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Date	18 May 2015
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Copy no	2015-TL-RAP-0100285486
Number of pages	75 (incl. appendices)
Number of appendices	3
Sponsor	Dutch Ministry of Infrastructure and the Environment PO Box 20901 2500 EX THE HAGUE The Netherlands
Project name	In use compliance program for light-duty vehicles
Project number	060.14432

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Samenvatting

Uit onderzoek uitgevoerd in opdracht van het Ministerie van Infrastructuur en Milieu blijkt dat de NO_x-emissie van een aantal geteste Euro 6 dieselpersonenauto's onder praktijkomstandigheden flink hoger ligt dan op grond van de Euro 6 norm mag worden verwacht. De Euro 6 norm werd in 2014 van kracht en beoogt een substantiële verlaging van de schadelijk uitstoot van personenauto's en bestelwagens. Ondanks het aanscherpen van de NO_x-norm van 180 mg/km (Euro 5) naar 80 mg/km (Euro 6) ligt de praktijk NO_x-emissie van de geteste voertuigen op circa 500 mg/km. Daarmee ligt de NO_x-emissie van Euro 6 personenwagens op hetzelfde niveau als dat van Euro 4 en Euro 5 dieselpersonenauto's.

In opdracht van het Ministerie van Infrastructuur en Milieu heeft TNO onderzoek gedaan naar het praktijkemissiegedrag van Euro 6 personenwagens die zijn uitgerust met dieselmotor. In het bijzonder ging het om voertuigen die zijn voorzien van een SCR-katalysator voor het terugbrengen van de NO_x-uitstoot. Het onderzoek is een basis voor de vaststelling van de jaarlijkse emissiefactoren. Ook heeft het Ministerie aan TNO gevraagd adviezen op te stellen voor maatregelen die resulteren in lage praktijkemissies die in lijn zijn met de emissies in de typegoedkeuringstest.

Leeswijzer:

Dit onderzoek is gebaseerd op emissiemetingen aan zestien Euro 6 diesel personenwagens. De metingen zijn uitgevoerd in 2010 (fase 1), 2013 (fase 2) en 2015 (fase 3), zowel in een laboratorium als op de openbare weg. Vervolgens zijn de meetresultaten beoordeeld aan de hand van de toegepaste emissietechnologie. Als laatste worden op basis van deze resultaten aanbevelingen gedaan voor de regulering van praktijkemissies in de toekomstige emissiewetgeving.

Resultaten: praktijkemissies liggen flink hoger dan Euro 6 limietwaarde

Bij de uitgevoerde testen gaat het zowel om metingen in het laboratorium op de rollenbank als om metingen met mobiele meetapparatuur (PEMS en SEMS) op de openbare weg. De testen laten zien dat alle zestien geteste voertuigen op basis van de NEDC *typekeuringstest* aan de Euro 6 NO_x-norm van 80 mg/km voldoen. Onder *praktijkomstandigheden* ligt de NO_x-uitstoot echter tot wel een factor acht hoger. De deeltjesemissies van de voertuigen waren wel ruim beneden de wettelijke norm van 4,5 mg/km. Dit is toe te schrijven aan de aanwezigheid van gesloten roetfilters in deze Euro 6 voertuigen.

Per onderzoeksfase volgt nu een toelichting.

- Voor fase 1 van het onderzoek zijn in 2010 vier pre-productie 'Euro 6' dieselpersonenauto's op een rollenbank getest. Het ging om voor de Amerikaanse markt bestemde typen voertuigen die voorzien waren van technologie om de emissies tot Euro 6 niveau terug te brengen, maar die nog niet officieel de Euro 6 typekeuring hadden doorlopen. De vier voertuigen van fase 1 zijn in 2010 alleen op een rollenbank getest. In de meer praktijkgerichte CADC-testcyclus presteerden de voertuigen gemiddeld goed, met een NO_x-

- uitstoot van 80 tot 270 mg/km. Deze resultaten vormden de basis voor hoge verwachtingen van de NO_x-prestaties van toekomstige Euro 6 voertuigen.
- Voor fase 2 zijn in 2013 zes productie-dieselpersonenauto's met verschillende technologieën zowel op de rollenbank als op de weg in de praktijk getest. De NO_x-praktijkemissies van deze voertuigen lopen zeer sterk uiteen, van 10 tot wel 800 mg/km. Voor het merendeel van de voertuigen lagen de gemiddelde NO_x-praktijkemissies tussen 400 en 800 mg/km. Eén getest voertuig presteerde wel goed en haalde onder praktijkomstandigheden 35-95% van de NO_x-limietwaarde.
 - Voor fase 3 van het project is in 2014 en 2015 specifiek onderzoek gedaan naar Euro 6 dieselpersonenauto's met EGR en SCR. Aan deze combinatie van technologieën wordt namelijk een grote potentie toegekend voor het terugbrengen van de NO_x-emissies. Er zijn zes productievoertuigen met EGR- en SCR-technologie op de rollenbank en uitgebreid op de weg getest. Ook bij deze voertuigen variëren de praktijkemissies zeer sterk en zijn deze in bijna alle gevallen veel hoger dan in het laboratorium. Deze gemiddelde NO_x-praktijkemissies liggen tussen 150 en 850 mg/km. Slechts één van de zes geteste voertuigen maakte met een praktisch NO_x-uitstoot van 150 g/km de hoge verwachtingen van de combinatie van EGR- en SCR-technologie waar. Voor fase 3 zijn geen Euro 6 voertuigen met alleen EGR of met EGR en LNT gemeten.
 - Vier van de zes voor fase 3 geteste voertuigen zijn nader onderzocht door voor en na de SCR-katalysator de NO_x-emissie te meten. Uit dit onderzoek blijkt dat de afstellingen van de motoren en de EGR-systemen meer invloed hebben op de NO_x-emissies van het voertuig dan de afstellingen van de SCR-systemen. De NO_x-emissies die voor de SCR-katalysatoren zijn gemeten, liggen voor een gecombineerde rit tussen 650 en 1250 mg/km. De bijdrage van de SCR-systemen aan de totale NO_x-reductie ligt tussen 400 en 700 mg/km.
 - De NO_x-emissie van 150 mg/km van het zeer goed presterende voertuig wordt gerealiseerd door een lage NO_x-emissie van de motor van 650 mg/km in combinatie met een NO_x-reductie van 500 mg/km in het SCR-systeem. De resultaten van dit onderzoek tonen aan dat lage NO_x-praktijkemissies van Euro 6 dieselveertuigen mogelijk zijn door een goede afstelling van de motor en het EGR-systeem in combinatie met een SCR-systeem dat voldoende NO_x-reductiepotentieel heeft.

Bijna alle gemeten Euro 6 voertuigen stoten in een praktijkrit op de weg fors meer NO_x uit dan tijdens een typekeuringstest in het laboratorium. Eén voertuig laat in praktijkritten op de weg een gemiddelde NO_x-uitstoot zien van circa 650 mg/km, terwijl dit voertuig in het laboratorium tijdens alle rollenbankmetingen, dus ook tijdens andere cycli dan de typekeuring, ruimschoots aan de Euro 6 limiet van 80 mg/km voldeed. Het is opmerkelijk dat de NO_x-uitstoot in de praktijk meer dan acht maal zo hoog is als de typekeuringswaarde. Het verschil toont aan dat de regelingen van de motor, de EGR en de SCR tijdens een gecombineerde praktijkrit niet zodanig zijn dat een lage NO_x-emissie wordt gerealiseerd.

Het is de verwachting dat de kleinere dieselveertuigen die in 2015 op de markt komen net als Euro 5 voertuigen slechts zijn uitgerust met alleen EGR-technologie. Gezien de praktijk bij de reeds geteste Euro 5 voertuigen is het niet uitgesloten dat ook de praktijkemissies van die voertuigen relatief hoog zullen blijken te zijn. Een snelle en relatief goedkope screening van de praktijkemissies van deze voertuigen is mogelijk met een Smart Emissions Measurement System (SEMS).

Praktijkemissies al jaren fors hoger dan typekeuringswaarde

Ondanks een voortdurende aanscherping van de NO_x-emissienormen van Euro 1 naar Euro 6, zijn voor rijomstandigheden op de snelweg de NO_x-praktijkemissies van dieselpersonenauto's de laatste tien jaar ongeveer gelijk gebleven, variërend tussen de 400 – 600 mg/km. In stadsverkeer is wel sprake van een reductie, maar de NO_x-emissie ligt nog altijd ver boven de limietwaarde van de typegoedkeuring van 80 mg/km.

Wat is nodig voor de realisatie van lage praktijkemissies?

Dit onderzoek toont aan dat Euro 6 voertuigen tot wel acht keer hogere praktijkemissies hebben dan de limietwaarde. Tot op heden ontbreekt het echter aan wetgeving die praktijkemissies reguleert. Momenteel wordt evenwel in Brussel gewerkt aan wetgeving voor een nieuwe typekeuringstest die de NO_x-uitstoot van dieselpersonenauto's onder rijomstandigheden in de praktijk moet gaan reguleren. De kwaliteit van deze wetgeving en vooral de kwaliteit van de onderliggende testprocedures en protocollen zullen van grote invloed zijn op de uiteindelijke resultaten in de praktijk.

Welke technische verbeteringen zijn mogelijk?

Uit detailonderzoek van de emissieprestaties van voertuigen met SCR-katalysatoren blijkt dat lagere NO_x-emissies in de praktijk mogelijk zijn. Lagere NO_x-emissies kunnen worden gerealiseerd door wijzigingen van motorafstellingen, in combinatie met wijzigingen van de in te spuiten hoeveelheid AdBlue. Dit vereist echter wel een herontwikkeling van deze motoren omdat de operationele condities in dat geval sterk wijzigen. Voor de meeste huidige dieselpersonenwagens, die een AdBluetank hebben van circa 15 tot 25 liter groot, zal in dat geval bovendien tussen onderhoudsbeurten door AdBlue moeten worden bijgevuld. Eén van de geteste voertuigen heeft een AdBluetank die groot genoeg is voor het voldoende verlagen van de NO_x-uitstoot.

Hoe presteren de twee evaluatiemethoden van praktijkemissies (EMROAD en CLEAR), die in toekomstige RDE wetgeving worden geïmplementeerd?

Op basis van meetdata van een vaste referentierit op de weg in Nederland zijn de genormaliseerde emissies van diverse voertuigen met twee verschillende evaluatiemethoden (EMROAD en CLEAR) verkend. De verschillen in resultaten van de evaluatiemethoden variëren tussen +23 en -26%. EMROAD blijkt gemiddeld kleinere correcties toe te passen dan CLEAR en deze EMROAD-correcties lijken ook meer consistent. Op basis van deze beperkte dataset kan geen definitief oordeel worden gegeven over de twee evaluatiemethoden. Daarvoor zijn meer testresultaten met verschillende rijstijlen van Euro 6 voertuigen nodig.

Wat is de potentie van EGR- en SCR-technologie?

In de afgelopen decennia zijn de driewegkatalysator voor benzinemotoren en het roetfilter voor dieselmotoren doorontwikkeld tot volwaardige producten die in de praktijk omzettingsrendementen van 90-99% behalen. Dit succes kan nu een vervolg krijgen met EGR-, LNT- en SCR-technologieën. Hiervoor is wetgeving nodig waarin praktijkemissies worden gereguleerd.

Summary

A study conducted on behalf of the Dutch Ministry of Infrastructure and the Environment reveals that NO_x emissions of a number of tested Euro 6 diesel passenger vehicles are significantly higher under real-world conditions than would be expected on the basis of the Euro 6 standard. The Euro 6 standard, which came into force in 2014, has aimed at a substantial reduction of pollutant emissions from passenger vehicles and light commercial vehicles. Despite the tightening of the NO_x standard from 180 mg/km (Euro 5) to 80 mg/km (Euro 6), NO_x emissions of the tested vehicles measure in practice at around 500 mg/km. This means that NO_x emissions of Euro 6 passenger vehicles are at the same level as those of Euro 4 and Euro 5 diesel passenger vehicles.

TNO was commissioned by the Dutch Ministry of Infrastructure and the Environment to investigate the real-world emissions of Euro 6 diesel-engine passenger vehicles, and in particular vehicles fitted with an SCR catalyser to reduce the NO_x emissions. The study forms a basis for determining Dutch annual emission factors. The Ministry also instructed TNO to advise on measures to reduce real-world emissions in line with the type approval emissions.

Structure of the study:

This study is based on the emission measurements of sixteen Euro 6 diesel passenger vehicles. The measurements were performed in 2010 (phase 1), 2013 (phase 2), and 2015 (phase 3), both in laboratory conditions and on the open road. The measurements were then analysed on the basis of the applied emission reduction technologies. Lastly, on the basis of these results, recommendations have been drawn up for the regulation of real-world emissions within future legislation on emissions.

Results: real-world emissions are significantly higher than the value limit set by Euro 6

The tests performed included both measurements on a chassis dynamometer under laboratory conditions and measurements using portable equipment (PEMS and SEMS) on the road. The tests reveal that on the basis of the NEDC type approval test, all sixteen vehicles satisfy the Euro 6 NO_x standard of 80 mg/km. Under real-world conditions, however, NO_x emissions were higher than this by a factor of up to eight. The particulate emissions of the vehicles were well below the regulatory limit of 4.5 mg/km. This is attributed to the presence of closed diesel particulate filters in these Euro 6 vehicles. An explanation is given of each phase of the investigation.

- In 2010, in phase 1 of the investigation, four pre-production Euro 6 diesel passenger vehicles were tested only on a chassis dynamometer. These were vehicles intended for the US market equipped with the technology to reduce emissions to Euro-6 level, but that had not yet officially been given Euro-6 type approval. In the CADC test cycle, which is closer to real-life conditions, the vehicles performed averagely well, with NO_x emissions of between 80 and 270 mg/km. These results formed the basis for greater expectations for the NO_x performance of future Euro 6 vehicles.
- In 2013, in phase 2, six production diesel passenger vehicles with various technologies were tested both on the chassis dynamometer as well as on the road. The NO_x real-world emissions of these vehicles varied very considerably

from 10 to as high as 800 mg/km. The average NO_x real-world emissions of the majority of the vehicles were between 400 and 800 mg/km. One of the vehicles performed well, achieving 35% to 95% of the NO_x limit value under real-world conditions.

- In 2014 and 2015, in phase 3, investigation of Euro 6 diesel passenger vehicles with EGR and SCR technology was undertaken, since this combination of technologies offers considerable potential for reducing NO_x emissions. Six production vehicles with EGR and SCR technology were tested on the chassis dynamometer and extensively on the road. In the case of these vehicles too, the real-world emission varied very strongly and in almost all cases the readings were much higher than the laboratory readings. The average NO_x real-world emissions were measured at between 150 and 850 mg/km. Only one of the six vehicles justified the high expectations of the combination of EGR and SCR technology, with real-world NO_x emissions of 150 g/km. In phase 3 no Euro 6 vehicles with just EGR or EGR and LNT were measured.
- Four of the six vehicles tested for phase 3 were further investigated by measuring the NO_x emissions before and after the SCR catalyser. These tests revealed that the settings of the engines and the EGR systems have more influence on the vehicles' NO_x than the settings of the SCR systems. For a combined test trip, representing typical Dutch operational conditions, the NO_x emissions for the SCR catalysers measure between 650 and 1250 mg/km. The SCR systems contribute to the total NO_x reduction by between 400 and 700 mg/km.
- The vehicle that performed well achieved NO_x emissions of 150 mg/km due to low NO_x emissions from the engine of 650 mg/km, combined with an NO_x reduction of 500 mg/km in the SCR system. The results of this investigation reveal that low real-world emissions of Euro 6 diesel vehicles are possible with effective settings of the engine and the EGR system in combination with an SCR system that has sufficient potential to reduce NO_x emissions.

Virtually all the Euro 6 vehicles tested emit significantly more NO_x on real-world test trips on the road than during a type approval test in the laboratory. One vehicle easily satisfied the Euro 6 limit of 80 mg/km during all chassis dynamometer measurements in the laboratory, i.e. also during test cycles other than the official test protocol. In real-world driving tests on the road, however, the vehicle measured an average NO_x emission of around 650 g/km. It is remarkable that the NO_x emission under real-world conditions exceeds the type approval value by a factor of eight. It demonstrates that the settings of the engine, the EGR and the SCR during a real-world test trip are such that they do not result in low NO_x emissions in practice. In other words: In most circumstances arising in normal situations on the road, the systems scarcely succeed in any effective reduction of NO_x emissions.

It is anticipated that the smaller diesel vehicles to be introduced onto the market in 2015 will only be fitted with EGR technology alone, like the Euro 5 vehicles. Given what was revealed from previous real-world testing of Euro 5 vehicles, the possibility cannot be excluded that real-world emissions of these vehicles will also be relatively high. A quick and relatively cheap screening of the real-world emission of these vehicles is possible using an SEMS measuring system.

For years the real-world emissions have been significantly higher than the type approval value

Despite the gradual tightening of NO_x emission standards from Euro 1 to Euro 6, over the last ten years NO_x real-world emissions of diesel passenger vehicles driving on the highway have remained more or less constant, varying between 400-600 mg/km. And although NO_x emissions in city trips have decreased, they nevertheless remain far higher than the limit value of the type approval of 80 mg/km.

What is required to achieve low real-world emissions?

This study reveals that real-world emissions of Euro 6 vehicles are up to eight times higher than the limit value. However, to date, there is no legislation to regulate real-world emissions, although steps are being taken in Brussels to draft legislation for a new type approval test intended to regulate the NO_x emissions of diesel passenger vehicles driving under real-world conditions. The quality of this legislation and in particular the quality of the underlying test procedures and protocols will significantly influence the ultimate results in practice.

What technical improvements are possible?

A detailed study of emission performances of vehicles fitted with SCR catalysers reveals that lower real-world NO_x emissions are possible. Lower NO_x emissions can be achieved by applying effective engine settings, combined with changes to the amount of AdBlue to be injected. This does require, however, a redesign of these engines because in such a situation the operational conditions would be very different. Having an AdBlue tank capacity of between 15 and 25 liters, for most of the vehicles that are currently available this would imply the tanks would have to be filled up with AdBlue in between maintenance checks. One of the tested vehicles has an AdBlue tank with a capacity that is adequate for a sufficient reduction of the NO_x emission under real-world conditions.

How do the two methods for calculating real-world emissions (EMROAD and CLEAR) – to be implemented in future RDE legislation – perform?

On the basis of measurement data taken from a fixed reference trip on the road in the Netherlands, the standardized emissions of various vehicles are explored using two different evaluation methods (EMROAD and CLEAR). The differences in the results from the two evaluation methods vary between +23% and -26%. On average, EMROAD applies smaller corrections than CLEAR, and these corrections also appear to be more consistent. However, it is not possible to deliver a definitive judgment on the two evaluation methods on the basis of this limited set of data, and more test results for various driving conditions for Euro 6 vehicles are needed.

What is the potential for EGR and SCR technology?

Over the past decades the three-way catalyser for petrol engines and the closed particulate filters for diesel engines have been developed into fully-fledged products that in real-world situations achieve conversion rates of 90-99%. This success may now be followed up by EGR, LNT, and SCR technologies. This requires legislation to regulate real-world emissions.

Contents

Samenvatting	2
Summary	5
1 Introduction	9
1.1 Background.....	9
1.2 Aim and approach.....	10
1.3 Structure of the report.....	10
2 Method	11
2.1 Test methods	11
2.2 Tested vehicles	17
2.3 Test cycles and routes.....	19
3 Experimental results	20
3.1 Chassis dynamometer results	20
3.2 Performance of SEMS test equipment on a chassis dynamometer.....	23
3.3 On-road NO _x emission test results of Euro 6 vehicles	26
3.4 Evaluation of Real Driving Emissions.....	29
3.5 Detailed overview of SEMS results of SCR vehicles.....	32
4 The potential of vehicles with SCR systems	39
4.1 Considerations.....	39
4.2 Investigations of NO _x reductions and SCR conversion rates of tested vehicles	40
4.3 Investigation of vehicles with SCR technology and their characteristics.....	42
4.4 Required amount of AdBlue for low real-world NO _x emissions	44
5 Discussion	47
6 Conclusions	50
7 Recommendations	51
8 References	52
9 Signature	53
Appendices	
A TNO chassis dynamometer test results	
B Pre-SCR and post-SCR emissions	
C AdBlue calculations	
D Additional tables for RDE evaluation	

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 passenger cars of category M1 must comply with the Euro 5B+ standard.

