg/km.

In the CADC tests of Figure 2 the urban phase with cold and hot start of most vehicles gain equal NO_x emissions. However vehicles M1, N1 and O1 clearly show higher emissions after cold start; probably the SCR-catalyst operates after the cold start below the light off temperature. Most vehicles have high NOx emissions in the motorway phase (200–1200 mg/km). Vehicles J1 and J2 which are not equipped with LNT or SCR show high emissions, while vehicle J2 even exceeds the value of 1000 mg/km. On the contrary the vehicles A2, E4, H6, M1 and O1 show relatively low emissions in all CADC-phases. These vehicles are all equipped with LNT or SCR technology. The residual SCR-equipped vehicles have relatively high emissions on the highway phase (200-400 mg/km)

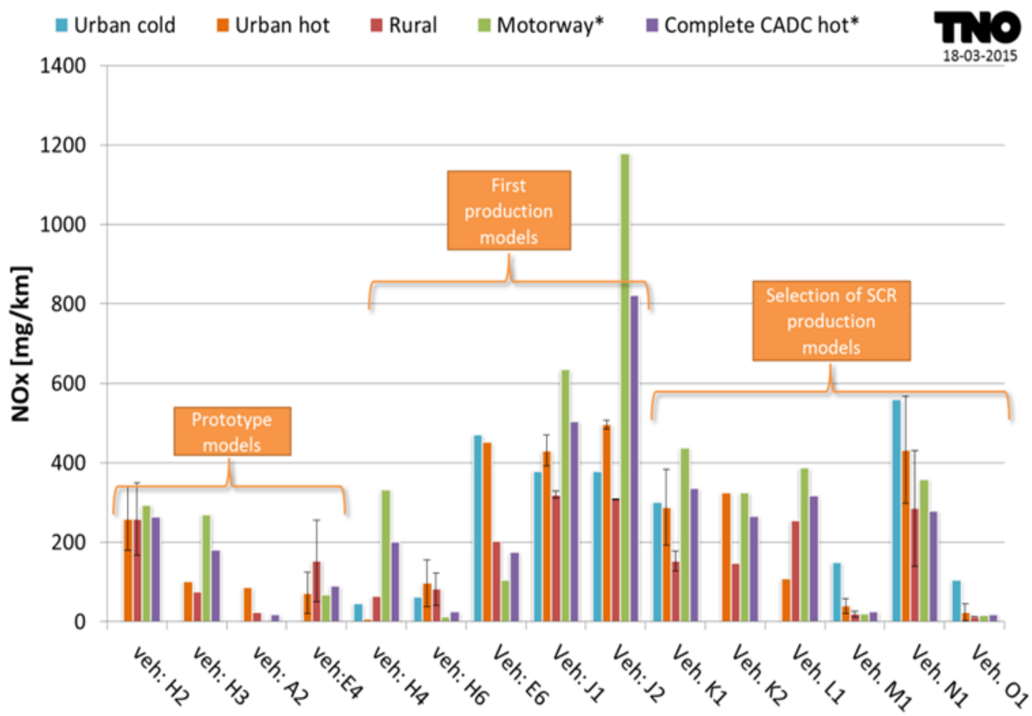

Figure 2: NOx emissions per phase in CADC tests

<u>NO_x emissions in on-road urban, reference and highway trips:</u>
Figure 3 shows the on-road NO_x emissions of urban, reference and highway trips. The urban and reference trips are in some way comparable because they were started with a hot engine and driven with a regular driving style. The highway trips are not comparable because the average vehicle speed already differs significantly per trip. The error bars at the highway trips show the variation of the trip speed (horizontal) and the variation of NOx emissions (vertical).

In urban and reference trips the NO_x emissions are between approximately 80 to 700 mg/km. In highway trips NO_x emissions range from 80 to around 1100 mg/km. Overall, on-road NO_x emissions of the measured vehicles show a very scattered pattern, with values ranging from 80 to 1100 mg/km, the latter value being 14 times higher than the Euro 6 NEDC limit value. In highway trips the NO_x emission performance is not stable because the average vehicle speed per trip differs. Only one vehicle has relatively low NOx emissions in all trips, ranging from 50 to 200 mg/km. Remarkably, both the best-performing vehicle and the worst-performing vehicle are equipped with SCR technology. However the best performing vehicle also has a LNT.

The real-world NO_x emission of Euro 6 diesel passenger cars is in the range of 50 to >2000 mg/km. On average real-world NO_x emissions are 5 to 6 times higher than the type approval limit value of 80 mg/km. This seems to indicate that emission control technologies perform differently on the road than they do on the chassis dynamometer. Moreover, the real world NO_x emission per road type of the different vehicles differ widely. Also driving behavior and gear shift patterns can strongly influence the NO_x

emission results. Proper RDE-legislation, possibly in combination with independent testing can improve these real driving emissions.