Since September 2014 all new type approved vehicles must comply with Euro 6 regulations and from September 2015 onwards all registered vehicles need to comply with the Euro 6 limits, therefore the tested vehicles are relatively early models. The focus of the test programme were compression ignition (diesel) vehicles. In this report only passenger cars are reported

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 NO₂ emitted, reducing NO_x emissions of vehicles are an important measure in bringing down the ambient NO₂ concentration. In the Netherlands, the ambient NO₂ 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.

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.

In this report the results of sixteen Euro 6 diesel passenger cars are discussed.

1.2 Aim and approach

The objective of this research is to assess the real-world emission performance of Euro 6 M1 diesel passenger cars and to assess the NO_x reduction performance of Euro 6 technologies.

Emission measurements on the chassis dynamometer and on the road were performed with Euro 6 compliant vehicles, equipped with a Portable Emission Measurement System (PEMS) and/or TNO's Smart Emission Measurement System (SEMS).

1.3 Structure of the report

Chapter 2 first describes the test methodologies and the tested vehicles. In Chapter 3, the experimental results are described. Then, Chapter 4 provides an analysis of the potential of SCR technology. Chapter 5 then places the results described in chapters 3 and 4 in perspective, after which in Chapter 6 conclusions are drawn. Recommendations are the topic of Chapter 7.

2 Method

2.1 Test methods

Both the chassis dynamometer tests as well as the on-road tests using PEMS and/or SEMS were performed in various test cycles with all sixteen vehicles.

2.1.1 Chassis dynamometer testing

Most of the vehicles were tested according to the official test procedure (UNECE Reg 83), but different driving cycles with cold start or hot start conditions were also conducted.



Figure 1: Emission test on a chassis dynamometer.

The following regulated emissions were measured: CO (carbon monoxide), THC (total hydrocarbons), NO_x (nitrogen oxides), PM (particulate mass) and PN (particulate number). Additionally, CO₂ (carbon dioxide) was measured. Table 1 gives an overview of the measuring methods.

Table 1: Measurement principles.

Component	Analyse
CO	Non Dispersive Infrared (NDIR)
HC	Heated Flame Ionization Detection (HFID)
NO _x	Chemo Luminescence (CLA)
CO ₂	Non Dispersive Infrared (NDIR)
PM	Gravimetric
PN	Condensation Particle Counter (CPC) with Volatile Particle Remover (VPR)

For the tests regular diesel (trade fuel) was used.

Road load settings were for each vehicle provided by the manufacturer. In addition WLTP road load settings were used. For some vehicles the manufacturer provided the WLTP road load settings; in case WLTP settings were not available they were calculated. If necessary also a chassis dynamometer ‘test mode’ was activated in order to avoid problems with start stop, ESP, etc. In some cases the manufacturer was present during the tests.

Chassis dynamometer test cycles

The following test cycles were used to assess the emission performance of the Euro 6 vehicles:

– NEDC (New European Driving Cycle)

The NEDC (see Figure 2) is used for the official type approval of a vehicle. During this test the emissions needs to comply with the applicable limit. The NEDC consist of the UDC (Urban Driving Cycle) and the EUDC (Extra Urban Driving Cycle). According to the formal type approval procedure, the NEDC begins with a so-called cold start. The emission results of the NEDC with a cold start were used to check whether the vehicle complies with the Euro 6 limit and to check if the vehicle was technically in good condition. Some vehicles were additionally tested over an NEDC with a *hot* start to gain more information about the emission performances.

The NEDC is relatively short (± 11 km) and, as a result, the cold start effect is quite large. The largest part (in time, not in distance) of the NEDC is urban driving and engine loads are relatively low.

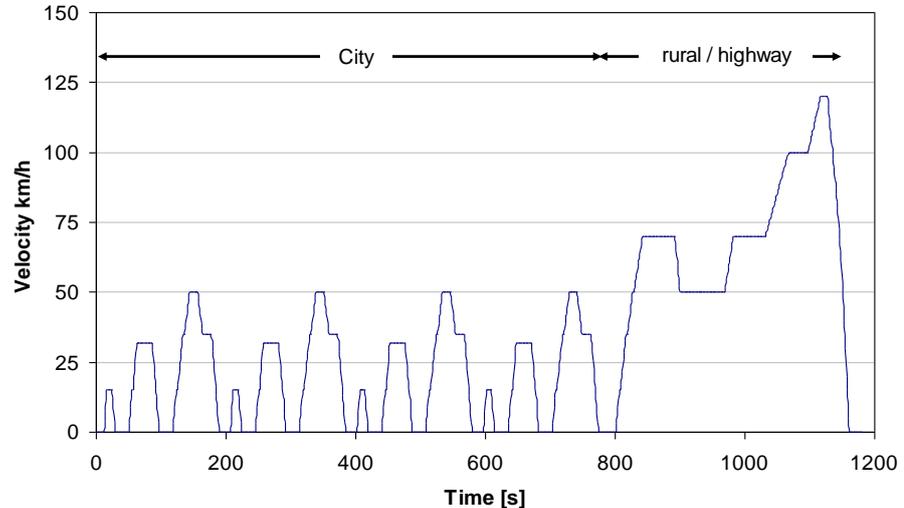


Figure 2: NEDC (New European Driving Cycle).

– CADC (Common Artemis Driving Cycle):

The CADC (see Figure 3) is a cycle which better represents real-world driving than the NEDC. The CADC, however, is not part of the official type approval procedure. The cycle consists of an urban, a rural and a motorway part. For the motorway part there are two possibilities: a maximum speed of 130 km/h or a maximum speed of 150 km/h. TNO used both versions.

A cold and hot start are both possible with the CADC. In this report, the CADC

with a hot start is shown for most tested vehicles. In the most recent tests also CADC's with a cold start were performed. During these tests, a second urban part was driven directly after the motorway part, resulting in a CADC with a cold urban part and a hot urban part. As can clearly be seen in Figure 3, the CADC is more dynamic and reaches higher speeds than the NEDC does. The cycle is significantly longer than the NEDC (± 23 km), hence the relative cold start effect is not very large on the total emission.

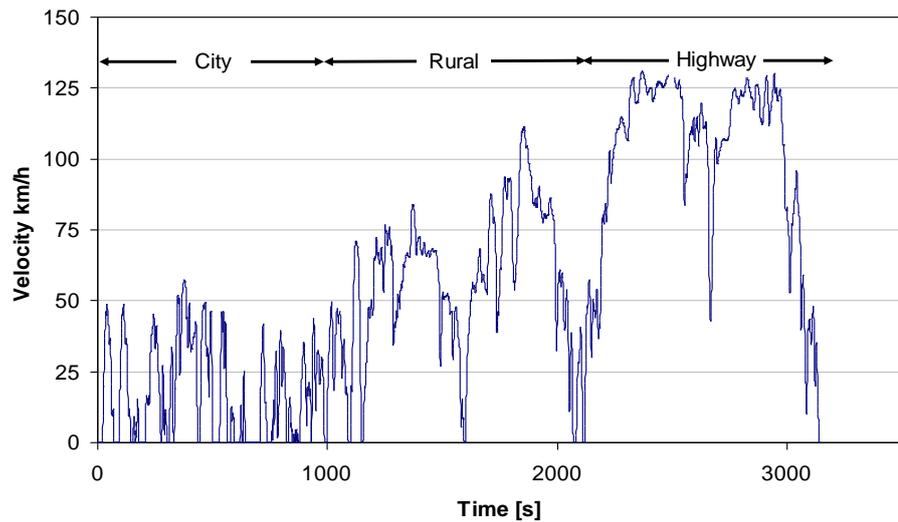


Figure 3: CADC (Common Artemis Driving Cycle).

- WLTC (Worldwide harmonized Light duty driving Test Cycle):
Currently a new worldwide harmonized type approval procedure (WLTP) for light duty vehicles is under development, which involves a new driving cycle: the Worldwide harmonized Light duty driving Test Cycle, or WLTC. The WLTC (see Figure 4) consists of four parts: low (speed), medium (speed), high (speed) and extra high (speed). In case the WLTC will be approved as part of official legislation it will, most likely, begin with a cold start. In this testing program, the WLTC was often performed with both a hot start and a cold start. Compared to the NEDC, the cold start effect on the WLTC is relatively low due to the length of the cycle (± 45 km). The WLTC is more dynamic and reaches higher speeds than the NEDC, however, it is less dynamic than the CADC.

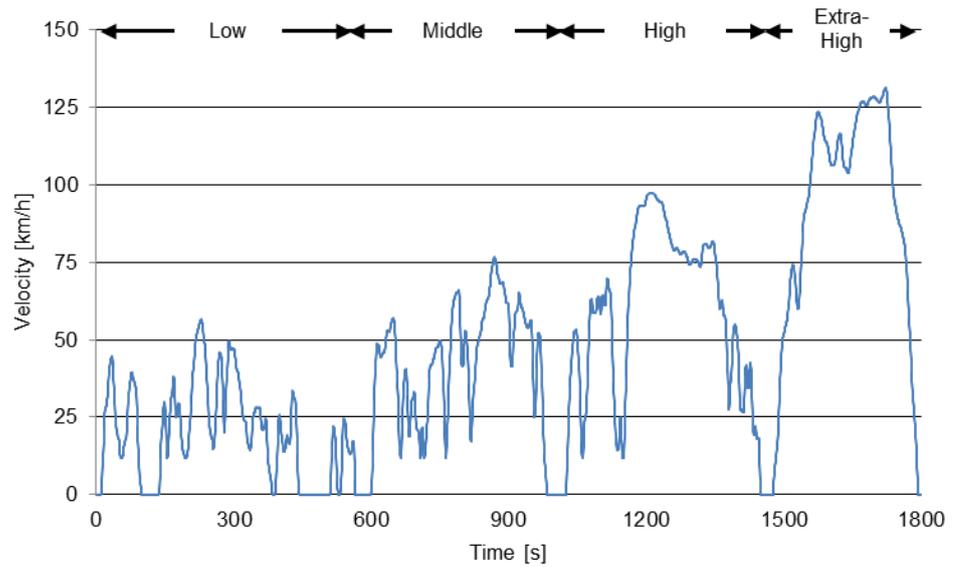


Figure 4: WLTC_v5 (Worldwide harmonized Light duty driving Test Cycle).

2.1.2 PEMS testing

Emission tests with different vehicles were performed on the road under real-world conditions using a so-called Portable Emission Measurement System (PEMS). PEMS equipment is capable of measuring CO, CO₂, HC, NO and NO₂ emissions. During the PEMS tests, the vehicle was loaded with a test driver, a test engineer and the test equipment (including a generator), amounting to a total test weight of approximately 200 kg.



Figure 5: A test vehicle equipped with a Portable Emission Measuring System (PEMS).

2.1.3 SEMS testing

In recent years, TNO has developed the so-called Smart Emission Measurement System (SEMS). Most vehicles in this testing program were also tested using SEMS.

SEMS is an emission screening tool which contains a data logger, an $\text{NO}_x - \text{O}_2$ 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 [TNO2012], [TNO2014]. 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 NO_x and CO_2 mass flow rates [mg/km]. The quality of the air mass rate signal determines the accuracy of the NO_x mass emissions.

Figure 6, Figure 7 and Figure 8 show an example of a SEMS-instrumented vehicle.



Figure 6: NO_x sensor and thermocouple mounted in the vehicle's tailpipe.



Figure 7: Load packages (the black box, left on the picture) and data logger of the SEMS (blue cradle).



Figure 8: The laptop used to monitor and control the SEMS equipment.

Calculation of the NO_x and CO₂ emissions

SEMS measures and stores data from the installed sensors and signals available from the On-Board Diagnostic (OBD) system. The CO₂ volume concentrations are based on the measured O₂ concentrations and fuel parameters (using the so-called carbon balance method). The CO₂ and NO_x mass flow rates are based on data from the SEMS equipment (mass air flow rate and measured/calculated volumetric emissions).

The test and data processing procedure contains the following steps:

- 1 The CO₂ volume concentration is determined from the measured O₂ volume concentration and the fuel C:H ratio.
- 2 The fuel mass flow rate is determined from the vehicle Mass Air Flow signal, the fuel C:H ratio and the measured CO₂ concentration.
- 3 The exhaust flow rate is determined from the mass air flow rate and the fuel mass flow rate.
- 4 The CO₂ and NO_x mass flow rates are determined from the measured volume concentrations and the exhaust mass flow rate.

This analysis requires two 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. This is determined via calibration measurements.

The sensors of the SEMS equipment are calibrated. 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 CO₂ 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.

2.2 Tested 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.

Table 5 specifies the executed tests per vehicle.

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					
Type	-	Wagon	Sedan	Sedan	Sedan	MPV	MPV
Applied system for NO _x reduction	-	LNT	LNT	LNT	SCR	EGR	EGR

Table 4: Phase 3: Selection of Euro 6 vehicles with an 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	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	17	17
Phase 3	Selection of Euro 6 SCR models	Veh. K1	19	-	-
		Veh. K2	7	16	16
		Veh. L1	12	11	16
		Veh. M1	7	14	37
		Veh. N1	7	-	55
		Veh. O1	7	14	20
Total			119	101	161

2.3 Test cycles and routes

2.3.1 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 6 shows the main characteristics of the test trips. All trips are started in Helmond, the Netherlands, and are carried out with a minimum payload.

Table 6: 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.

2.3.2 Driving styles

The test driver receives instructions for the required driving style. This can be 'economic', 'normal' or 'sportive'. Some vehicles were tested with more driving styles.

3 Experimental results

TNO performed chassis dynamometer tests, as well as PEMS and SEMS tests. The chassis dynamometer test results and real world (or on road) test results are reported separately in the next sections.

3.1 Chassis dynamometer results

CO emissions:

In chassis dynamometer tests the CO emissions of most Euro 6 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 Euro 6 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.

NO_x emissions:

In Figure 9 up to Figure 11 the NO_x 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.

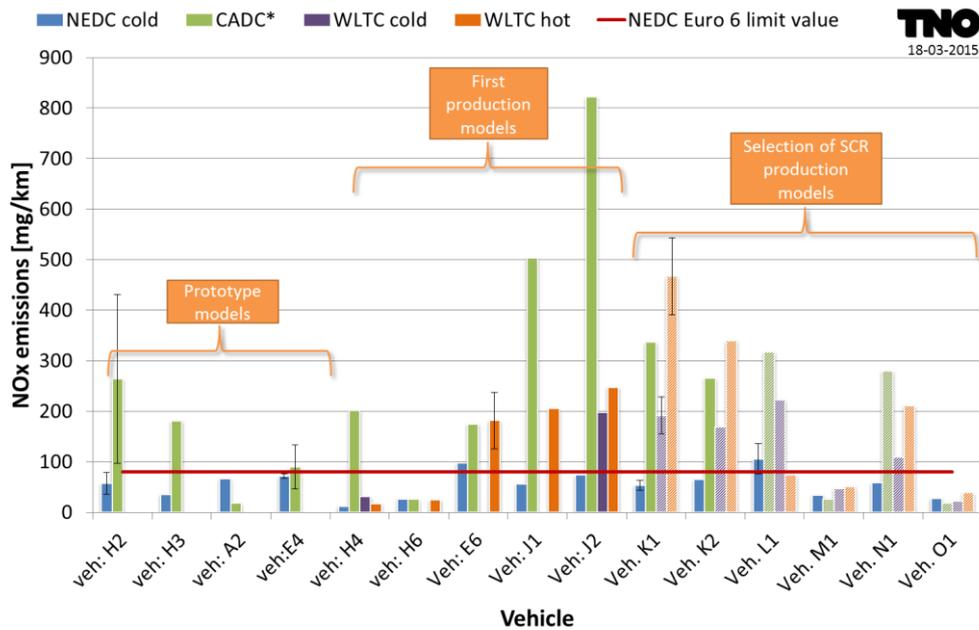


Figure 9: NO_x emissions per driving cycle.

*CADC with hot start, for veh: H2 to E6 motorway part 130 km/h was used, for veh: J1 to O1 motorway part 150 km/h was used.

**The bars in the figure that are shaded are tests with WLTP road load instead of NEDC road load.

Figure 10 and Figure 11 show the NO_x emission results per phase in NEDC and CADC tests. Some vehicles perform well in all types of chassis dynamometer tests; Vehicles A2, E4, H6, M1 and O1 have NO_x emissions below 80 mg/km. Vehicle H4 show very good results on all cycles as well, however, a DPF regeneration influenced the CADC result.

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 of WLTC tests are also often higher than the NEDC test results. Moreover the vehicles K1, K2 and N1 show significant higher NO_x 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 an 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 NEDC tests (Figure 10), in almost all cases the NO_x emissions of the urban phase are higher than in the extra urban phase. One exception exists: vehicle H6 has very low emissions in the urban phase after a hot start.

Vehicles E6, J1, J2 and N1 have significantly higher NO_x emissions in the NEDC urban phase with hot start than during this phase with cold start. Vehicle E6 and N1 show the same trend for the extra urban part of the NEDC. These results seem to indicate a selective use of NO_x control technologies in the different test cycles.

In the CADC tests of Figure 11 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 NO_x 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).

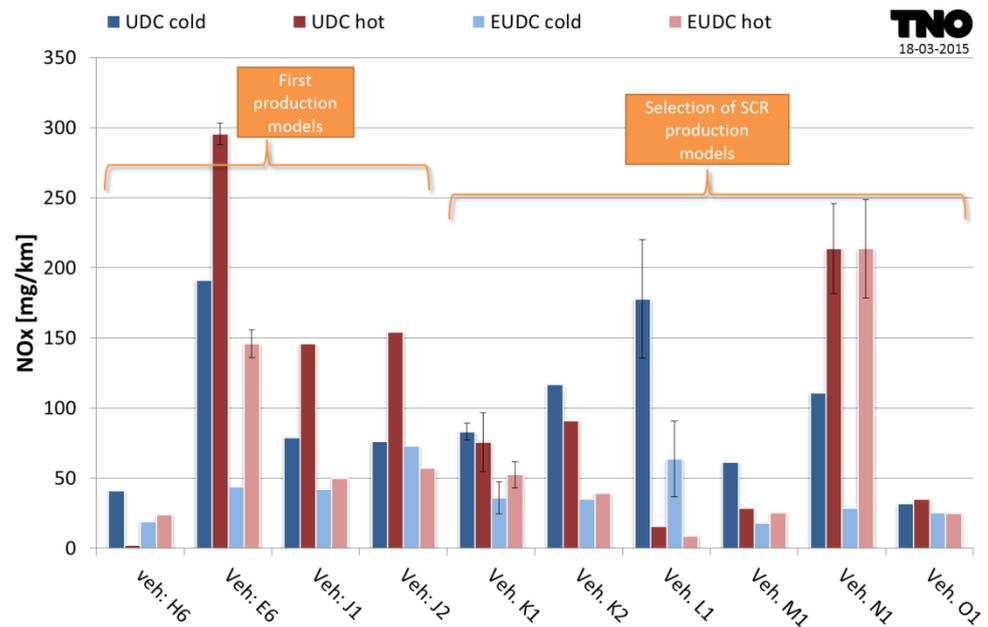


Figure 10: NO_x emissions per phase in the NEDC.