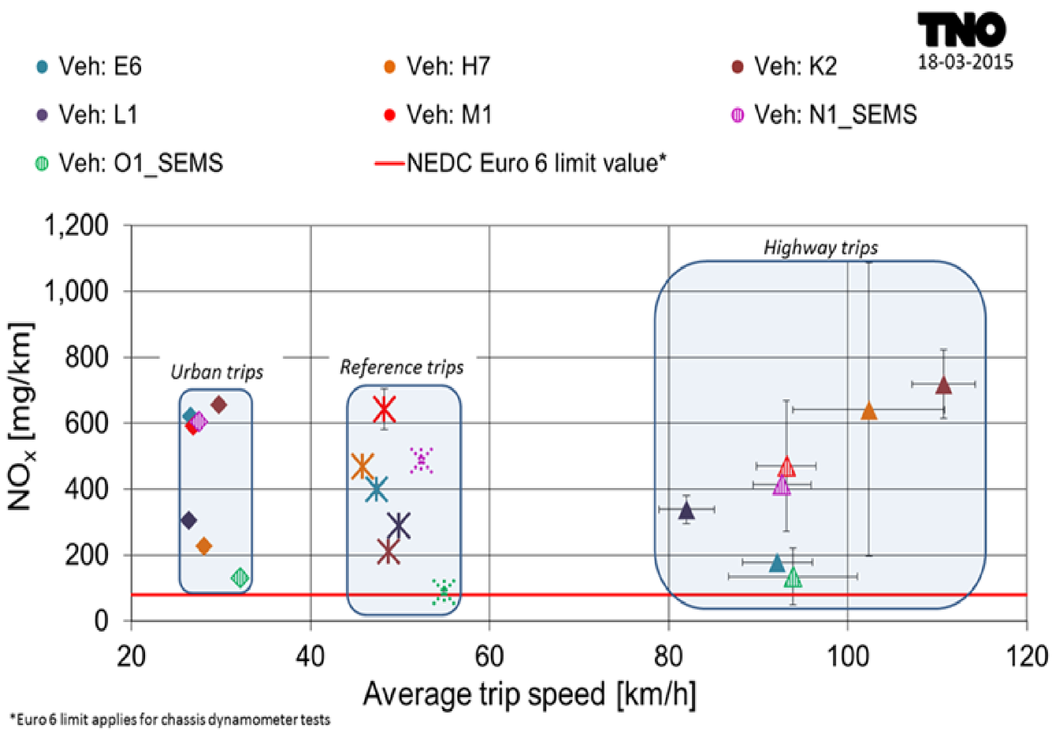

Figure 3: On road NOx emission test results Euro 6 passenger vehicles

Performance of SEMS test equipment on a chassis dynamometer:
The sensors of the SEMS equipment are calibrated, however the quality of the OBD mass air flow signal is not known. Therefore, 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 from 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 the accuracy of the measurements.

In order to validate the SEMS test results, validation tests were performed on a chassis dynamometer while testing vehicle N1. The CO_2 and NO_x test results are shown in Figure 4 and Figure 5. The SEMS test results are well in line with the chassis dynamometer test results. SEMS test results are partly based on Mass Air Flow data of the CAN-bus of the vehicle, the accuracy of which is unknown. In all emission tests the CO_2 deviation is 8% and the NO_x deviation is -14% to +12%. Both standard deviations for CO_2 are approximately 1%; for NO_x these equal 8 and 12%. The results show that SEMS is a screening tool which yields repetitive indicative results. One should keep in mind that the accuracy of these test results is directly related to the accuracy of the mass air flow signal of this vehicle type. Other vehicle types may gain different accuracies.

Although SEMS is less accurate than PEMS, the system is well suited for a quick screening of NO_x emissions of a vehicle. Its error margins are sufficiently low to identify emissions that are well beyond emission limits.