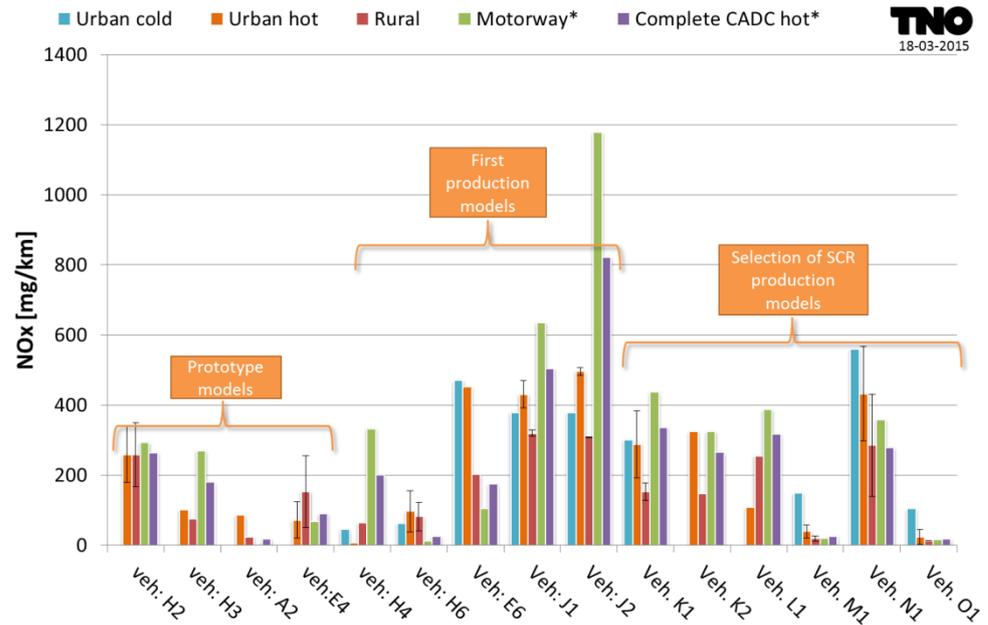


Figure 11: NO_x emissions per phase in the CADC.

The NO_x emission of all tested Euro 6 vehicles in type approval tests are below the type approval limit of 80 mg/km. However, the NO_x emission of these vehicles in other chassis dynamometer tests vary between 40 and 1150 mg/km.

3.2 Performance of SEMS test equipment on a chassis dynamometer

In order to validate the SEMS test results, validation tests were performed on a chassis dynamometer while testing vehicle N1. The CO₂ and NO_x test results are shown in Figure 12, Figure 13 and Table 7. 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 CO₂ deviation is 8% and the NO_x deviation is -14% to +12%. Both standard deviations for CO₂ 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.

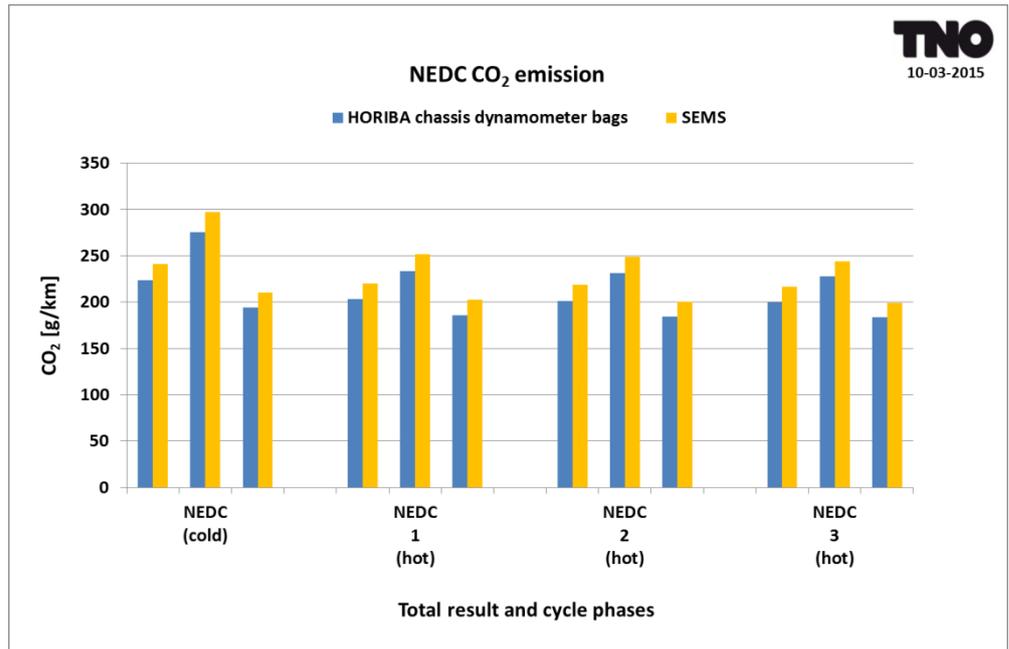


Figure 12: Validation CO₂ test results SEMS-chassis dynamometer.

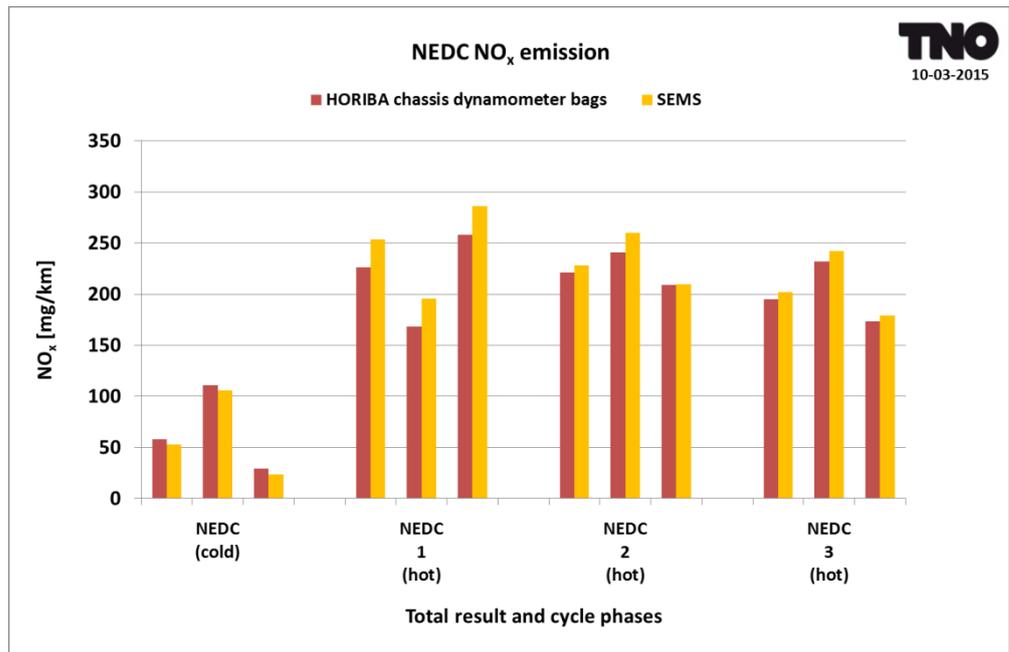


Figure 13: Validation NO_x test results SEMS-chassis dynamometer.

Table 7: SEMS and chassis dynamometer test results.

NEDC cold		Horiba	SEMS		Deviation
CO2					
Average	[g/km]	223.4	241.3		8.0%
St. Dev.	[g/km]	-	-		
NOx					
Average	[g/km]	58.0	50.0		-13.8%
St. Dev.	[g/km]	-	-		
3* NEDC hot					
CO2					
Average	[g/km]	201.4	218.1		8.3%
St. Dev.	[g/km]	1.8	2.6		
NOx					
Average	[g/km]	214.0	239.2		11.8%
St. Dev.	[g/km]	16.6	28.1		

In Figure 14 the NO_x and CO₂ volume concentrations of SEMS and the raw analyser of the chassis dynamometer are compared. Both measuring signals are in line, especially at lower volume concentrations. At higher NO_x concentrations, i.e. around 300 ppm, some deviation occurs.

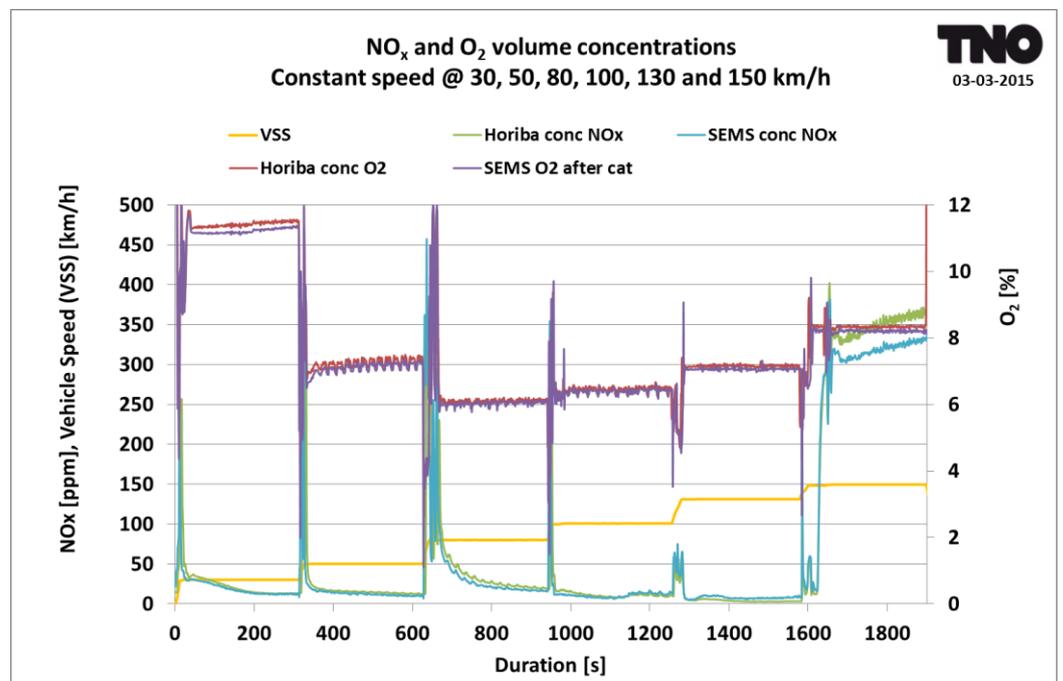


Figure 14: O₂ and NO_x volume concentrations with SEMS and chassis dynamometer analysers

The TNO 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.

3.3 On-road NO_x emission test results of Euro 6 vehicles

On-road NO_x emissions of seven Euro 6 vehicles were measured. Five vehicles were tested with PEMS and SEMS; two vehicles were tested with SEMS test equipment only.

NO_x emissions at constant speeds

In Figure 15 the on-road results of the NO_x emissions at constant speeds are shown. Overall the NO_x emissions of the different vehicles vary between almost 0 and 2000 mg/km. For most vehicles at speeds above 120 km/h the emissions increase substantially. Especially vehicle H7, K2 and M1 show very high emissions of approximately 850 to 2000 mg/km at speeds between 140 and 150 km/h. On the contrary vehicle O1 performs slightly above 200 mg/km.

Vehicle N1 has relatively low emissions at constant speeds. Until 130 km/h the emissions are below 80 mg/km almost at all speeds. In urban and reference trips vehicle N1 has higher emissions. Vehicle M1 also has relatively high emissions at most constant speeds.

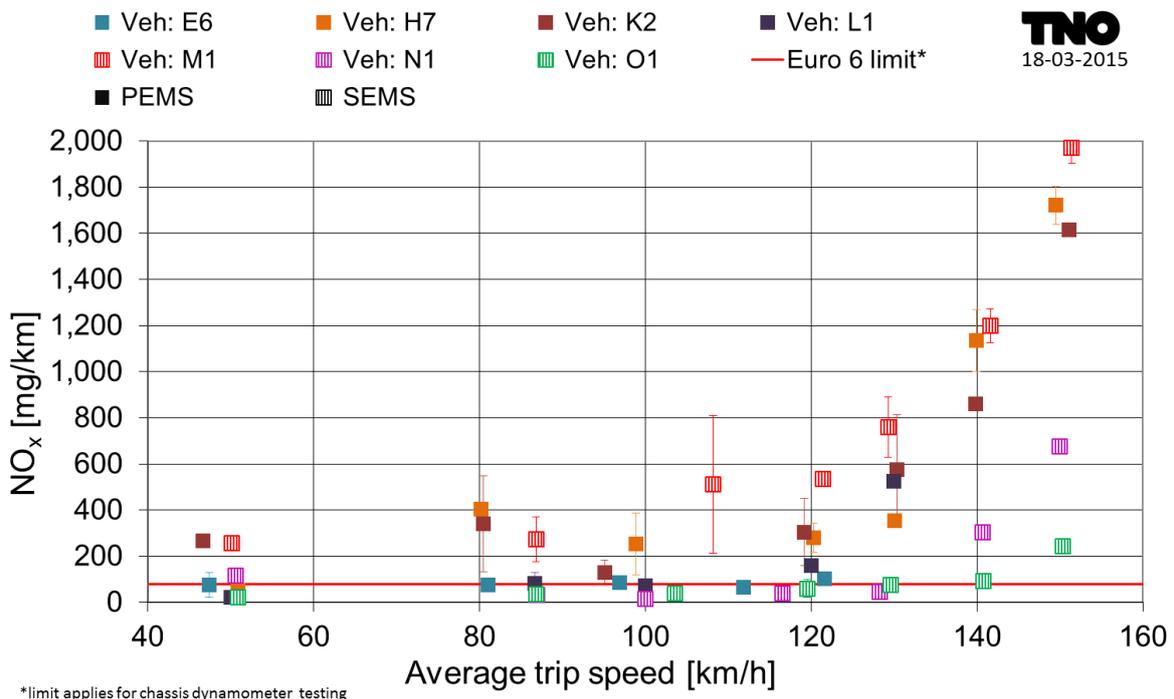


Figure 15: On road NO_x emissions at constant speeds.

For most vehicles the NO_x emission at constant speeds below 120 km/h is relatively low, above 120 km/h the NO_x emission increases substantially and ranges between 400 and 2000 mg/km.

NO_x emissions in urban, reference and highway trips

Figure 16 shows the 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 reference trip consists of an urban, rural and highway part. The highway trips are not comparable because the average vehicle speed differs per trip. The error bars at the highway trips show the variation of the trip speed (horizontal) and the variation of NO_x 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 NO_x 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.

A recent study by ICCT [ICCT2014], reporting PEMS results of 15 tested vehicles, seems to confirm the findings described above. NO_x emissions of the tested vehicles in that study vary between approximately 80 and 1800 mg/km. The study also shows some SCR-equipped vehicles have low NO_x emissions, whereas other SCR-equipped vehicles show very high NO_x emissions.

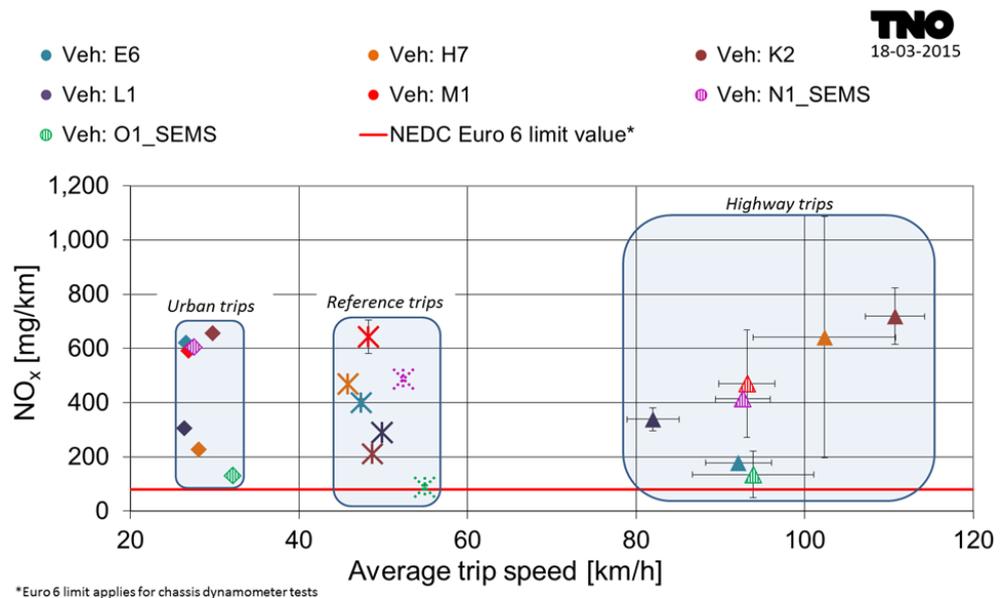


Figure 16: On road NO_x emission test results Euro 6 vehicles

In all on-road trips of seven vehicles the average NO_x emission varies between 100 and 700 mg/km. The results of the single vehicles are remarkable because most vehicles perform in the three trip types at a certain fixed level.

Influence of driving behaviour and starting conditions

In Table 8 and Table 9 results of the reference and urban trips are shown. These trips are performed with cold and hot starts and different driving behaviors.

The urban trip has a duration of approximately 60 minutes and the reference trip has a duration of approximately 90 minutes. In both trips the effect of a cold start is therefore moderate in most cases. The effect of driving style is however more pronounced than the starting conditions. A sportive driving style is characterized by relatively high accelerations and late gear shifts whereas the eco driving style is characterized by low accelerations, early gear shifts and a larger share of coasting. The sportive driving style results in high emissions. Also the eco driving style show or most vehicles lower NO_x emissions than the regular and sportive driving styles. Only vehicle K2 clearly shows higher emissions with the eco driving in the urban trip, but this is possibly due to the SCR operating temperature being too low. Driving style has a large effect on the NO_x emissions of vehicle K2, which scatter significantly showing values between 212 and 852 mg/km.

Table 8: NO_x emission in reference trips with cold and hot start and different behaviour.

	NO _x emissions [mg/km]	Reference trip				
		Cold start		Hot start		
		Regular	Eco	Regular	Eco	Sportive
Vehicle	E6	420	358	401	-	-
	H7	467	-	469	339	-
	K2	658	-	212	-	852
	L1	330	-	290	-	377
	M1	565	-	643	-	835
	N1	363	-	487	-	846
	O1	169	-	87	-	292

Table 9: NO_x emission in the urban trips with cold and hot start and different behaviour.

	NO _x emissions [mg/km]	Urban trip				
		Cold start		Hot start		
		Regular	Eco	Regular	Eco	Sportive
Vehicle	E6	665	-	619	568	-
	H7	-	-	228	-	455
	K2	-	-	657	989	841
	L1	-	-	306	251	306
	M1	-	-	592	622	828
	N1	-	-	606	320	1271
	O1	147	-	132	87	384

The effects on NO_x emission of a cold start differ per vehicle type. For most vehicles the NO_x emission increases with a cold start, in some cases it is the opposite. The effect of driving style on NO_x emission is more pronounced than starting conditions of a trip. Due to the driving style the NO_x emission can increase up to 4 times (i.e. 212 to 852 mg/km).

3.4 Evaluation of Real Driving Emissions

Table 10 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 10 and plotted in Figure 17.

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 are comparable (see Appendix D, Table 35, 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 10: NO_x 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

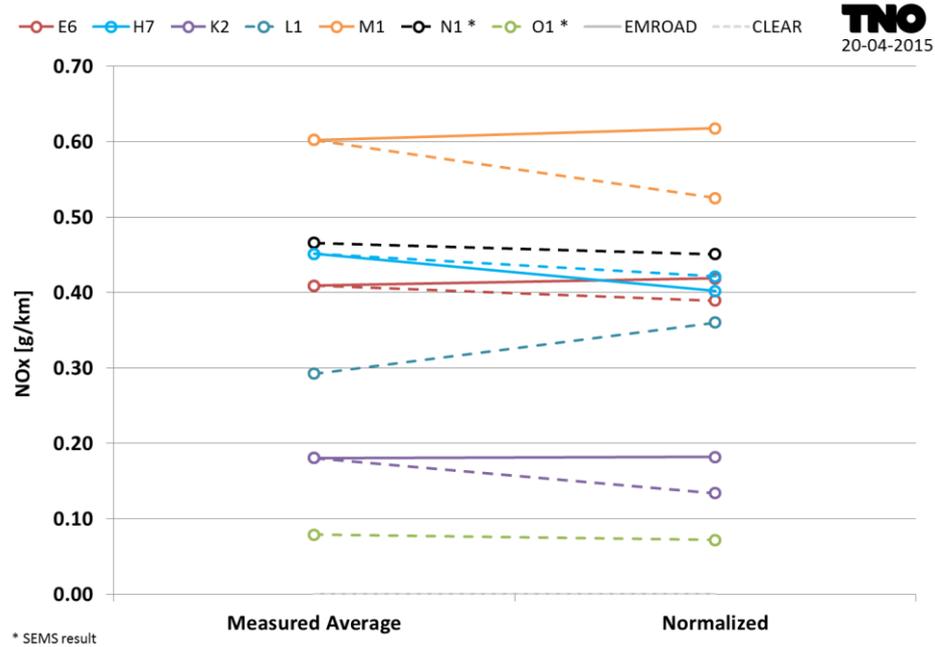


Figure 17: Measured and normalised NOx emissions of 7 vehicles in a reference trip with a hot start.