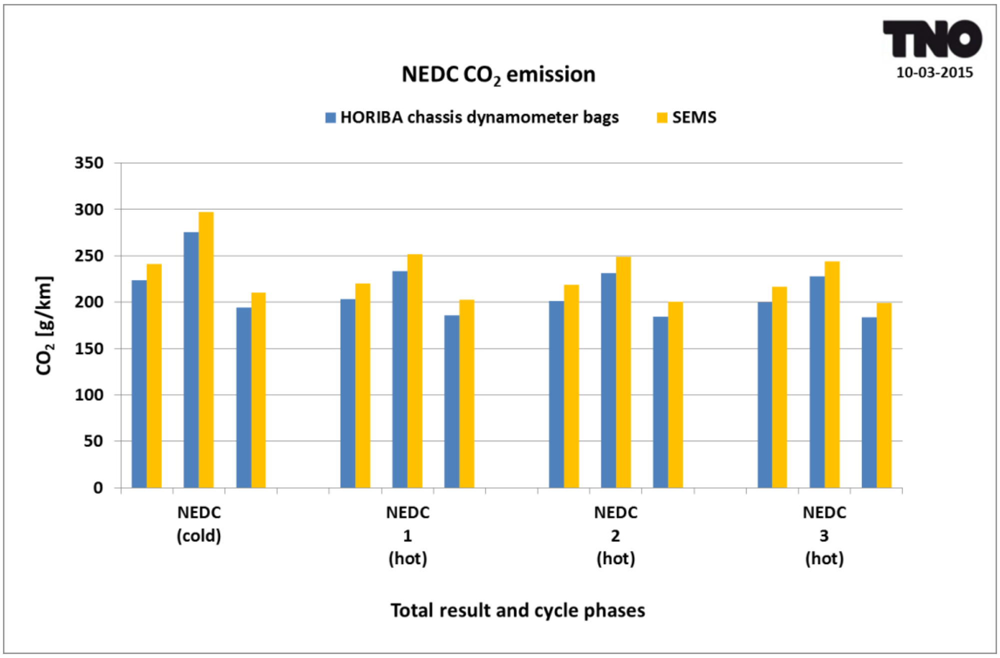

Figure 4: Validation CO_2 test results SEMS-chassis dynamometer on one vehicle (per test the total result and urban and extra urban results are shown) .

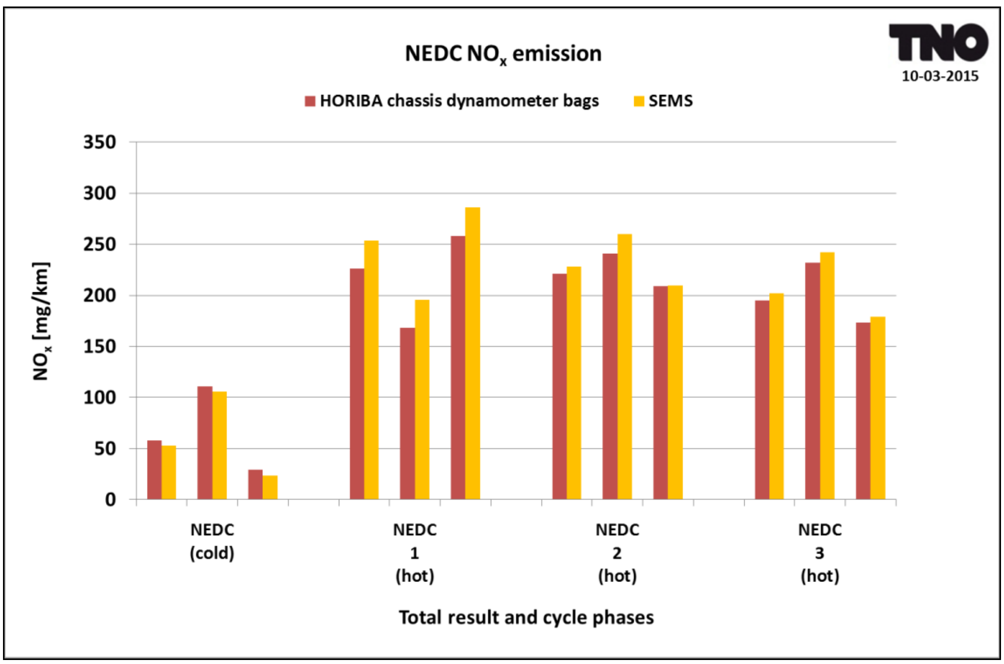

Figure 5: Validation NO_x test results SEMS-chassis dynamometer of one vehicle (per test the total result and urban and extra urban results are shown).

<u>Evaluation of Real Driving Emissions</u>

Table 7 shows the NO_x emissions of seven vehicles which are tested on the chassis dynamometer as well as on the road. The TNO reference trips have been normalised and weighted (1/3 for each road area) according to EMROAD (version 5.80) and CLEAR (version 1.8.6). The EMROAD and CLEAR results are reported in the final two columns of Table 7 and plotted in Figure 6.

In general the EMROAD tool applies small correction, ranging from -11% to +3%. The CLEAR tool applies larger corrections in both directions: the corrections vary from -26% to +23%. The executed TNO reference trips, with a normal driving style are comparable with the RDE reference hence it is notable that the result is in some cases lowered and in some cases increased. Moreover, in some cases CLEAR lowers the result where EMROAD increases the result. Obviously the tools choose a different method for normalisation.

In order to obtain a more balanced view on the performances of EMROAD and CLEAR more results of on-road test trips need to be evaluated.

Table 7: NOx emissions on the chassis dynamometer and on the road with hot start.

NO_x emissions in mg/km	NEDC	NEDC	CADC	TNO reference trip**		
	cold	Hot	hot	hot		
Vehicle	Average			Average	EMROAD Result and CF	CLEAR result and CF
E6	98	210	201	409	419 / 5.2	389 / 4.9
H7	27	16	79	451	402 / 5.0	422 / 5.3
K2	65	58	253	181	182 / 2.3	134 / 1.7
L1	106	11	126	293	-	360 / 4.5
M1	34	27	27	603	618 / 7.7	526 / 6.6
N1*	58	214	370	466	-	451 / 5.6
O1*	28	28	16	79	-	72 / 0.9

*SEMS data

** Not corrected for drift

The EMROAD correction values range from -11% to +3% and CLEAR applies corrections between -26 and + 23%, see Figure 6.

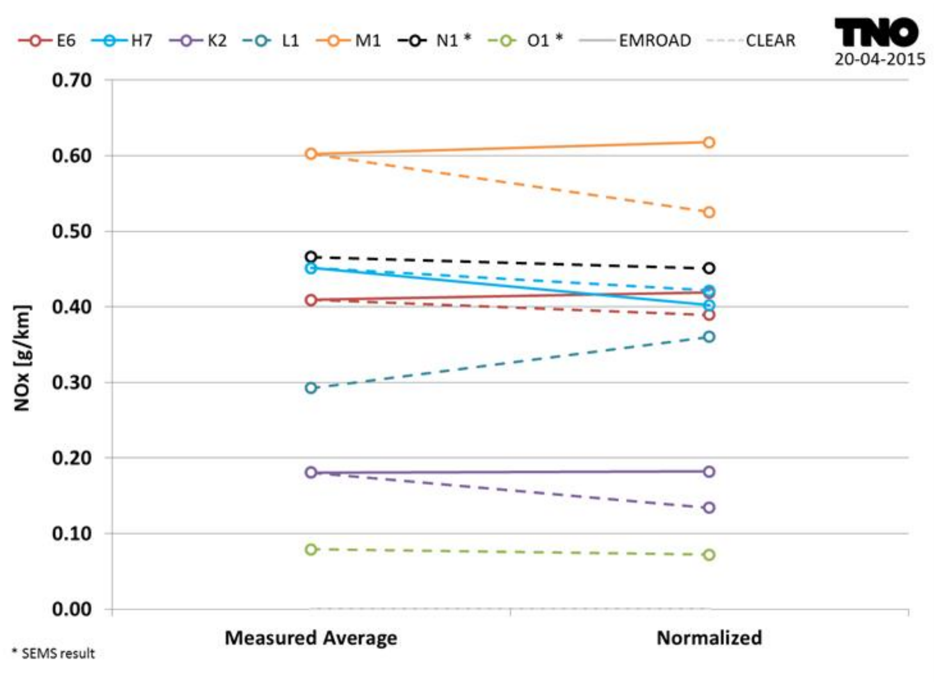

Figure 6: Measured and normalised NOx emissions of 7 vehicles in a reference trip with a hot start.

Driving style and driving at higher speeds

The TNO reference trip was executed with two driving styles (regular and sportive). Table 8 shows the differences in trip characteristics, mainly the higher average acceleration and RPA (Relative Positive Acceleration) indicate the sportive driving style. Additionally trips at higher speeds were performed and analysed with the normalisation tools.

Figure 7 shows the measured and normalised NO_x emissions of vehicle K2 in a reference trip with regular and sportive driving style. With EMROAD no overall normalised results were calculated, the trip was too sportive. The results as shown in **Error! Reference source not found.** were calculated based on the results per road area.
CLEAR yields an overall result, with a reduction of 40% after normalisation the result is lowered substantially.

Additionally a TNO reference trip with highway speeds of 150 km/h was processed with EMROAD. It seems that EMROAD does not take these higher speeds in to account at all for the overall result.

From these results it seems that the normalisation tools do not report sportive driving and driving at high speeds or the result is lowered substantially, however, in real world operation this kind of driving does occur.

Table 8: Trip characteristics

Reference trip	Trip distance	Average speed	Average acceleration	Average Relative Positive Acceleration
Vehicle	[km]	[km/h]	[m/s^2]	[m/s^2]
K2_regular	76.5	49.8	0.43	4.85
K2_sport	76.3	49.4	0.55	6.98

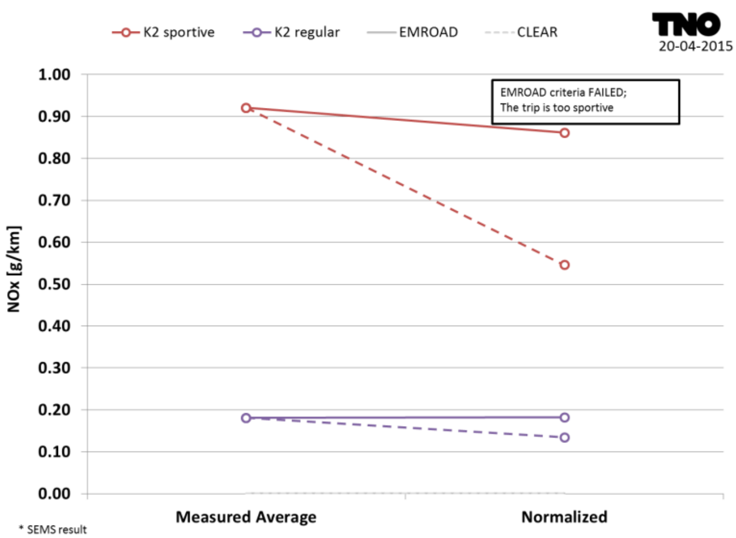

Figure 7: Measured and normalised NO_x emissions of vehicle K2 in a reference trip with regular driving style versus a reference trip with sportive driving style.