Normalised results per road area

This paragraph shows the normalised NO_x emissions per road area. Results per road area are relevant because the weighing of 1/3 for each road area is not certain yet. The weighing method of the road areas can have a large influence at the total result but also differs per method.

In Table 11 the NO_x emissions of the TNO reference trip per road area are reported. For CLEAR no rural and motorway results are available, hence the rural and motorway result is calculated based on the urban and total result. It should be noted that EMROAD and CLEAR use different speed bins to categorize urban, rural and motorway.

Table 11: NOx results in mg/km per road area

NO _x emissions in mg/km during TNO reference trip	Average			EMROAD			CLEAR		
	urban 0 - 60 km/h	rural 60 -90 km/h	motorway >90 km/h	urban 0 - 45 km/h	rural 45 -80 km/h	motorway >80 km/h	urban 0 - 60 km/h	rural 60 -90 km/h	motorway >90 km/h
E6	648	337	211	679	395	183	492	338	
H7	277	369	672	195	333	679	214	570	
K2	117	45	369	78	61	407	67	168	
M1	805	402	535	817	530	507	522	527	

During the TNO reference trips CLEAR normalizes the data substantially in the urban speed bin, i.e. the results are lowered with 50 to 283 mg/km. With EMROAD the emissions in the urban speed bin are both lowered and increased between -82 and +31 mg/km.

Vehicle M1 is an interesting example to show the differences between CLEAR and EMROAD; As shown in Figure 17 the NO_x emission of vehicle M1 is lowered with CLEAR but increases with EMROAD. This is mainly the result of normalisation with CLEAR in the urban speed bin.

The results in Table 11 also show that there are large differences between emissions per road area. Considering these large differences and the substantial amount of normalisation in some cases it must be concluded that the weighing method and normalisation method can have a large influence on the total result. This is already for the case that the same reference trip was executed in similar manners, i.e. normal driving, and the emissions of most vehicles have similar characteristics expect for one LNT vehicle.

Driving style and driving at higher speeds

The TNO reference trip was executed with two driving styles (regular and sportive). Table 12 shows the differences in trip characteristics, mainly the higher average acceleration and RPA indicate the sportive driving style. Additionally trips at higher speeds were performed and analysed with the normalisation tools.

Figure 18 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 Figure 18 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 12: 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

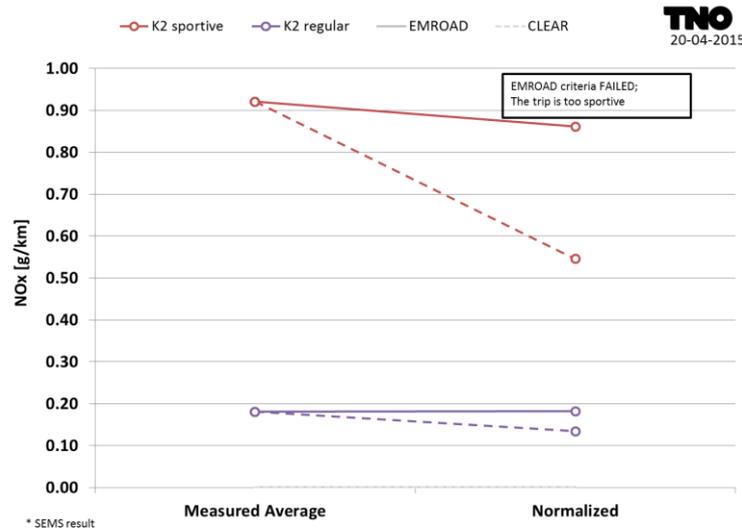


Figure 18: Measured and normalised NO_x emissions of vehicle K2 in a reference trip with regular driving style versus a reference trip with sportive driving style.

3.5 Detailed overview of SEMS results of SCR vehicles

In this section the NO_x test results of four SCR-equipped vehicles are reported in detail.

Vehicle L1, M1, N1 and O1 were vehicles equipped with an SCR catalyst. TNO instrumented the SCR catalysts with a NO_x sensor and a temperature sensor *before and after* the SCR catalyst. Additionally, an NH₃ sensor was fitted post SCR. SEMS data were logged during the chassis dynamometer tests and during on-road tests.

On the chassis dynamometer NEDC, WLTC, CADC and constant speed tests were performed. Furthermore the on-road test program consists of prescribed and non-prescribed tests. The prescribed tests are defined in Table 6. The non-prescribed real-world tests were random city trips and commuting trips with cold and hot starts and different driving styles.

Test results of vehicle L1

In Figure 19 and Figure 20 the on-road pre-SCR and post-SCR NO_x test results of vehicle L1 are shown. The size of the markers indicate the distance of the trip. During the chassis dynamometer tests SEMS was not installed.

The emission results of vehicle L1 in Figure 19 – Figure 20 show:

- The pre-SCR NO_x emissions are relatively low (<900 mg/km). This indicates an active EGR system which is reducing NO_x emissions in the combustion engine.
- Overall the real-world post-SCR NO_x emissions range from 15 to 500 mg/km. At constant speed driving with speeds up to 100 km/h, the emissions are below 200 mg/km.
- For dynamic trips, the tailpipe NO_x emissions are between 250 and 500 mg/km and for constant speeds the tailpipe NO_x emissions vary from 15 to 280 mg/km. Obviously at constant speeds relatively low post-SCR NO_x emissions are possible.

- In all test trips the amount of NO_x converted by the SCR varies from 200 to 500 mg/km.

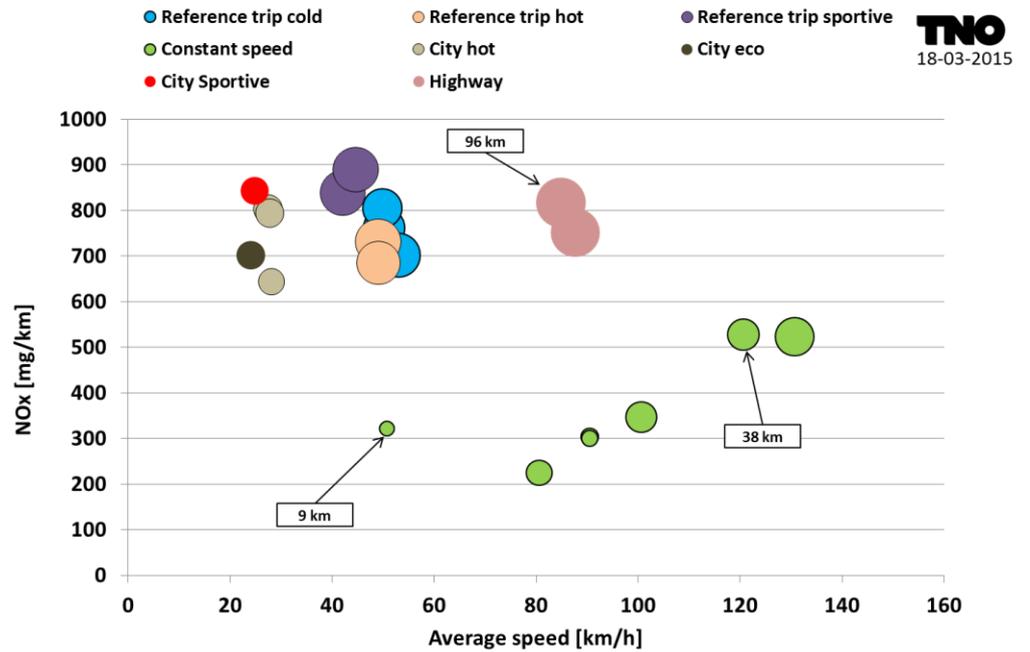


Figure 19: Pre-SCR NO_x emissions of vehicle L1 of on-road trips.

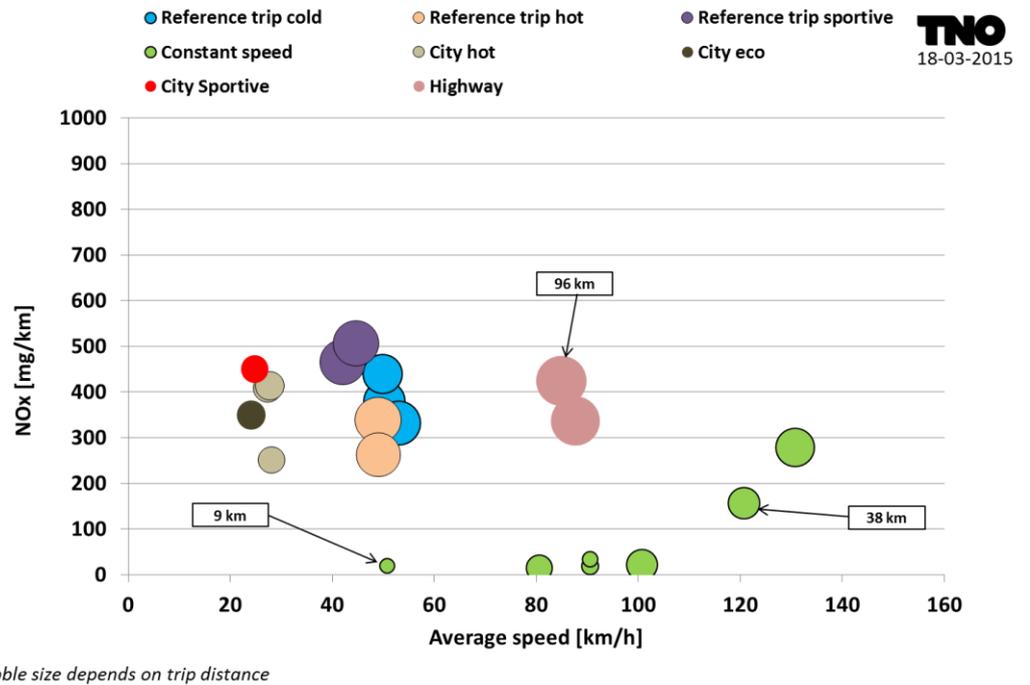


Figure 20: Post-SCR NO_x emissions of vehicle L1 of on-road trips.

Test results of vehicle M1

Overall the NO_x real-world emissions of vehicle M1 are relatively high, especially during the very short trips (small bubbles) and trips at high speeds. However, all tests on the chassis dynamometer show very low NO_x emissions (Euro 6 level), even at short trips with a cold start and at trips at 150 km/h.

The emissions results of vehicle M1 displayed in Figure 21 and Figure 22 show the following:

- In chassis dynamometer tests the engine out NO_x emissions are 100 to 450 mg/km, indicating an effective EGR system which reduces NO_x emissions in certain chassis dynamometer tests. In real-world tests the EGR system seems to be less effective or not effective at all, as engine out NO_x emissions in real-world tests range from 450 to as much as 2250 mg/km.
- For dynamic road trips the tailpipe NO_x emissions are approximately 250 to 750 mg/km and for most constant speeds it ranges from 250 to 2000 mg/km (Figure 22). However all chassis dynamometer test results are below or near the type approval limit value of 80 mg/km. This seems to indicate a selective use of emission control technologies, because on-road emissions are far higher than chassis dynamometer test results.
- In on-road trips the emission control systems are less effective than in chassis dynamometer tests.
- In all test trips the amount of NO_x converted by the SCR ranges from approximately 100 to 500 mg/km.

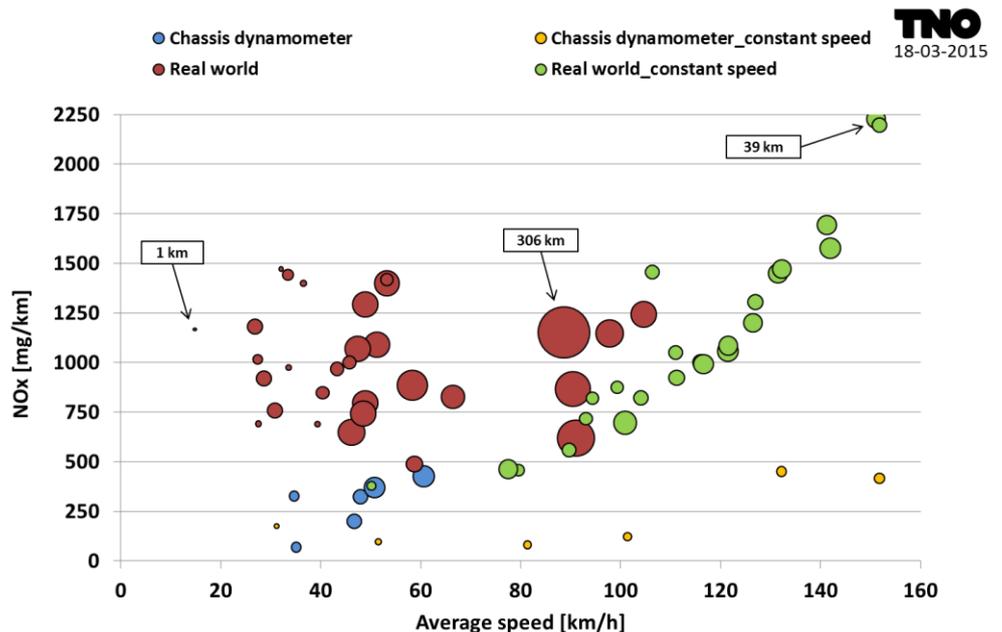
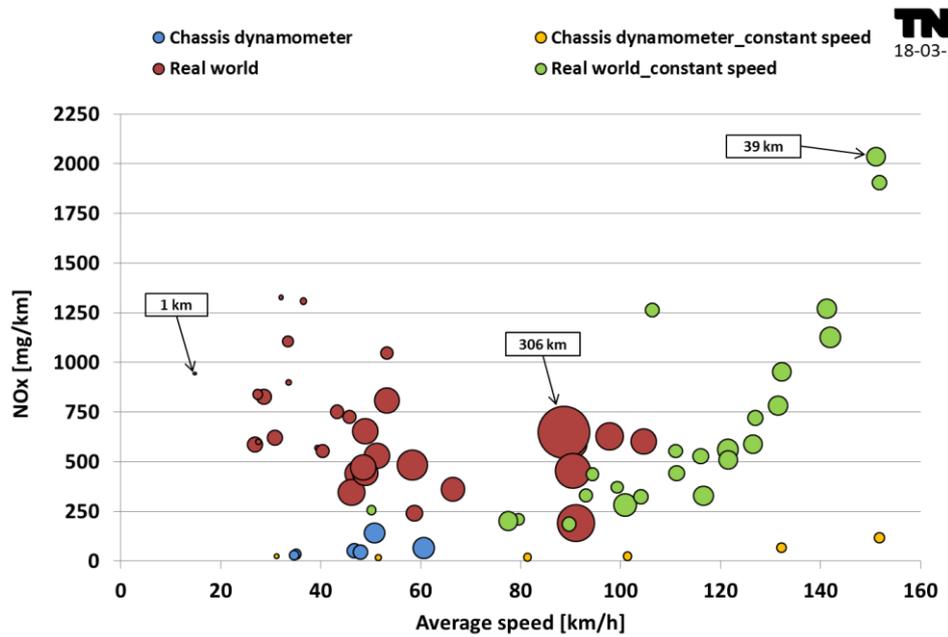


Figure 21: **Pre-SCR** NO_x emissions of vehicle M1 of on-road trips and chassis dynamometer tests.



Bubble size depends on trip distance

Figure 22: **Post**-SCR NO_x emissions of vehicle M1 of on-road trips and chassis dynamometer tests.

Test results of vehicle N1

The NO_x emission of vehicle N1 scatters greatly in real-world operation as well as in the chassis dynamometer tests and depends significantly on driving behaviour and on hot or cold starting conditions. At constant speeds up to 130 km/h the NO_x emissions are very low, both on the chassis dynamometer and real world.

The emissions results of vehicle N1 in Figure 23 and Figure 24 show the following:

- In chassis dynamometer tests the engine out NO_x emissions are 200 to 1100 mg/km, see Figure 23. In cold NEDC tests the NO_x emissions are relatively low. This seems to indicate an active but selective use of the EGR system. In real-world tests on the road this system is less effective; NO_x emissions vary between approximately 400 and 1400 mg/km.
- For dynamic road trips the tailpipe NO_x emissions are approximately 10 to 1000 mg/km and for most constant speeds it is below 100 mg/km (see Figure 24).
- During on road trips the emission control systems are less effective than in chassis dynamometer tests.
- In all test trips the amount of NO_x converted by the SCR is 100 to 750 mg/km.

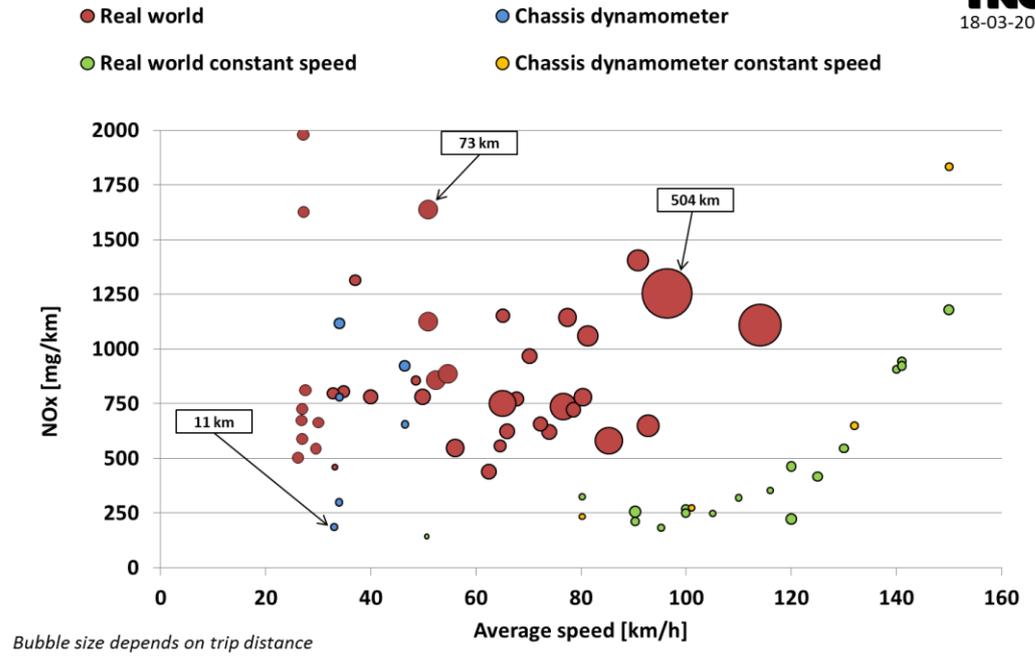


Figure 23: **Pre-SCR** NOx emissions of vehicle N1 of on-road trips and chassis dynamometer tests.