<u>Investigations of NOx reductions and SCR conversion rates of tested vehicles:</u>

In Figure 8 the relationship of the converted NO_x in the SCR catalyst and the pre-SCR NO_x emissions (also measured with a Continental UniNOx sensor) of the different vehicles are reported. From this figure the following observations can be made:

- the maximum amount of converted NO_x of these SCR catalysts is 400 to 600 mg/km.
- with low engine-out emissions, i.e. less than 400 mg/km, the SCR catalysts are able to reduce a large amount of NO_x. High SCR conversion rates are possible.
- with higher engine out emissions, i.e. over 500 mg/km, the SCR catalyst does not seem able to reduce all residual NO_x. Operating temperatures and adverse exhaust gas flow conditions are likely to restrict the performance of SCR catalysts in some cases. In other cases, where the operating conditions are in fact favourable, a lack of injected AdBlue is the cause for elevated vehicle emissions.

For vehicles L1, M1 and N1 to achieve post-SCR emissions like vehicle O1, their engine-out NO_x emissions would need to be lowered *and* the SCR system would to reduce a larger share of NO_x.

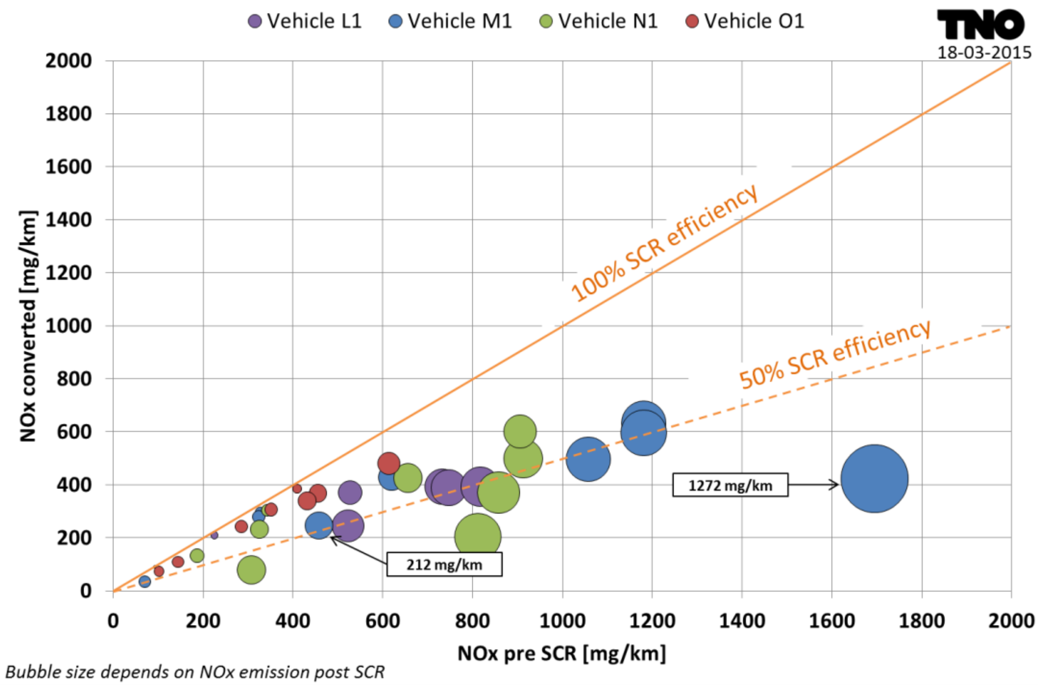

Figure 8: Converted NOx related to engine out NOx emissions in chassis dynamometer and on-road tests.

On-road test results of Euro Light Commercial Vehicles:

Figure 9 shows the (SEMS) 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. These measurement results confirm findings in another study of another European research institute, IIASA from Austria, which found comparable real-world NOx emissions of 1300 mg/km in a Remote Emission Sensing experiment in Zurich (Borken-Kleefeld 2014a).
Vehicle 2 has relatively low NO_x emissions, which is mainly due to the fact that it is a N1 class II vehicle with a lower weight and more stringent emission limit 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%.