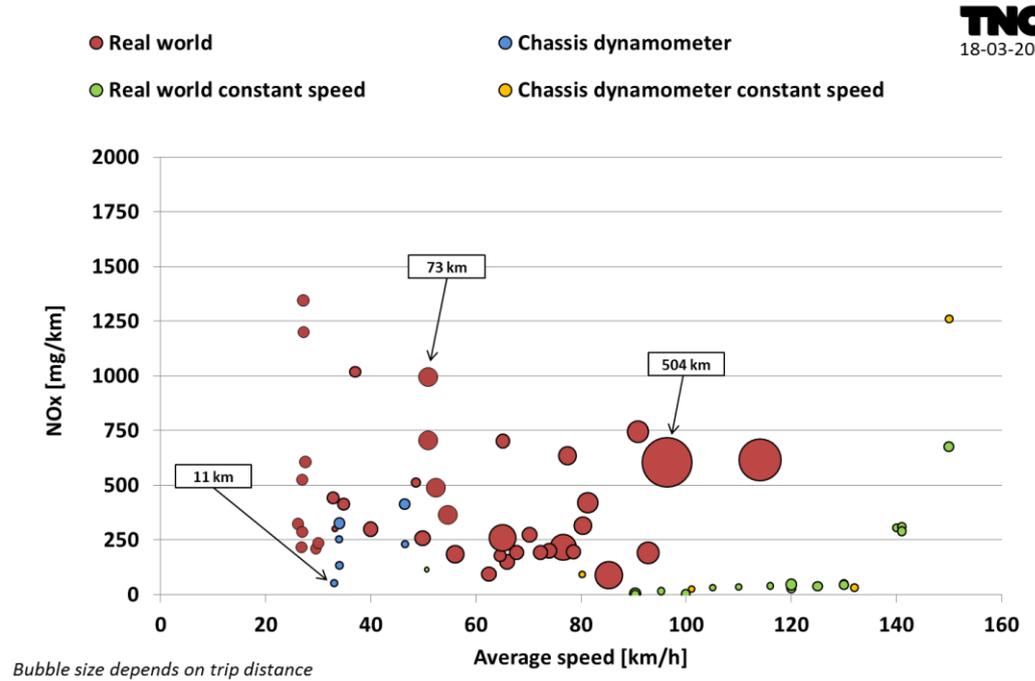


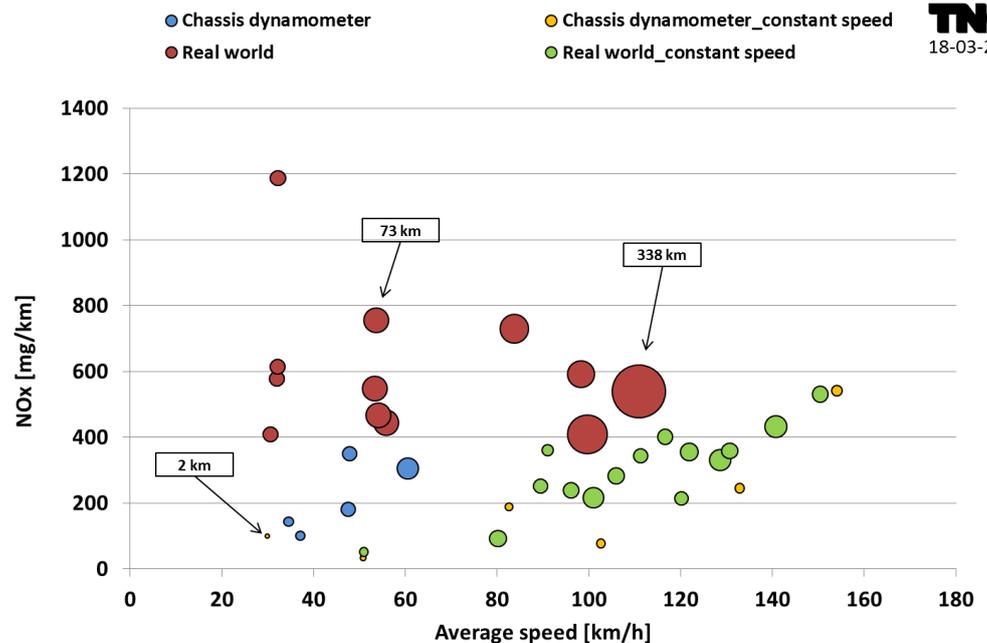
Figure 24: **Post-SCR** NOx emissions of vehicle N1 of on-road trips and chassis dynamometer tests.

Test results of vehicle O1

Overall the NO_x emission of vehicle O1 is relatively low during both the real-world tests and the chassis dynamometer tests. All chassis dynamometer results are below 80 mg/km. The highest NO_x emission in this graph is the result of a sportive driving style. Vehicle O1 can be considered as the best performer of all vehicles tested.

The emissions results of vehicle O1 in Figure 25 – Figure 26 show the following:

- In chassis dynamometer tests the engine out NO_x emissions are 100 to 380 mg/km (Figure 25). This is a relatively low level and indicates an effective EGR system which avoids NO_x formation in the engine.
- In cold NEDC tests the tailpipe NO_x emissions are relative low, indicating an active EGR system which avoids NO_x emission in the combustion engine. In real-world tests on the road the system is less effective; NO_x emissions vary between approximately 100 and 800 mg/km.
- For dynamic road trips the tailpipe NO_x emission is 50 – 400 mg/km and for most constant speeds it is below 100 mg/km, see Figure 26. This shows that an emission control system consisting of an EGR and an SCR is able to realize on-road NO_x emissions ranging from 0 to 300 mg/km.
- In the on-road trips the EGR and SCR systems seem to be comparably active as during the chassis dynamometer tests.
- This vehicle is the only one in this research project with a real-world emission Conformity Factor of 1-3. This shows that a good performance of the EGR system is needed, thus allowing the SCR to further reduce the remainder of NO_x to realize low tailpipe NO_x emissions. This makes an optimal combination of SCR and EGR technologies for low real-world emissions.
- In all test trips the amount of NO_x converted is approximately 100 to 450 mg/km.



Bubble size depends on trip distance

Figure 25: **Pre-SCR** NO_x emissions of vehicle O1 of on-road trips and chassis dynamometer tests.

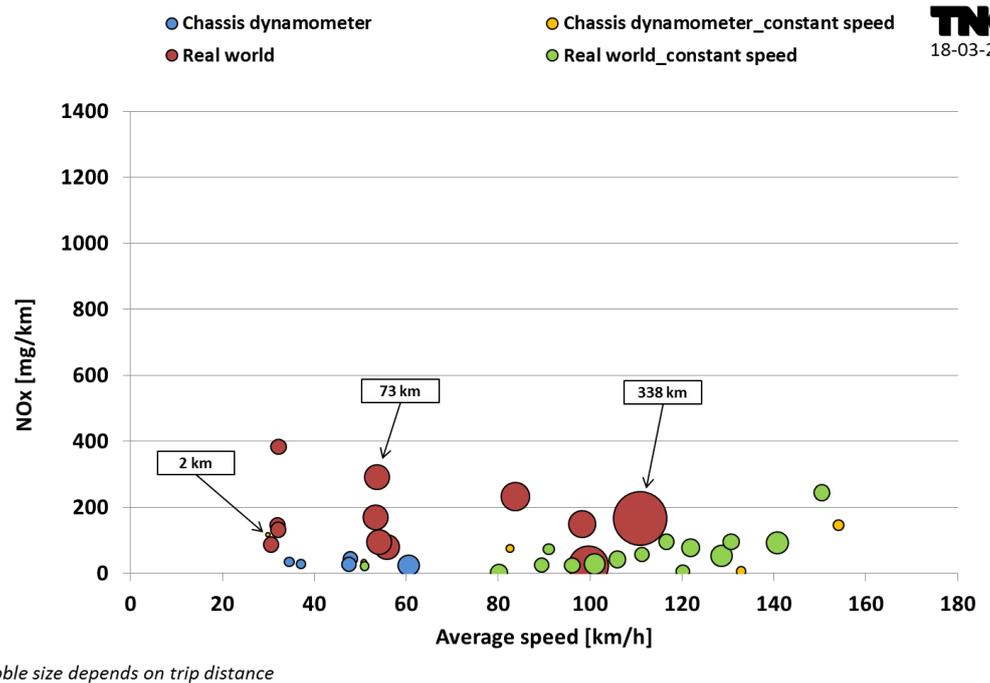


Figure 26: **Post-SCR** NO_x emissions of vehicle O1 of on-road trips and chassis dynamometer tests.

In the chassis dynamometer tests all SCR-equipped vehicles perform below the type approval limit value of 80 mg/km and the next emission control strategies are applied:

- Reduction of NO_x formation in the engine by means of an EGR system. As a result of this strategy the engine-out NO_x emissions are relatively low.
- Reduction of 400 to 700 mg/km NO_x in the SCR-catalyst.

However, in the on-road tests the pre-SCR NO_x emissions are 2 to 5 times higher than in chassis dynamometer tests. This elevated NO_x emissions before the SCR-catalysts is the main cause for the high vehicle emissions and is further discussed in the next chapter.

4 The potential of vehicles with SCR systems

4.1 Considerations

The results of Chapter 3 show that real-world NO_x emissions of Euro 6 diesel passenger vehicles are significantly higher than the Euro 6 Type Approval emission levels. And although all vehicles fulfil the requirements during type approval testing, the goal of emission legislation is to ensure low *real-world* emissions. The large differences in real-world emission performance of the measured vehicles leads to the question: Are current SCR systems able to perform better? This chapter describes the causes for high real-world emissions and the potential of SCR systems in more detail. In order to define improvements of SCR-equipped vehicles detailed measuring data were investigated and analyzed.

The vehicles TNO tested were equipped with various NO_x reduction technologies:

- Reduced engine compression ratio in combination with a high pressure EGR;
- SCR (selective catalytic reduction) in combination with a high pressure EGR;
- LNT (Lean NO_x Trap) in combination with a high pressure EGR.

The working principles of these technologies are explained in more detail in [TNO2013].

In general, the following trends are observed in the applied technology per vehicle category:

- Small vehicles: EGR technology (low and high pressure);
- Medium vehicles: EGR (high pressure) + LNT or SCR;
- Large vehicles: EGR (high pressure) + SCR or LNT.

In heavy-duty vehicles, the EGR+SCR technology shows very good real-world performance [TNO2014A]. Hence it seems that EGR+SCR technology has the potential to achieve low emissions, provided that the system is designed and calibrated for low emissions on the road.

Regarding exhaust aftertreatment systems vehicle manufacturers have to deal with many system requirements, issues and parameters. In case of real-world emissions these are, amongst others:

- system packaging: The emission control system may not exceed certain sizes because the available space is limited;
- operational possibilities and restrictions (space, velocity, operating temperature, durability requirements);
- system price: the price of the vehicle must be competitive and must be as low as possible;
- maintenance and Adblue refill must be restricted to a minimum level because user comfort must not be disturbed;
- operational costs must be as low as possible.

This faces vehicles manufacturers with great challenges, fulfilling emission legislation standards on the one side and fulfilling customer demands on the other.

4.2 Investigations of NO_x reductions and SCR conversion rates of tested vehicles

To assess the SCR performance of the tested vehicles the conversion rates of the SCR catalysts are analysed in this section. The conversion rate of an SCR is defined as the amount of NO_x that is reduced by the SCR divided by the NO_x emission before the SCR, i.e. the engine-out NO_x emission.

The main parameters which determine the conversion rate of SCR systems are:

1. The size of the SCR catalyst and the exhaust mass flow rate;
2. The operating temperature of the exhaust gas and the SCR catalyst;
3. The exhaust gas composition, more specifically the available share of NO₂;
4. The NO_x mass flow rate which is offered to the SCR catalyst;
5. The amount of added AdBlue (NH₃/NO_x – ratio);
6. The homogeneity of the NO_x/NH₃ gas mixture;
7. The AdBlue storage capacity of the SCR catalyst.

TNO tested four vehicles with SCR technology on the chassis dynamometer and on the road. The vehicles were equipped with SEMS in all experiments, i.e. on the road as well as during the chassis dynamometer tests. Figure 27 shows an overview of the SCR conversion rates. Figure 28 shows an overview of the corresponding converted NO_x mass flow rates. In both figures the size of the marker represents the post-SCR NO_x emission.

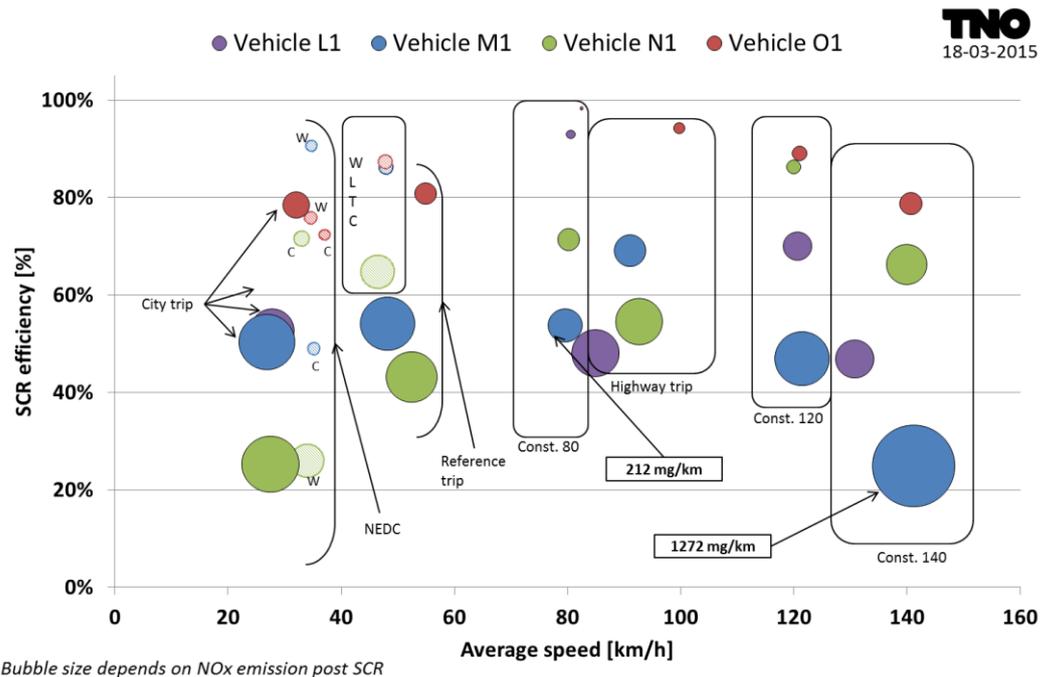


Figure 27: SCR conversion rate in chassis dynamometer and on-road tests. Tests with hot starts are indicated by "W" (warm), cold-start tests are indicated by "C".

Figure 27 shows:

- all vehicles perform better in NEDC tests than on the road.
- overall the SCR conversion rates vary between 15 and 98%. The highest conversion rates are measured in constant speed trips and chassis

dynamometer tests. In those tests the NO_x emissions of the vehicles are very low.

- in urban (city) and reference trips the SCR conversion rates vary between 20 and 80% for the different vehicles. Trips at higher speeds show relatively large variations in SCR conversion rates and post-SCR NO_x emissions.
- vehicles L1 and M1 have approximately similar SCR conversion rates during the city trip and the constant speed at 120 km/hr (vehicle M1) versus 130 km/hr (vehicle L1), however the post-SCR NO_x emissions of vehicle M1 are higher (larger bubble diameter). This means that vehicle L1 has lower engine out NO_x emissions.
- vehicle M1 has an SCR conversion rate of approximately 90% with low post-SCR NO_x emissions on the chassis dynamometer; during on-road measurements, however, the conversion rates are between 25 and 70% with high post-SCR NO_x emissions. This indicates a high engine-out NO_x emission.
- in the cold NEDC test vehicle N1 has an SCR conversion rate of over 70%. In the hot NEDC test, however, the SCR conversion rate is only 15%, obviously leading to a higher tailpipe NO_x emission (larger bubble diameter).
- vehicle O1 has overall SCR conversion rates of 80 to 99% and low post-SCR NO_x emissions of 50 to 250 mg/km, both on the chassis dynamometer as well as on the road. The main cause for these low tailpipe NO_x emissions is the relatively low *engine-out* NO_x emission of less than 800 mg/km of the vehicle. This, combined with a well-performing SCR, makes this vehicle 'best in class'.

Figure 28 shows:

- maximum SCR conversion rates are reached when the pre-SCR (engine-out) NO_x emissions are below approximately 460 mg/km. In these cases also the post-SCR NO_x emissions are low. Hence it seems that the *combination* of low engine-out emissions and sufficient SCR performance are key for low vehicle NO_x emissions.
- the maximum NO_x conversion is 400 to 600 mg/km. Vehicle M1 has the highest NO_x conversion, but it also has the highest pre-SCR NO_x emissions.
- from the four tested vehicles, vehicle O1 clearly shows the lowest pre-SCR NO_x emissions. With this combination of low engine-out emissions and good SCR conversion rate the post-SCR NO_x emissions are very low.

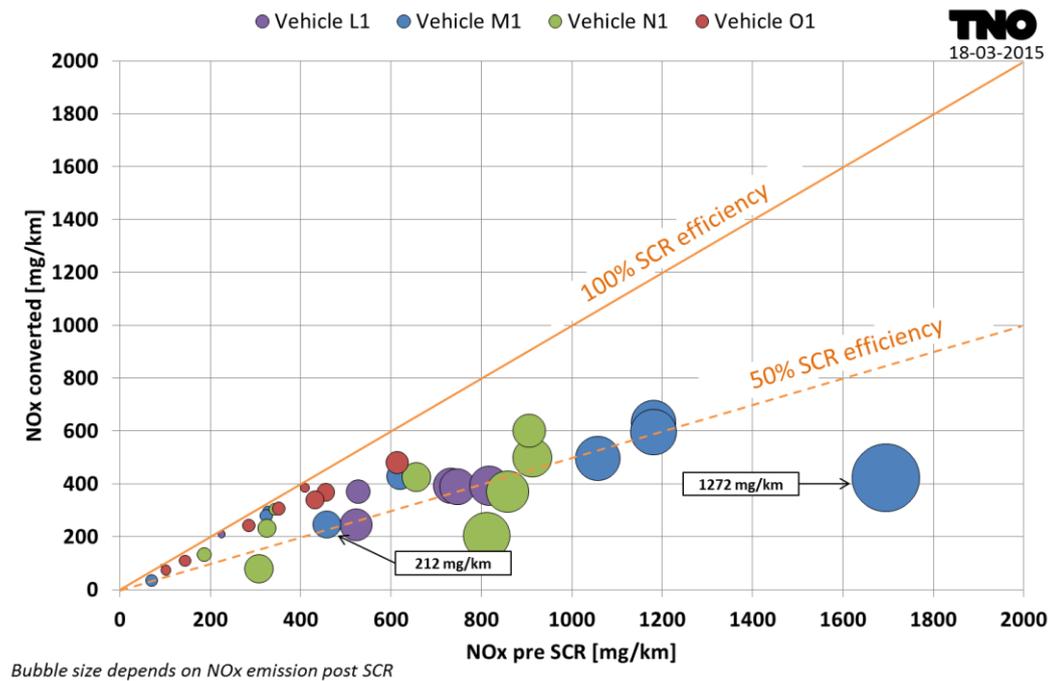


Figure 28: Converted NO_x in chassis dynamometer and on-road tests.

In Figure 28 the relationship of the converted NO_x in the SCR catalyst and the pre-SCR NO_x emissions 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 is not 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.

4.3 Investigation of vehicles with SCR technology and their characteristics

In order to comply with Euro 6 type approvals eight manufacturers have offered SCR-equipped vehicles to the market. To explore typical characteristics of SCR-equipped vehicles an inventory of vehicles using SCR technology was made.

Given the nature of this research, the inventory focused on the following characteristics:

- 1 capacity of the AdBlue tank;
- 2 estimated average AdBlue consumption;
- 3 estimated range with AdBlue tank capacity, following from the first two parameters.

Table 13 gives an overview of the vehicle characteristics per manufacturer. The capacities of the AdBlue tanks vary between 7.8 and 25 liter. According to the manufacturers the estimated range between refills of the AdBlue tank varies from 11.000 to 25.000 km.

Table 13: Characteristics of SCR-equipped passenger car. From each manufacturer one model is shown.

Vehicle model	Vehicle type	Capacity AdBlue tank	Estimated range*	Estimated average AdBlue consumption*	Refill location	Remark
	[-]	[l]	[km]	[km/l]	[-]	[-]
Manufacturer A	MPV	17.0	20.000	1.200	Trunk	not tested in this programme
Manufacturer B	MPV	7.8	11.000	1.450	Next to fuelcap	Vehicles K1 and K2 correspond to this vehicle model
Manufacturer C	Hatchback	17.0	20.000	1.200	Trunk	not tested in this programme
Manufacturer D	Hatchback/ Wagon	17.0	20.000	1.200	Trunk	Vehicle L1 corresponds to this vehicle model
Manufacturer E	Sedan/ Wagon	25.0	22.000	900	Next to fuelcap	Vehicle M1 corresponds to this vehicle model
Manufacturer F	Sedan/ Wagon	15.0	15.000	1.000	Next to fuelcap	Vehicle O1 corresponds to this vehicle model
Manufacturer G	SUV	23.0	25.000**	1.100	Next to fuelcap	Vehicle N1 corresponds to this vehicle model
Manufacturer H	MPV	17.0	25.000	1.450	Trunk	not tested in this programme

* Dependent on driving behaviour, environmental conditions, type of trips, payload etc.

** Due to unavailable specifications the estimated range is based on a common service interval.

Table 13 shows that most SCR vehicles belong to the relatively large segments, such as MPV's, SUV's, sedans and wagons. Most manufacturers designed the SCR system in such a way that the AdBlue tank only need a refill during service intervals, hence the user comfort is unlikely to be influenced. As an exception to this, vehicle of manufacturer B needs a refill in between the service intervals. Sometimes AdBlue filler caps are placed near diesel filler caps but for some vehicles the filler cap is located in the trunk.

The estimated average AdBlue consumption for the different vehicles varies between 900 and 1450 kilometre per litre. This is an estimation, since the AdBlue consumption is dependent on the NO_x emissions before the SCR catalyst and operational conditions varying with driving behaviour, environmental conditions, type of trips, payload etc.

Based on the estimated average AdBlue consumption no conclusions can be made about the post-SCR NO_x emissions of these vehicles. Only precise knowledge on for instance momentary engine-out emissions, SCR characteristics, operating conditions in combination with the momentary AdBlue mass rates determine the vehicle emission.

4.4 Required amount of AdBlue for low real-world NO_x emissions

In this chapter the amount of AdBlue for achieving NO_x emissions of 80 mg/km in real-world operation is calculated for the tested vehicles that are equipped with an SCR. The calculations were performed for the reference trip and for an NEDC trip with a cold start. The results are shown in Table 14.

As described earlier, in many cases lower engine-out NO_x emissions and/or higher NO_x reduction of the SCR system are needed to achieve post-SCR NO_x emissions in the order of the Euro 6 80 mg/km NEDC limit. To lower the engine-out NO_x emissions, improved EGR or readjusted injection timing is needed. To increase the NO_x reduction by the SCR, the SCR conversion rate needs to be improved. The latter is possible by improving the main parameters that affect the SCR conversion rate:

1. proper size of the SCR catalyst (sufficient surface);
2. low light-off temperature;
3. quick warming-up above the light-off temperature;
4. optimal gas composition (available share of NO₂);
5. sufficient AdBlue injection (without NH₃ slip);
6. sufficient mixing of exhaust gas and AdBlue.

Table 14: Specified and calculated characteristics of the tested SCR equipped passenger cars

Vehicle model	Specification of the manufacturer		Tank capacities and vehicle ranges for achieving NO _x emissions of 80 mg/km			
	Capacity AdBlue tank	Estimated range*	Reference trip		NEDC with cold start	
			Capacity AdBlue tank required for 80 mg/km NO _x	Vehicle range with current AdBlue tank capacity in case of reducing NO _x emission to 80 mg/km	Capacity AdBlue tank required for 80 mg/km NO _x	Vehicle range with current AdBlue tank capacity in case of reducing NO _x emission to 80 mg/km
[l]	[km]	[l]	[km]	[l]	[km]	
Vehicle L1	17	20.000	24.6	13.797	n/a	n/a
Vehicle M1	25	22.000	45.8	12.019	0.0	-
Vehicle N1	23	25.000**	36.8	15.641	5.0	114.041
Vehicle O1	15	15.000	10.6	21.131	0.6	361.737

* Dependent on driving behaviour, environmental conditions, type of trips, payload etc.

** Due to unavailable specifications a common service interval was assumed.

Table 14 shows that, based on the pre-SCR NO_x emissions and the specified AdBlue tank capacity, the installed AdBlue tanks of most of the tested vehicles are too small to reduce emissions to a level of 80 mg/km in reference trips. Only vehicle O1 has sufficient tank capacity due to its low pre-SCR NO_x emissions. The AdBlue tank capacity of the tested vehicles would need to be increased by roughly 40 to 80%, or the refill ranges should be shortened with the same percentages. During the NEDC with cold start the pre-SCR NO_x emissions are a lot lower, hence not much AdBlue is needed. In this calculation it is assumed that the SCR catalyst can process the offered AdBlue, this means the mentioned parameters above allow for an optimal NO_x reduction.

More detailed results are reported in Appendix C.

As can be seen in Table 13, the AdBlue consumption of the vehicles not tested in this programme is rather low, especially that of vehicles of manufacturer B and H. For these vehicles low pre-SCR NO_x emissions, together with a sufficient amount of AdBlue injection will be essential for achieving low real-world NO_x emissions.

The results shown in Table 13 and Table 14 are consistent with the emission performance of vehicle O1.

Table 15 shows the calculated maximum pre-SCR NO_x emission of the tested vehicles to achieve post-SCR NO_x emission of 80 mg/km. This pre-SCR NO_x

emission varies between 440 and 681 mg/km and is far less than the actual pre-SCR NO_x emission in a reference trip.

Table 15: Maximum pre-SCR NO_x emissions required for achieving post-SCR NO_x emissions of 80 mg/km.

Manufacturer / Vehicle model	Capacity AdBlue tank	Estimated range*	Maximum calculated pre-SCR NO _x emission	Actual pre-SCR NO _x emission TNO reference trip
	[l]	[km]	[mg/km]	[mg/km]
A / -	17	20.000	530	n/a
B / -	7.8	11.000	455	n/a
C / -	17	20.000	530	n/a
D / L1	17	20.000	530	732
E / M1	25	22.000	681	1181
F / O1	15	15.000	609	456
G / N1	23	25.000	567	858
H / -	17	25.000	440	n/a

* Dependent on driving behaviour, environmental conditions, type of trips, payload etc.

5 Discussion

What are the main emission characteristics of the tested Euro 6 diesel 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 NO_x emissions and the vehicle with the highest real-world NO_x emissions?

The real-world NO_x 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 NO_x emissions of this vehicle are relatively low, ranging from 350 to 750 mg/km, indicating an effective EGR system which avoids the formation of NO_x. In addition the residual NO_x is mainly reduced in the SCR catalyst 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 NO_x 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.

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 NO_x is reduced by the SCR catalyst at an operational temperature up to 250 °C. This results in a 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 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.

What are the effects of 'adding more EGR', i.e. of recirculating a larger share of exhaust gases to the engine?

Besides reduction of engine-out NO_x emissions the (side) effects of EGR are:

- higher exhaust gas temperatures, causing an improved catalyst conversion rate;
- higher engine-out PM emissions and consequently more DPF regenerations;
- more engine deterioration, smaller maintenance intervals.

In case more EGR would be applied, vehicle manufacturers would need to re-optimize their engines. Especially durability issues will have to be tackled and the DPF regeneration strategies must be optimized.

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 EGR technology only. 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.

For heavy-duty vehicles, the Euro VI legislation requires an obligatory on-road emission test as part of the type approval. This has led to significantly lower real-world emissions of the heavy commercial vehicles. On average, the NO_x emission of Euro VI trucks and buses has decreased sharply compared to Euro V trucks and buses. Especially the Euro VI long-haulage trucks are much cleaner than preceding generations [TNO2014A].

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 NO_x 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 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. One of the possible reasons for this restricted activation is the AdBlue consumption. If more NO_x is reduced by the SCR catalyst the AdBlue tank must be filled more frequent (i.e. every 10.000 km) or must be expanded (from 20 to 40 litres). Furthermore more NO_x reduction capacity may be needed and therefore a larger SCR catalyst must be mounted.

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 NO_x aftertreatment technologies.

6 Conclusions

In several emission test programs TNO has tested sixteen Euro 6 diesel passenger cars. 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 cold start on CO₂ emission is equal; a cold start yields some additional CO₂ emission. The effect of a hot start on NO_x emission differs widely; for some vehicles the NO_x emission decrease but for other vehicles it increases a factor 3.
3. the range of NO_x 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 NO_x 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 NO_x 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 NO_x emissions.
5. only one vehicle has sufficient AdBlue tank capacity. Based on the measured pre-SCR NO_x emissions and the installed AdBlue tanks, nearly all vehicles have insufficient amounts of AdBlue on board to reduce NO_x emissions to 80 mg/km in real-world use. To reach this NO_x emission limit value, most vehicles would need a 45 to 80% larger AdBlue tank or, alternatively, their refill ranges should be shortened equally. Furthermore, a recalibration and optimisation of the engine would be needed to create the required operating conditions for improvement of real-world NO_x emissions.
6. 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 EGR only. This signifies a risk of high NO_x emissions similar to Euro 5, in particular on the motorway. Euro 6 mainstream compact cars are expected to enter the market as of September 2015.
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 NO_x 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.

7 Recommendations

Development of dedicated RDE legislation to improve real-world emissions

In order to improve real-world emissions, a dedicated RDE legislation is recommended. This legislation must contain the next items:

1. definition of the road trip (urban, rural and highway part);
2. sequence of the different parts;
3. vehicle mass and load;
4. definition of driving styles (eco, regular, sportive);
5. vehicle state (control strategy of gear box);
6. use of normalisation tools and boundaries;
7. definition of Conformity Factor;
8. limit values of Conformity Factor;
9. ammonia slip criteria and limit values.

Screening real-world emissions of Euro 6 vehicles yet to enter the market

TNO's Smart Emission Measurement System (SEMS) is a cost-effective CO₂ and NO_x emission screening tool. By means of SEMS a quick assessment of the real-world emissions of vehicles in their full operation can be performed. In case SEMS measurements reveal high emissions, this may provide arguments for the execution of a more comprehensive RDE testing program, possibly using a Portable Emission Measurement System (PEMS).

In order to get a better view on real-world emissions of new types of Euro 6 vehicles it is recommended to install SEMS on new Euro 6 vehicles when they enter the market. A one-day testing program already can shed a clear light on the main emission characteristics of the vehicle. Gathering data over a longer period will only marginally increase the measurement costs, while at the same time producing a larger data set yielding more reliable test results.

8 References

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9 Signature

Delft, 18 May 2015

TNO



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A TNO chassis dynamometer test results

Compliance with the Euro 6 legislation:

TNO tested Euro 6 vehicles in 2010 and from 2012 to 2015. The upcoming tables show the emission results over different driving cycles of the tested vehicles. It should be noted that the tested vehicles in 2010 were prototypes or were meant for the USA market.

The Table 16 up to Table 30 show that almost all vehicles are compliant with the Euro 6 limit values during the NEDC with cold start. The next vehicles exceed the limit value:

- H4 exceeds the PN limit with almost 50%, the PN emissions in the other cycles are also relatively high, no technical defects were found.
- E6 exceeds the NO_x limit with 22,5%, this is considered as marginal.
- J2 exceeds the CO limit with 32%, this is considered as marginal, in addition, in other tests the CO emissions are no issue, no technical defects were found.

Also in other test cycles the CO, PM and PN (except vehicle H4) emissions are all less than the Euro 6 limit value. THC + NO_x emissions are often higher than the limit value, this is caused by the high NO_x emissions, THC emissions are not an issue. The high NO_x emissions are discussed in the next paragraph.

The CO₂ emissions of all NEDC tests with cold start are in all cases higher than the declared value, the deviation varies between the 3 and 17%.

Table 16: Results vehicle H2

Emissions vehicle H2	Unit	Limit (Euro 6)	NEDC cold**	CADC hot**
Road load setting	[-]	NEDC	NEDC	NEDC
CO	[mg/km]	500	270	385
CO ₂	[g/km]	152*	174	178
NO _x	[mg/km]	80	58	264
THC+NO _x	[mg/km]	170	109	346
PM	[mg/km]	4.5	0.3	2.0
PN	[-/km]	6.0E+11	-	-
Fuel consumption	[l/100 km]	-	-	-

*Type approval value

**Average of multiple tests

Table 17: Results vehicle H3

Emissions vehicle H3	Unit	Limit (Euro 6)	NEDC cold	CADC hot
Road load setting	[-]	NEDC	NEDC	NEDC
CO	[mg/km]	500	119	210
CO2	[g/km]	178*	212	215
NOx	[mg/km]	80	35	181
THC+NOx	[mg/km]	170	79	227
PM	[mg/km]	4.5	0.3	0.8
PN	[-/km]	6.0E+11	-	-
Fuel consumption	[l/100 km]	6.80*	-	-

*Type approval value

Table 18: Results vehicle A2

Emissions vehicle A2	Unit	Limit (Euro 6)	NEDC cold	CADC hot
Road load setting	[-]	NEDC	NEDC	NEDC
CO	[mg/km]	500	244	8
CO2	[g/km]	184*	207	174
NOx	[mg/km]	80	66	18
THC+NOx	[mg/km]	170	97	20
PM	[mg/km]	4.5	0.5	1.2
PN	[-/km]	6.0E+11	-	-
Fuel consumption	[l/100 km]	-	-	-

*Type approval value

Table 19: Results vehicle E4

Emissions vehicle E4	Unit	Limit (Euro 6)	NEDC cold**	CADC hot**
Road load setting	[-]	NEDC	NEDC	NEDC
CO	[mg/km]	500	49	7
CO2	[g/km]	-	177	166
NOx	[mg/km]	80	72	90
THC+NOx	[mg/km]	170	88	92
PM	[mg/km]	4.5	0.4	1.5
PN	[-/km]	6.0E+11	-	0.0E+00
Fuel consumption	[l/100 km]	-	-	0.00

*Type approval value

**Average of multiple tests

Table 20: Results vehicle H4

Emissions vehicle H4	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold***	CADC hot**_***	CADC 150 hot	WLTC cold	WLTC hot
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC
CO	[mg/km]	500	36	-	268	269	-	131	122
CO2	[g/km]	124*	128	-	150	149	-	135	131
NOx	[mg/km]	80	12	-	205	201	-	31	17
THC+NOx	[mg/km]	170	35	-	272	273	-	107	94
PM	[mg/km]	4.5	0.4	-	2.2	2.2	-	0.1	0.2
PN	[-/km]	6.0E+11	8.9E+11	-	2.6E+12	2.8E+12	-	2.3E+11	3.8E+10
Fuel consumption	[l/100 km]	4.7*	4.76	-	5.61	5.58	-	5.05	4.89

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

***A DPF regeneration occurred during the test

Table 21: Results vehicle H6

Emissions vehicle H6	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot	80	100	130	150
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC
CO	[mg/km]	500	88	62	82	83	99	-	43	153	21	19	1
CO ₂	[g/km]	109*	112	108	119	118	123	-	110	74	90	121	135
NO _x	[mg/km]	80	27	16	28	26	79	-	25	73	15	3	308
THC+NO _x	[mg/km]	170	53	54	77	76	142	-	77	84	58	16	308
PM	[mg/km]	4.5	0.0	0.1	0.1	0.1	0.2	-	0.0	-	-	-	-
PN	[#/km]	6.0E+11	2.6E+09	4.E+10	4.8E+09	4.1E+09	8.0E+10	-	1.6E+10	2.7E+10	7.3E+10	7.6E+10	3.0E+11
Fuel consumption	[l/100 km]	4,1*	4.18	4.03	4.46	4.40	4.60	-	4.11	2.75	3.36	4.52	5.05

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

Table 22: Results vehicle E6

Emissions vehicle E6	Unit	Limit (Euro 6)	NEDC cold	NEDC hot***	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC
CO	[mg/km]	500	124	4	5	2	-	-	3
CO ₂	[g/km]	127*	149	131	142	140	-	-	129
NO _x	[mg/km]	80	98	201	177	175	-	-	182
THC+NO _x	[mg/km]	170	135	206	180	176	-	-	183
PM	[mg/km]	4.5	0.1	0.0	0.6	0.6	-	-	0.0
PN	[-/km]	6.0E+11	2.9E+09	2.E+08	2.8E+09	1.9E+09	-	-	4.4E+08
Fuel consumption	[l/100 km]	4.9*	5.57	4.88	5.31	5.22	-	-	5.00

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

***Average of two tests

Table 23: Results vehicle J1

Emissions vehicle <u>J1</u>	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot	80	100	130	150
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC
CO	[mg/km]	500	372	6	57	20	8	-	5	11	1	0	1
CO2	[g/km]	119*	127	112	151	149	150	-	119	81	112	176	194
NOx	[mg/km]	80	55	85	447	456	504	-	205	41	35	110	2663
THC+NOx	[mg/km]	170	100	99	473	477	520	-	214	53	44	117	2667
PM	[mg/km]	4.5	0.2	0.0	0.1	0.1	0.1	-	0.1	-	-	-	-
PN	[#/km]	6.0E+11	4.7E+11	3.E+09	5.5E+07	3.1E+07	1.0E+10	-	4.3E+06	2.6E+06	1.5E+06	5.5E+06	1.0E+08
Fuel consumption	[l/100 km]	4.60*	4.76	4.17	5.62	5.54	5.61	-	4.45	3.04	4.16	6.56	7.22

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

Table 24: Results vehicle J2

Emissions vehicle <u>J2</u>	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC
CO	[mg/km]	500	661	8	47	7	14	90	20
CO2	[g/km]	119*	127	112	151	150	152	125	119
NOx	[mg/km]	80	74	93	716	729	822	198	247
THC+NOx	[mg/km]	170	148	113	737	745	841	217	275
PM	[mg/km]	4.5	0.1	0.3	0.3	0.3	0.5	0.2	0.1
PN	[#/km]	6.0E+11	8.1E+10	6.E+09	9.7E+07	3.1E+07	6.2E+09	5.2E+09	5.3E+06
Fuel consumption	[l/100 km]	4.60*	4.80	4.17	5.64	5.58	5.67	4.67	4.45

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

Table 25: Results vehicle K1

Emissions vehicle K1	Unit	Limit (Euro 6)	NEDC cold***	NEDC hot***	CADC cold	CADC hot**	CADC 150 hot	WLTC cold***	WLTC hot***	80	100	130	150
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	WLTP	WLTP	NEDC	NEDC	NEDC	NEDC
CO	[mg/km]	500	311	11	184	86	73	798	517	19	3	4	4
CO2	[g/km]	117*	136	130	147	147	146	152	151	86	113	166	196
NOx	[mg/km]	80	53	61	253	239	336	192	467	58	47	39	635
THC+NOx	[mg/km]	170	71	64	256	241	338	197	470	58	47	39	635
PM	[mg/km]	4.5	0.1	0.5	0.0	0.0	0.3	0.3	0.3	-	-	-	-
PN	[#/km]	6.0E+11	2.1E+09	1.E+09	1.4E+10	3.1E+09	4.3E+09	3.4E+09	2.4E+09	4.9E+08	3.3E+09	3.3E+09	2.9E+10
Fuel consumption	[l/100 km]	-	5.15	4.91	5.56	5.57	5.55	5.80	5.73	3.24	4.27	6.30	7.44

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

***Average of three tests

Table 26: Results vehicle K2

Emissions vehicle K2	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot	CADC 150 hot	WLTC cold	WLTC hot
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	NEDC	WLTP	WLTP
CO	[mg/km]	500	298	14	-	-	51	629	520
CO2	[g/km]	109*	129	120	-	-	143	146	143
NOx	[mg/km]	80	65	58	-	-	265	169	340
THC+NOx	[mg/km]	170	82	61	-	-	267	174	342
PM	[mg/km]	4.5	0.4	-	-	-	-	0.4	0.4
PN	[#/km]	6.0E+11	6.5E+10	7.E+08	-	-	1.5E+09	1.8E+10	3.1E+09
Fuel consumption	[l/100 km]	4.10*	4.84	4.48	-	-	5.34	5.49	5.34

*Type approval value

Table 27: Results vehicle L1

Emissions vehicle L1	Unit	Limit (Euro 6)	NEDC cold***	NEDC hot	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot	80	100	130	150
Road load setting	[-]	NEDC	NEDC	NEDC	NEDC	NEDC	WLTP	WLTP	WLTP	NEDC	NEDC	NEDC	NEDC
CO	[mg/km]	500	258	21	40	20	19	199	114	186	9	8	20
CO2	[g/km]	85*	104	100	114	112	133	122	120	73	87	127	148
NOx	[mg/km]	80	106	11	122	113	317	222	74	133	25	6	25
THC+NOx	[mg/km]	170	113	11	122	113	317	223	74	133	25	6	25
PM	[mg/km]	4.5	0.3	0.1	0.0	0.0	0.5	0.4	0.0	-	-	-	-
PN	[#/km]	6.0E+11	1.2E+10	9.E+07	1.9E+09	7.3E+08	5.8E+08	1.1E+08	2.5E+08	3.3E+07	2.3E+07	3.3E+07	1.7E+08
Fuel consumption	[l/100 km]	3.20*	3.90	3.72	4.23	4.16	4.95	4.56	4.46	2.72	3.25	4.72	5.52