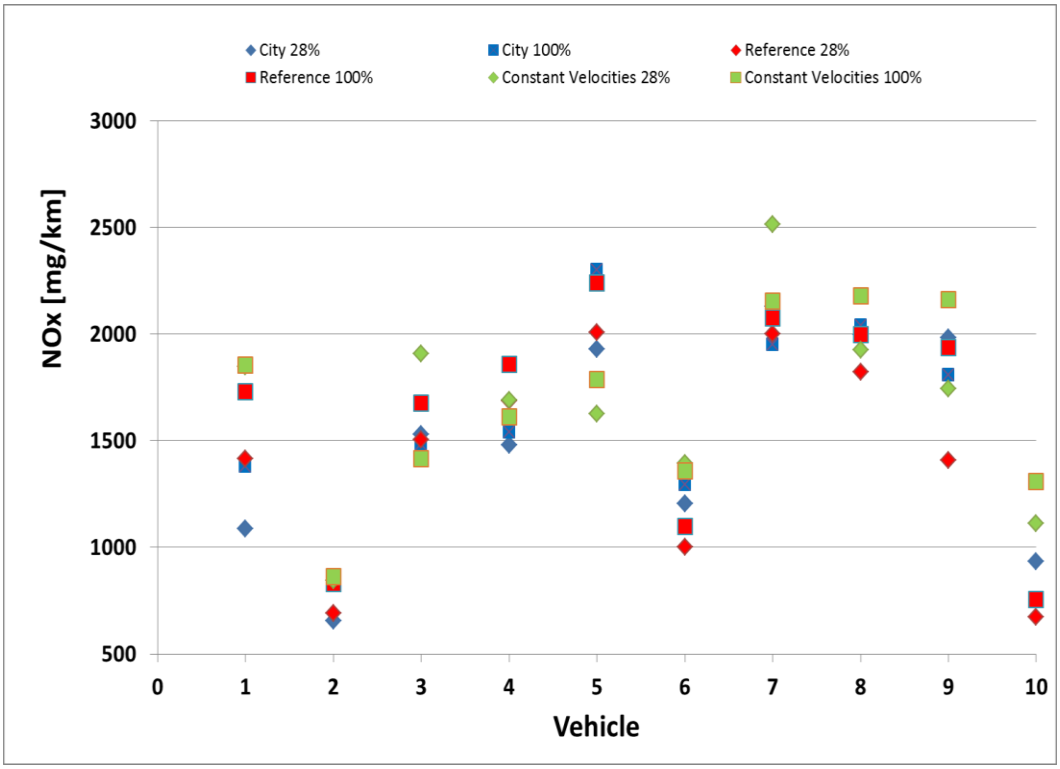

Figure 9: NOx emission SEMS test results of 10 Euro 5 commercial vehicles.

The CO_2 emission (SEMS) test results of the on-road test trips are shown in Figure 10. In real-world tests the CO_2 emissions per kilometre are 7% to 52% higher than the declared CO_2 emissions in the type approval tests. Some LCV's (i.e. number five) are built up with a square box which results in a relative large frontal area without an aerodynamic spoiler; this results in relative high CO_2 emissions at higher vehicle velocities.

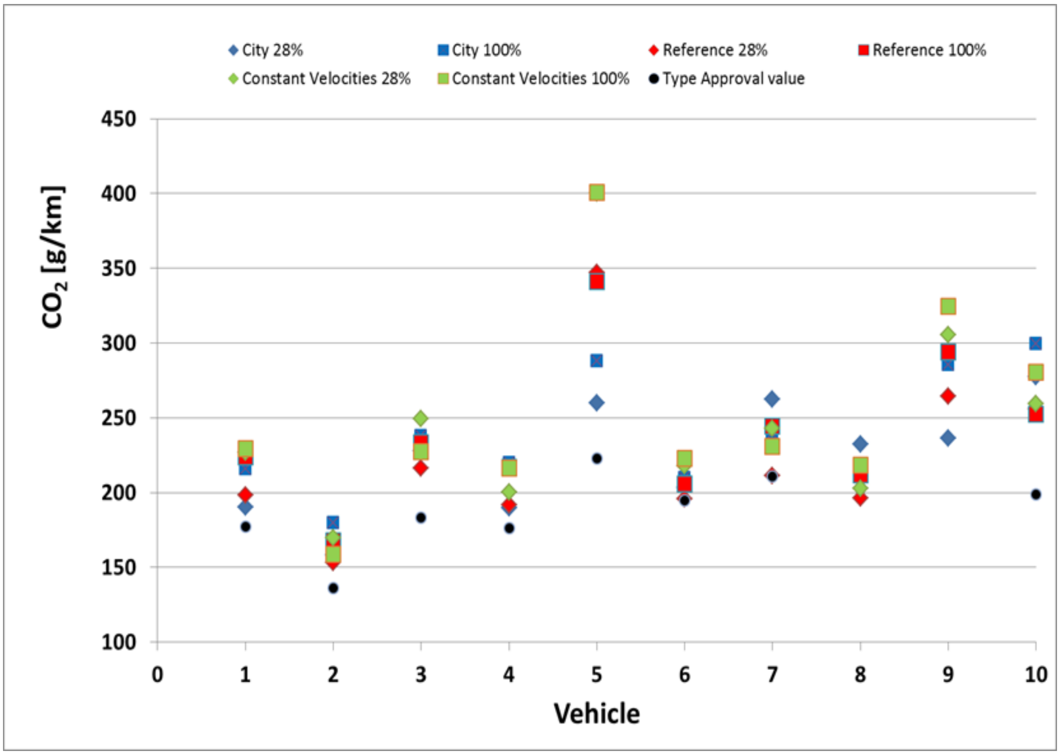

Figure 10: CO2 emission SEMS test results per trip of 10 Euro 5 commercial vehicles

These new emission data are input for an upgrade of current emission factors.

In Table 9 the old and newly proposed NO_x 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%.

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%

5 Discussion

Euro 6 passenger vehicles:

What are the main emission characteristics of the tested Euro 6 diesel passenger vehicles?

The test results of the sixteen tested vehicles show good CO, THC and PM10 real-world emissions because the applied technologies for controlling these emissions are intricately robust. In almost all conditions the emissions are low. However the real-world NO_x emission of all vehicles varies from 0 to 2000 mg/km. Although the type approval emissions of all vehicles are below 80 mg/km, the average real-world NO_x emission of all tested Euro 6 vehicles varies between 150 and 650 mg/km.

What are the characteristics of the vehicle with the lowest real-world NOx emissions and the vehicle with the highest real-world NOx emissions?

The real-world NOx emission of vehicle O1 is 150 mg/km and the corresponding Conformity Factor (CF) is less than 2. Measuring data show clearly that the pre-SCR NOx emissions of this vehicle are relatively low, ranging from 350 to 750 mg/km, indicating an effective EGR system and LNT catalyst which avoid the emission of NO_x. In addition the residual NO_x is mainly reduced in the SCR catalysts which results in an average tailpipe emission of 150 mg/km. In most trips up to 500 mg/km is reduced by the SCR catalyst at an operational temperature up to 380 °C. These data provide clear evidence for the fact that low real-world NOx emissions can be achieved by means of adequate appliance of an EGR, which, in turn, facilitates the maximum SCR performance as SCR operating temperatures in that case are higher allowing for higher SCR conversion rates. At low engine load the LNT seems effective in the conversion of NO_x to harmless components.

On the contrary vehicle M1 has a real-world pre-SCR NO_x emission up to 1250 mg/km. This value deviates strongly from pre-SCR emissions in chassis dynamometer tests, which amount to 50 to 150 mg/km. In real-world tests 0 to 750 mg/km NOx is reduced by the SCR catalyst at an operational temperature up to 250 °C. This results in an average tailpipe emission ranging from 0 to 2000 mg/km, with an average value of about 650 mg/km.

These large differences between NO_x emissions in a chassis dynamometer tests and NO_x emissions in real-world operation are most likely caused by the control strategy dependence on ambient temperatures, the differences in EGR system settings and adjustments. Contrary to the EGR performance, the performances of the different SCR systems are relatively at a constant level: for all tested vehicles the maximum SCR NO_x reduction performance ranges from 350 to 750 mg/km.

Would injecting more AdBlue result in a larger NO_x reduction by the SCR?

Theoretically, more AdBlue could result in a larger NO_x reduction. However, the size of the SCR catalyst, operating conditions of the engine and the operating temperature of the SCR catalyst together determine its maximum NO_x reduction performance. Moreover, ammonia slip is undesirable. The test results of some vehicles show a maximum quantity of reduced NO_x of around 600 to 750 mg/km. It is likely that the maximum performance of these SCR catalysts is already reached and injecting more AdBlue would yield an ammonia slip, which would cause penetrant odours which are not desirable.

Test results do however indicate that for some of the tested vehicles, such as vehicle M1, which has low SCR conversion rates and relatively cold exhaust gas, injecting more AdBlue may result in improved NO_x reduction.

Are the test results representative for all Euro 6 diesel vehicles?
The sixteen tested vehicles can be classified as medium and large vehicles. Most of these vehicles are equipped with LNT or SCR technology and are not representative for the whole Euro 6 diesel fleet. It is expected that the bulk of the small and medium size diesel vehicles, that will become available in September 2015, will be equipped with cheaper technology. Especially their NO_x emissions on the highway are expected to be relatively high. Possibly, the overall real-world NO_x emission performance of Euro 6 vehicles will turn out to be equal to Euro 4 and Euro 5 diesel vehicles.

How can real-world NO_x emissions of Euro 6 vehicles be improved?
In order to improve real-world emissions Real Driving Emission legislation (RDE) is needed. This legislation describes the test procedure and data evaluation methods for determination of real-world emission levels or Conformity Factors. Currently negotiations between the European Commission and the automotive industry are ongoing and it is expected that RDE-legislation for light duty vehicles will be implemented in 2017 or 2020.

How can SCR-technology be assessed?
In order to assess SCR-technology it is benchmarked with two other technologies. From 1988 onwards the three-way catalyst technology on petrol engines has been applied. Currently the engine control systems and the catalyst technologies are well developed and the real world CO, THC and NOx emissions have been reduced with 90-99%. Since 2002 the closed diesel particulate filters have entered the market and their PM-filter efficiencies of more than 99% are remarkable. Furthermore, this technology is robust against varying circumstances because all exhaust gas is filtered.
Fortunately Euro VI heavy duty vehicles show significant reductions of their real world NO_x emissions. The only cause for this huge NO_x reduction can be found in the emission legislation. On the contrary the real world NO_x emission of Euro 5 and 6 light duty vehicles still strongly exceed the type approval limit values (3 – 10 times) because no RDE legislation is in to force. Some current Euro 6 vehicles have been equipped with DPF, EGR and SCR technologies and they have the potential to yield low real world emissions but the EGR and SCR technologies are only partly activated.

Summarizing the current status and real world emission of Euro 6 diesel vehicles and the available engine and aftertreatment technologies and the current status of heavy duty vehicles it is clear that the next step must be a proper RDE legislation for Euro 6 vehicles. This RDE legislation will be the main actor to ensure low real world emissions of light duty vehicles and will determine the real world effectiveness of NOx aftertreatment technologies.