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

***Average of three tests

Table 28: Results vehicle M1

Emissions vehicle M1	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot	80	100	130	150
Road load setting	[-]	NEDC	NEDC	NEDC	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP
CO	[mg/km]	500	237	5	8	5	5	48	5	3	3	5	4
CO2	[g/km]	110*	123	121	137	133	137	136	124	85	97	133	152
NOx	[mg/km]	80	34	27	27	15	26	47	51	22	24	41	48
THC+NOx	[mg/km]	170	59	28	29	16	26	52	51	22	24	42	49
PM	[mg/km]	4.5	0.0	0.1	0.1	0.0	4.6	0.3	0.3	10.3			
PN	[#/km]	6.0E+11	5.0E+09	5.E+08	5.5E+09	2.4E+09	2.8E+09	8.7E+09	9.2E+08	7.6E+07	6.4E+08	5.1E+09	5.2E+09
Fuel consumption	[l/100 km]	4.40*	4.60	4.51	5.10	4.96	5.10	5.06	4.62	3.16	3.60	4.96	5.67

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

Table 29: Results vehicle N1

Emissions vehicle N1	Unit	Limit (Euro 6)	NEDC cold	NEDC hot***	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot	80	100	130	150
Road load setting	[-]	NEDC	NEDC	NEDC	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP
CO	[mg/km]	500	201	20	31	6	8	75	18	4	5	6	7
CO2	[g/km]	195*	223	201	256	252	255	250	235	170	204	276	299
NOx	[mg/km]	80	58	214	370	371	279	109	211	93	22	13	1043
THC+NOx	[mg/km]	170	73	218	372	371	279	115	213	93	22	13	1045
PM	[mg/km]	4.5	0.5	0.3	0.1	0.0	0.7	0.3	0.7	-	-	-	-
PN	[# / km]	6.0E+11	1.0E+11	2.E+10	7.7E+10	4.3E+10	3.6E+10	4.1E+10	3.4E+10	2.9E+10	3.8E+10	4.4E+10	2.3E+10
Fuel consumption	[l/100 km]	7.40*	8.34	7.51	9.55	9.37	9.49	9.33	8.75	6.33	7.60	10.28	11.14

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

***Average of three tests

Table 30: Results vehicle O1

Emissions vehicle O1	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot**	CADC 150 hot	WLTC cold	WLTC hot	80	100	130	150
Road load setting	[-]	NEDC	NEDC	NEDC	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP	WLTP
CO	[mg/km]	500	488	329	125	121	60	342	1111	117	427	44	5
CO2	[g/km]	152*	184	170	196	193	196	190	202	143	155	201	223
NOx	[mg/km]	80	28	28	16	6	18	22	39	88	4	1	142
THC+NOx	[mg/km]	170	147	118	65	54	53	95	248	142	120	21	145
PM	[mg/km]	4.5	0.1	0.1	0.0	0.0	0.3	0.0	0.1	-	-	-	-
PN	[# / km]	6.0E+11	1.0E+11	9.E+09	4.2E+09	1.6E+09	1.9E+09	2.0E+10	1.5E+10	2.6E+09	3.8E+08	8.1E+09	6.2E+09
Fuel consumption	[l/100 km]	5.80*	6.91	6.35	7.33	7.21	7.31	7.12	7.62	5.34	5.80	7.48	8.30

*Type approval value

**Same test as the CADC cold, an (hot) urban part is driven directly after the CADC cold

B Pre-SCR and post-SCR emissions

SCR conversion rate detailed per vehicle

To investigate the SCR performance in all kind of circumstances the SCR conversion rates and NO_x conversion rates of all performed tests are shown per vehicle in this paragraph. The tests include chassis dynamometer and on road tests, only with vehicle L1 no chassis dynamometer results are measured with SEMS. For the other vehicles chassis dynamometer tests consist of NEDC, WLTC, CADC and constant speed tests. The on road tests consist of prescribed and non-prescribed tests. The prescribed tests are defined in Table 6. The non-prescribed real world tests can be all kind of trips like non-prescribed city trips and commuting trips, the trips can be with both cold as hot start, also the driving style varies.

In the next graphs the NO_x conversion rate is shown as a function of the SCR temperature. Also the converted NO_x as a function of the pre SCR NO_x emissions is shown. In both graphs the size of the marker indicated the post SCR NO_x emissions.

Results vehicle L1

Overall the SCR conversion rate of this vehicle is between 40 and 60% during dynamic and high speed constant speed trips. The constant speed trips until 100 km/h have an conversion rate of 90% or higher due to low engine out NO_x emissions. NO_x reductions are mainly between 250 and 420 mg/km, where 420 mg/km seems to be the maximum possible conversion rate for this SCR catalyst. To achieve post SCR emissions with this vehicle which are around the Euro 6 NEDC limit, engine out NO_x emissions needs to be lowered or the SCR system needs to reduce more NO_x.

Figure 29 and
Figure 30 show that:

- The average exhaust temperature range during the measured trips is 150 – 320 °C which is moderate. It seems that there is hardly any relation between the average temperature and the conversion rate. Most likely this the result of relatively long trips where the cold start effect is minimal.
- There is a clear difference between constant speed and dynamic trips. The constant speed trips until 100 km/h have an conversion rate of 90% or higher, in these trips the engine out NO_x is also quite low with a maximum of 350 mg/km. At higher speeds than 100 km/h the conversion rate drops because the engine NO_x increases until over 500 mg/km. At a constant speed of 120 and 130 km/h the pre SCR NO_x emissions are both approximately 520 mg/km. However, at 120 km/h the converted NO_x is 370 mg/km while at 130 km/h the converted NO_x is 245 mg/km. Possibly the lower NO_x conversion rate is the result of a too high exhaust mass flow or a non optimal NO₂/NO_x ratio.
- Engine out NO_x emissions vary between 650 and 900 mg/km during the dynamic trips and the NO_x conversion rate is very stable between 350 and 420 mg/km. Possibly the operating temperature or catalyst size limit the maximum NO_x conversion rate.

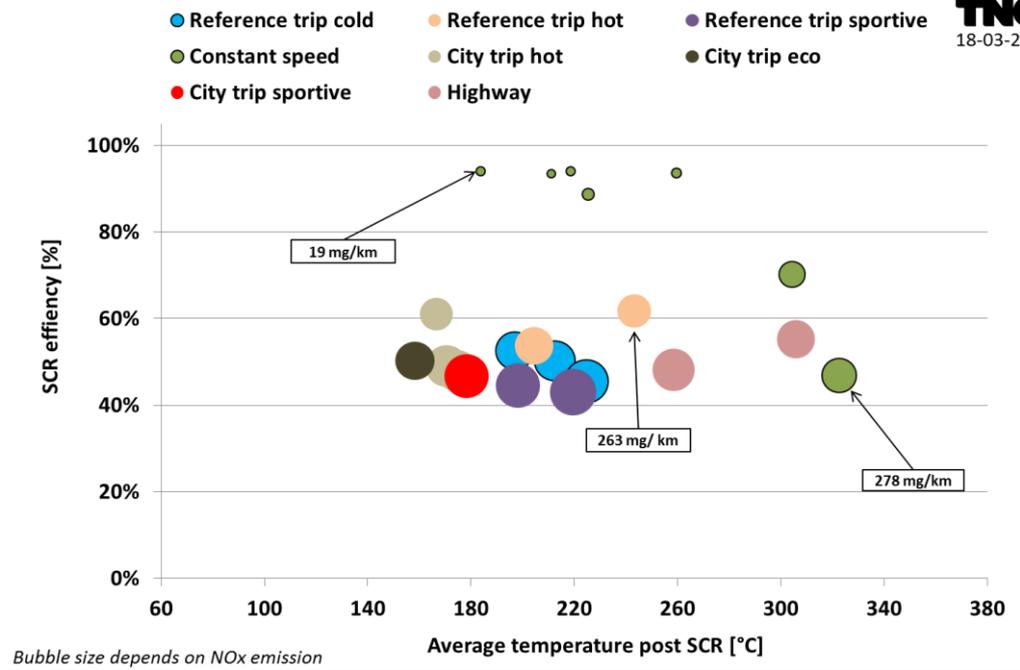


Figure 29: Average SCR operating temperature versus SCR conversion rates of vehicle L1

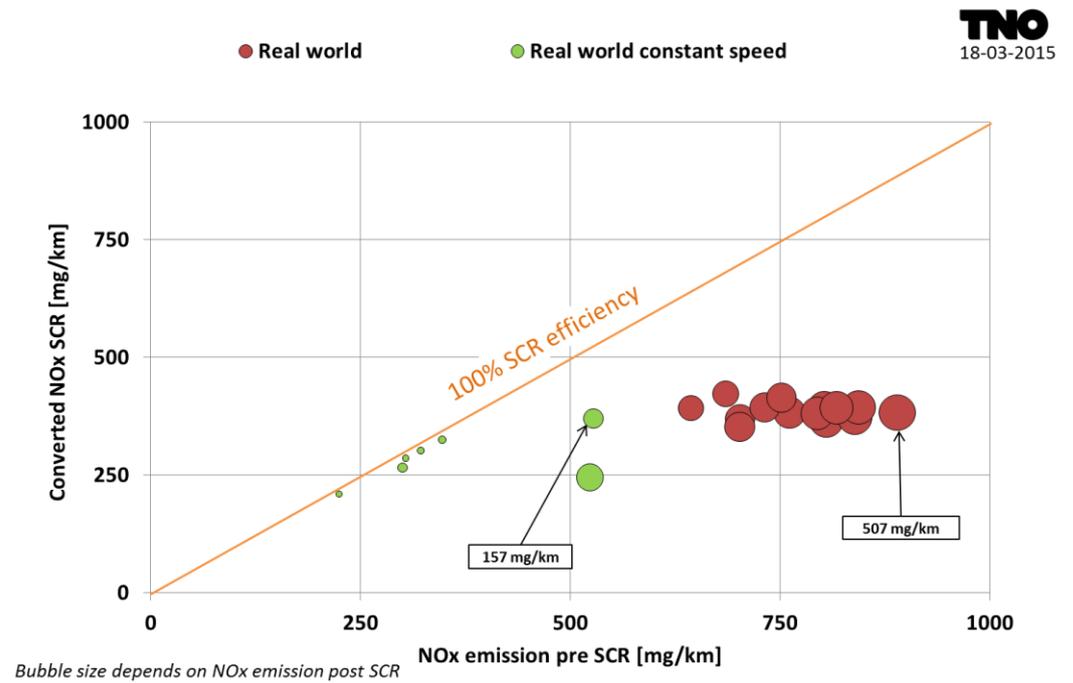


Figure 30: Converted NOx by the SCR of vehicle L1

Results vehicle M1

Overall the SCR conversion rate of this vehicle varies between 6 and 90%. This large variation is the result of low engine out emissions during chassis dynamometer tests and high engine out NO_x emissions during on road tests. It seems that a different NO_x reduction strategy is used during chassis dynamometer tests compared to on road tests. The NO_x reductions are 80 - 600 mg/km. Even though the maximum NO_x reduction for this catalyst seems to be 670 mg/km in real world operation, post SCR emissions are still high due to the very high engine out NO_x emissions. To achieve post SCR emissions with this vehicle which are around the Euro 6 NEDC limit, engine out NO_x emissions needs to be lowered or the SCR system needs to reduce more NO_x.

Figure 31 and Figure 32 show that:

- The average exhaust temperature range during the tests of this SCR is 70 – 250 °C which is relatively low. When the average temperature is 140 degrees Celsius or higher, conversion rates of over 70% can be reached on the chassis dynamometer. During on road measurements the average exhaust temperature needs to be 175 degrees Celsius to reach an conversion rate of 50%. The tests with an average exhaust temperature below 150 °C are mostly very short trips with a cold start, or urban trips where the catalyst does not reach high temperatures. At these trips the maximum SCR conversion rate is 25%. During five constant speed trips the average temperature is higher than 200 °C but the conversion rates are lower than 40%. These are tests at speeds exceeding the 130 km/h with very high NO_x emissions, both pre as post SCR. At the constant speed of 150 km/h the NO_x reduction is lower than 300 mg/km, probably the exhaust mass flow rate restricts the NO_x conversion rate.
- The SCR conversion rate is high during most of the chassis dynamometer tests. In some chassis dynamometer tests the conversion rate is 50 or 60%, however, the post SCR NO_x emissions are below 80 mg/km because the engine out NO_x emissions are low (max. 450 mg/km), probably the EGR-system is active. At the same time the NH₃ emissions during chassis dynamometer test are high at dynamic or high speed trips. During the CADC the average NH₃ emissions are almost 70 mg/km, NH₃ volume concentrations above 85 km/h are on average 50-100 ppm. It seems that too much AdBlue is injected at these operating conditions of the SCR-catalyst.
- In real world operation the engine out NO_x emissions are very high, up to 2200 mg/km. Probably the EGR-system operates not or very poor. The SCR conversion rate in real world operation is 70% at best point, most of the time the conversion rate is between 40 and 60%. With this conversion rate the SCR-system has in most trips a NO_x reduction performance between 300 and 600 mg/km. Also NO_x reductions of more than 600 mg/km are reached. Reductions of over 600 mg/km occurred during various trips, such as, constant speed, highway, urban and reference trips. However the post SCR NO_x emissions are even with those reductions high, often higher than 500 mg/km.

These results show clearly that different control strategies of the engine are applied in chassis dynamometer tests and on the road. The high NO_x reductions in chassis dynamometer tests also gain high ammonia emissions (>

10 ppm). Although ammonia emission limit values are not applicable, it is common practice not to exceed an average ammonia slip of 10 ppm.

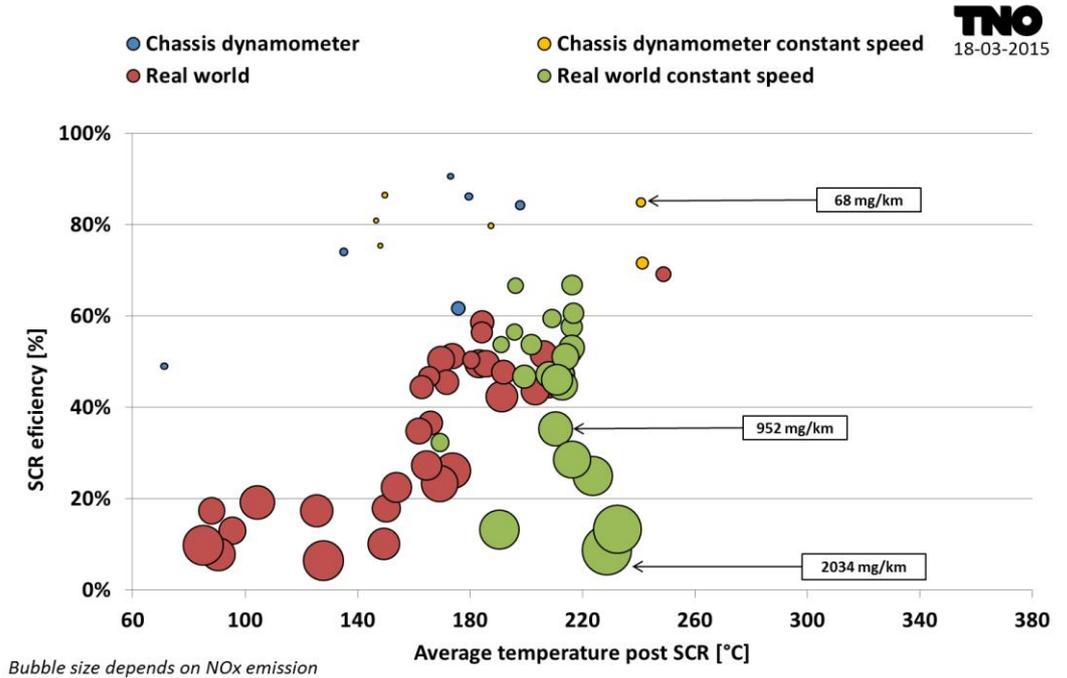


Figure 31: Average SCR operating temperature versus SCR conversion rates of vehicle M1

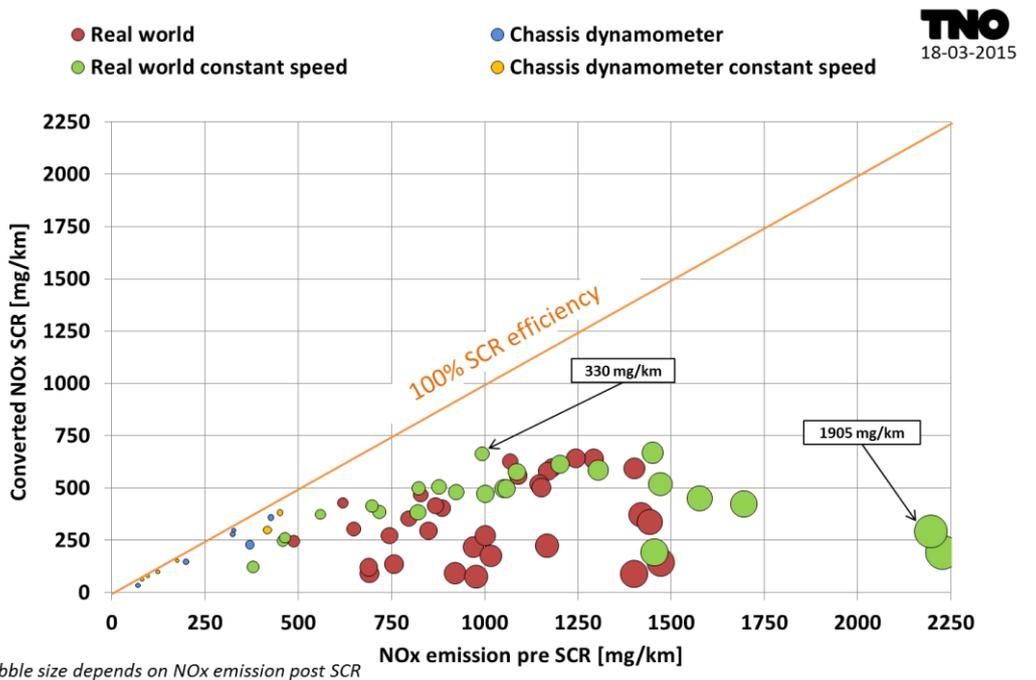


Figure 32: Converted NOx by the SCR of vehicle M1

Results vehicle N1

Overall the SCR conversion rate of this vehicle varies between 18 and 99%. High conversion rates occur at the constant speed trips up to 130 km/h, both on the chassis dynamometer as on the road. Low conversion rates occur mostly during urban trips or trips with a sportive driving style. NO_x reductions are mostly between 200 and 700 mg/km. The maximum NO_x reduction for this catalyst seems to be almost 800 mg/km. To achieve post SCR emissions with this vehicle which are around the Euro 6 NEDC limit, engine out NO_x emissions needs to be lowered or the SCR system needs to reduce more NO_x.