Euro 5 light commercial vehicles:
The selected and tested vehicles are mainstream light 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 of specific vehicle models.

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.

Despite of the continuous tightening of the NO_x type approval limit values from Euro 1 to Euro 5 real-world NOx emission factors have stabilized at around 1430 mg/km in the last decade, as **Figure 11** clearly shows. In other words: the difference between type approval NO_x emissions and real-world NOx 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.

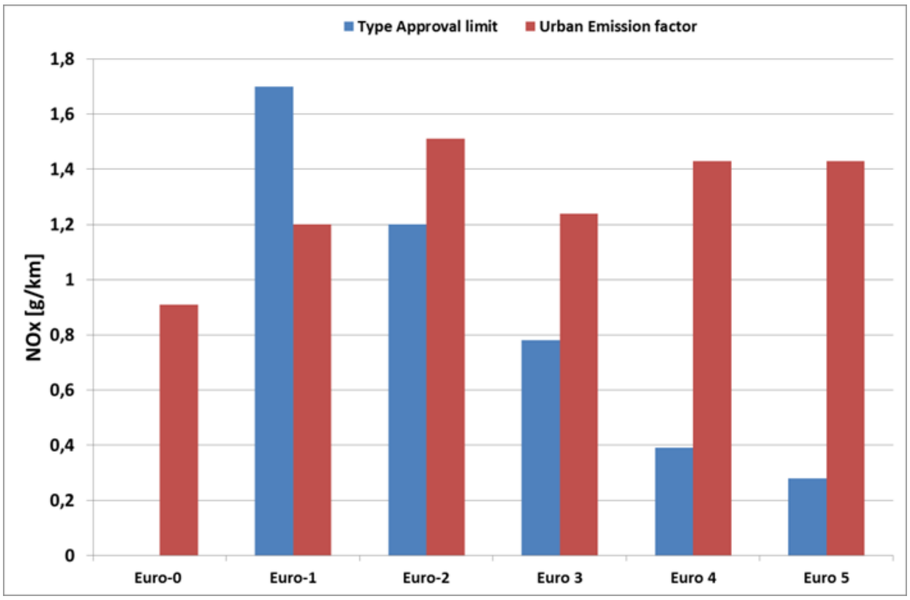

Figure 11: NOx emission factors in the city and type approval limit values of diesel commercial vehicles.

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.

6 Conclusions

In several emission test programs TNO has tested sixteen Euro 6 diesel passenger cars and 10 Euro 5 Light Commercial Vehicles. The tests were carried out on a chassis dynamometer and on the road with mobile test equipment. From the measurements, TNO draws the following conclusions:

1. all sixteen Euro 6 diesel passenger cars comply with or perform very near the type approval CO, THC, NO_x, PM and PN limit values. Especially the prototypes in the test program of 2010 performed well on the chassis dynamometer. These vehicles were however not tested on the road.
2. for all tested vehicles the effect of a hot start on NOx emission differs widely; for some vehicles the NOx emission decrease but for other vehicles it increases a factor 3.
3. the range of NOx emissions of Euro 6 diesel passenger cars in real-world tests is very large with values from 50 to more than 2000 mg/km. On average real-world emissions are 5 to 6 times higher than the type approval limit value of 80 mg/km. This seems to indicate that emission control technologies perform differently on the road than they do on the chassis dynamometer. Moreover the real world NOx emission per road type of the different vehicles differ widely. Only proper RDE-legislation can improve these real driving emissions.
4. current Euro 6 diesel vehicles with low real-world NOx emissions run with active and well-functioning EGR and SCR systems. Vehicles with higher real-world emissions seem to operate with EGR systems that are inactive or partly inactive. In that case, the SCR system is not able to reduce the high engine-out NOx emissions.
5. it is expected that for Euro 6 compact cars the simplest and cheapest emission control technology will be applied, i.e. it is likely that these vehicles will be equipped with limited emission control technology. This signifies a risk of high NO_x emissions similar to Euro 5, in particular on the motorway.
7. TNO's Smart Emission Measurement System yields repetitive emission test results which are in line with chassis dynamometer test results. Therefore SEMS is classified as a road vehicle emission screening tool.
8. normalisation of real-world NOx emissions of a couple of TNO reference trips with two normalisation tools, EMROAD and CLEAR, yield different results. EMROAD correction values range from -11% to +3% and CLEAR applies corrections between -26 and + 23%. However these results only represent a regular driving style. In order to judge the quality of these two normalisation tools more data and more research with different driving styles is needed.
9. the average NO_x emissions of the N1 class III Euro 5 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 NOx emissions of around 1300 mg/km in a Remote Emission Sensing experiment. The only vehicle showing relatively low NOx emissions was an N1 class II vehicle, with a relatively low weight. The effect of payload on NOx emissions is moderate. In city trips and reference trips an increase of the payload

from 28% to 100% results in an average increase of NOx 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.

10. The large and increasing difference between the NO_x 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.

11. The new emission data have been used to update the current Dutch emission factors for light commercial vehicles. Except for the emission factor for congested motorway operation, NOx emission factors increase with 33% to 85%.

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