Figure 33 and Figure 34 show that:

- The average exhaust temperature range during the tests of this SCR is 100 – 370 °C which is moderate. When the average temperature is 100 degrees Celsius or higher, conversion rates of over 70% can be reached on the chassis dynamometer. During on road measurements the average exhaust temperature needs to be 180 degrees Celsius to reach conversion rates of higher than 50%. The tests with an average exhaust temperature of lower than 190 degrees Celsius and a SCR conversion rate below the 40% are mostly urban trips with a cold start. The highest conversion rates are reached at average exhaust temperatures which are higher than 340 degrees Celsius.
- For this vehicle there is no clear difference in SCR conversion rate between chassis dynamometer and on road tests, except for the NEDC which has a SCR conversion rate of approximately 70% at an average SCR temperature of 100 °C. However the engine NO_x emission at this test is already very low, 187 mg/km.
The conversion rates during dynamic trips, both real world as on the chassis dynamometer vary between 20 and 80%. At those conversion rates the NO_x reduction is between 200 and 700 mg/km. The low conversion rates occur mostly at urban trips or trips with a sportive driving style. The higher conversion rates are mostly at trips with a large highway part.
- The highest SCR conversion rates with this vehicle are reached during constant speed tests, both on the chassis dynamometer as on the road. Conversion rates are close to 100% until the pre SCR NO_x emissions exceed the 650 mg/km. The conversion rate drops below 70% when the constant speeds are 140 km/h or higher. At this speeds the engine NO_x also exceeds the 900 mg/km.
- Reductions around the 700 mg/km are no exception for this vehicle. However the engine NO_x emissions are most of the trips a lot higher than 750 mg/km, hence post SCR NO_x emissions are not very low at most dynamic trips.

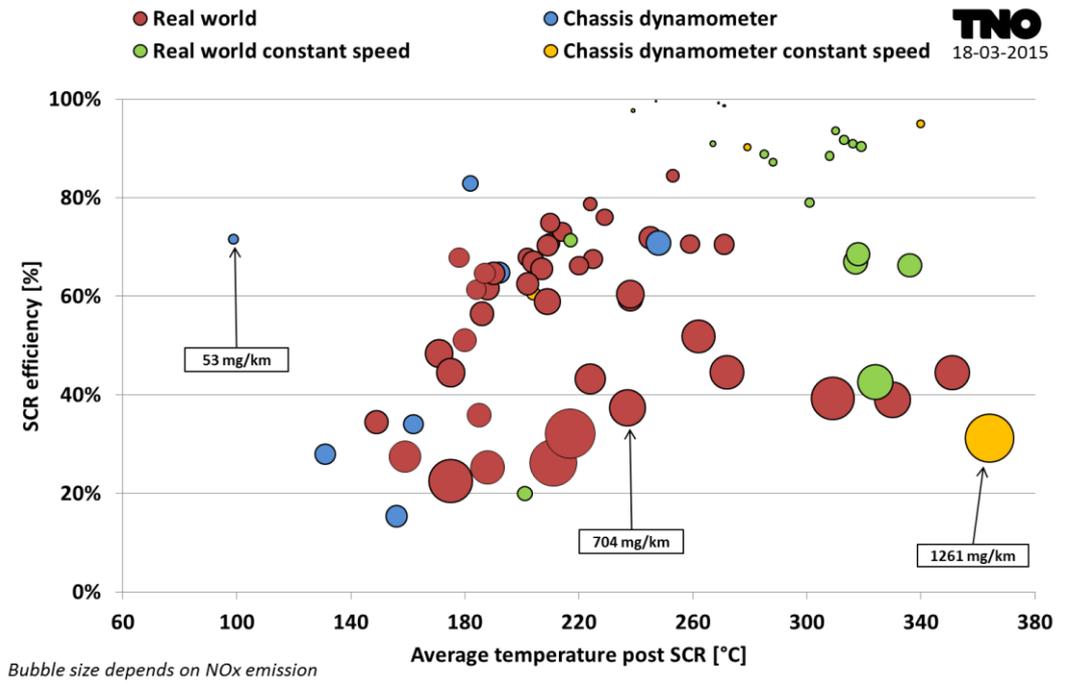


Figure 33: Average SCR operating temperature versus SCR conversion rates of vehicle N1

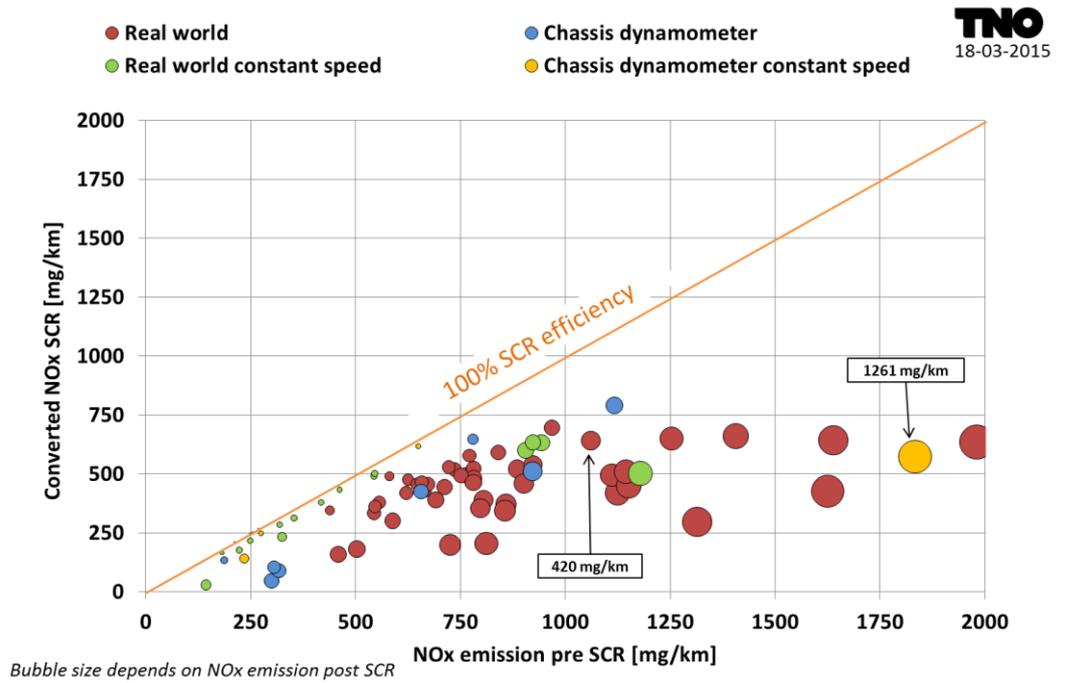


Figure 34: Converted NOx by the SCR of vehicle N1

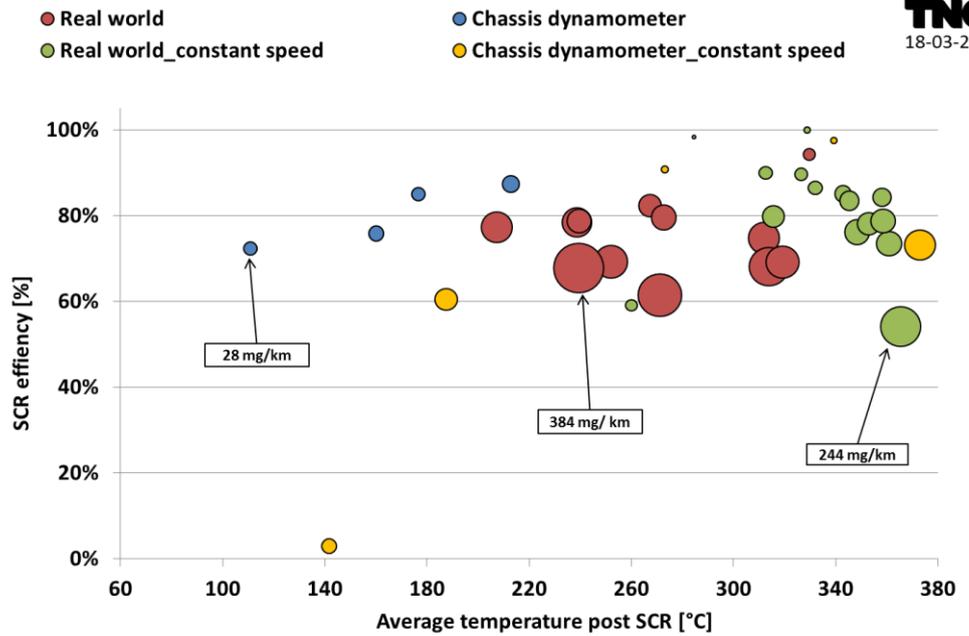
Results vehicle O1

Overall the SCR of this vehicle performs very good during both chassis dynamometer and on road tests with conversion rates between mainly 60 and 99%. The highest conversion rates occur during constant speed and chassis dynamometer tests. The highest post and pre SCR NO_x emissions with lower SCR conversion rates occur during trips which include speeds of 150 km/h or a sportive driving style.

Overall NO_x reductions are between 0 and 800 mg/km, a lot more is not needed for this vehicle. The combination of low engine out emissions and good SCR conversion rate result in very low post SCR NO_x emissions.

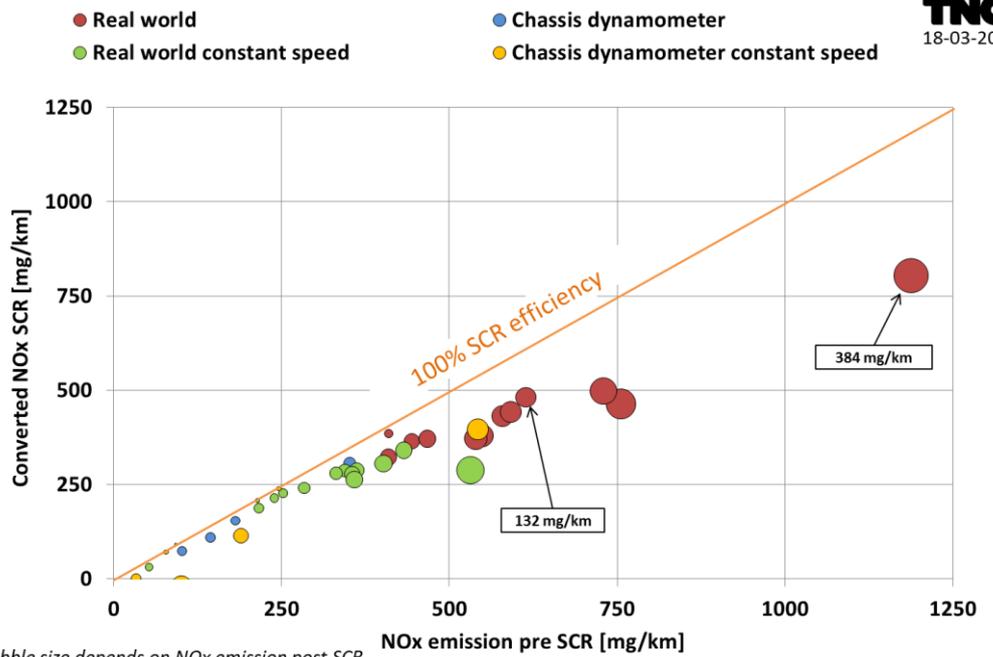
Figure 35 and Figure 36 show that:

- Overall the SCR conversion rate of this vehicle is very high and varies between 50 and 99%, with one exception of approximately 5%. This exception occurs at the constant speed test at 50 km/h, with a pre SCR NO_x emission of 33 mg/km reduction is not needed. The highest SCR conversion rate of 99% occurred during the 120 km/h constant speed test.
- The average exhaust temperature range during the tests of this SCR is 110 – 380 °C which is moderate. It seems that there is only little relation between the average exhaust temperature and the SCR conversion rate. Most likely this the result of relatively long trips where the cold start effect is minimal. When the average temperature is 100 degrees Celsius or higher, conversion rates of over 70% can be reached on the chassis dynamometer. During on road measurements the average exhaust temperature is during all tests 200 °C or higher, also at city trips and reference trips with cold start. The highest conversion rates are reached at average exhaust temperatures which are higher than 280 degrees Celsius.
- This vehicle has high SCR conversion rates during both chassis dynamometer and on road tests. The conversion rates during dynamic chassis dynamometer trips are approximately 80%. During dynamic on road tests conversion rates are between 60 and 80%, with one exception of 94% during a highway trip.
- At dynamic on road trips the NO_x reduction is the highest and are most of the tests between 300 and 500 mg/km with one exception of 800 mg/km at a sportive urban trip. During these on road trips the pre SCR NO_x emissions are also the highest, especially in the sportive urban trip. The pre SCR emissions are lowest during chassis dynamometer and constant speed tests up to 130 km/h.



Bubble size depends on NOx emission

Figure 35: Average SCR operating temperature versus SCR conversion rates of vehicle O1



Bubble size depends on NOx emission post SCR

Figure 36: Converted NOx by the SCR of vehicle O1

C AdBlue calculations

Calculation of required Adblue for NOx conversion

In this paragraph the calculation method is explained to calculate the required AdBlue mass rate for reduction of a certain amount of NOx.

The mass balance equation is applied where NH₃ oxidation is assumed to be negligible:

- $NH_3 \text{ injected [ppm]} - NH_3 \text{ slip [ppm]} - \alpha \cdot (\text{pre-SCR NOx concentration [ppm]} - \text{post-SCR NOx concentration [ppm]}) = NH_3 \text{ loss} = 0 \text{ [ppm]}$
 - α is the average NH₃ to NOx stoichiometric ratio and is typically assumed one
 - Expressing the NH₃ loss relative to the amount of NH₃ injected gives the relative mass balance error

1 part of NH₃ is needed to reduce 1 part of NOx.

$$NH_3 \text{ injected [ppm]} = NO_x \text{ engine out [ppm]} = \frac{AdBlue [g/h] \cdot 0.325 \cdot 2}{\frac{M_{H_4N_2CO}}{\dot{m}_{exh} \cdot 1000} \cdot M_{exh}} * 10^6$$

Where:

- Mexh = Average exhaust molecule mass = 28,8 [g/mol]
- MH_{4N₂CO} = Urea molecule mass = 60 [g/mol]
- Mexh = Exhaust mass flow in [kg/h]

Simplified for Adblue injection in g/s

$$Adblue [g/s] = \frac{NO_x \text{ engine out [ppm]} * \dot{m}_{exh}}{M_{exh}} * 10^{-6} * 3600^{-1} \cdot \frac{2}{0.325 * M_{H_4N_2CO}}$$

Or $M_{ua}/M_{nox} = 2,06$

For total reduction of 1 gram NOx 2,06 gram AdBlue is required.

The results per vehicle are described below in more detail.

Vehicle L1

Vehicle L1 has in the dynamic trips quite stable pre SCR NOx emissions. To achieve average NOx emissions of 80 mg/km an AdBlue tank of approximately 26 liter is needed in real world dynamic operation, or the range should be shortened from 20.000 to 13.000 kilometer. However, with the actual achieved average reduction the range is 23.000 kilometer, this means the NOx reduction should be approximately 1.8 times higher than the actual performance to achieve an average NOx emissions of 80 mg/km.

This vehicle shows very low engine out NOx emissions at a constant speed of 80 km/h. Hence an AdBlue tank of only 5.5 liter instead 17 liter is needed to achieve average real world emissions of 80 mg/km at this speed, or the range can be extended to ±62.000 km. At this speed the post SCR emissions are lower than 80 mg/km, therefore the actual range with the specified tank is ±43.000 km.

The difference between the constant speed test at 120 and 140 km/h is interesting. With an almost equal engine out NOx emission approximately the same range is calculated to achieve average NOx emissions of 80 mg/km for both speeds. However, due to less NOx conversion rate the actual range is ± 12.500 longer at 140 km/h. It seems that at this speed less AdBlue is injected, possibly because the exhaust flow is too high.

Table 31: Estimated size of AdBlue tank to low NOx emissions and estimated range on AdBlue tank of vehicle L1

Specified range with AdBlue tank: 20.000 km Specified AdBlue tank capacity: 17 liter	NOx pre SCR	Actual range with specified tank capacity	Range with specified tank capacity for reduction to 80 mg/km	Needed tank capacity for reduction to 80 mg/km NOx with specified range
	[mg/km]	[km]	[km]	[L]
NEDC cold start				
NEDC hot start				
WLTC hot start				
Constant speed 80 km/h	225	42,837	62,035	5.5
Constant speed 120 km/h	527	24,292	20,101	16.9
Constant speed 140 km/h	523	36,687	20,305	16.7
Reference trip(s)	732	22,875	13,797	24.6
City trip(s)	747	23,118	13,486	25.2
Highway trip(s)	817	22,886	12,205	27.9
Average of all dynamic real-world tests	769	23,268	13,050	26.1

Vehicle M1

Vehicle M1 has driven 32 dynamic on road trips during the measurement programme. Therefore the average of all dynamic trips is quite representative for real world operation. To achieve average NOx emissions of 80 mg/km an AdBlue tank of approximately 39 liter is needed, or the range should be shortened from 22.000 to ± 14.000 kilometer. However, with the actual achieved average reduction the range is ± 37.500 kilometer, this means the NOx reduction should be approximately 2.65 times higher than the actual performance to achieve an average NOx emissions of 80 mg/km.

This vehicle shows good performance at chassis dynamometer. With the average NOx emissions during those tests the actual range is shorter than needed to achieve average NOx emissions of 80 mg/km, i.e. the NOx is reduced below the 80 mg/km. Moreover, with such low pre SCR emissions the range can be extended to approximately 54.000 km.

During the other tests it is the other way around. During the constant speed test at 80 km/h and the highway trip the engine out NOx emissions are also relatively low, hence the range is lower than specified when the average NOx emissions needs to be 80 mg/km. However the actual range is longer than the needed range, i.e. actual emissions are not reduced to 80 mg/km.

Especially at a constant speed of 140 km/h the actual range differs from the needed range. At this speed the NOx reduction should be approximately 3.8 times higher than the actual performance to achieve an average NOx emissions of 80 mg/km.

Table 32: Estimated size of AdBlue tank to low NOx emissions and estimated range on AdBlue tank of vehicle M1

	NOx pre SCR	Actual range with specified tank capacity	Range with specified tank capacity for reduction to 80 mg/km	Needed tank capacity for reduction to 80 mg/km NOx with specified range
	[mg/km]	[km]	[km]	[L]
<i>Specified range with AdBlue tank: 22.000 km</i>				
<i>Specified AdBlue tank capacity: 25 liter</i>				
NEDC cold start	70	-	-	-
NEDC hot start	328	44,546	53,390	10.3
WLTC hot start	324	47,404	54,279	10.1
Constant speed 80 km/h	458	53,670	34,959	15.7
Constant speed 120 km/h	1058	26,643	13,529	40.7
Constant speed 140 km/h	1695	31,227	8,190	67.2
Reference trip(s)	1181	20,883	12,019	45.8
City trip(s)	1182	22,215	12,009	45.8
Highway trip(s)	619	30,889	24,529	22.4
Average of all dynamic real-world tests	1017	37,459	14,118	39.0

Vehicle N1

Vehicle N1 has driven 46 dynamic on road trips during the measurement programme. Therefore the average of all dynamic trips is quite representative for real world operation. Moreover, the pre SCR NOx emissions during the selected on road dynamic trips are quite stable. To achieve average NOx emissions of 80 mg/km in real world operation an AdBlue tank of approximately 37.1 liter is needed, or the range should be shortened from 25.000 to ± 15.500 kilometer. However, with the actual achieved reduction the range is ± 27.000 kilometer, this means the NOx reduction should be approximately 1.75 times higher than the actual performance to achieve an average NOx emissions of 80 mg/km.

This vehicle shows its best performance during the NEDC and the constant speed test at 120 km/h. With the average NOx emissions during those tests the actual range is shorter than needed to achieve average NOx emissions of 80 mg/km, i.e. the NOx is reduced below the 80 mg/km.

During the NEDC with hot start and the constant speed test at 80 km/h the engine out NOx emissions are low enough to extend the range approximately 2 times. However, the actual range is even longer than the needed range, i.e. the actual reduction is not sufficient to reach an average NOx emission of 80 mg/km.

Table 33: Estimated size of AdBlue tank to low NOx emissions and estimated range on AdBlue tank of vehicle N1

	NOx pre SCR	Actual range with specified tank capacity	Range with specified tank capacity for reduction to 80 mg/km	Needed tank capacity for reduction to 80 mg/km NOx with specified range
	[mg/km]	[km]	[km]	[L]
<i>Specified range with AdBlue tank: 25.000 km (estimate)</i>				
<i>Specified AdBlue tank capacity: 23 liter</i>				
NEDC cold start	187	91,068	114,041	5.0
NEDC hot start	307	152,124	53,530	10.7
WLTC hot start	656	28,617	21,126	27.2
Constant speed 80 km/h	325	52,392	49,581	11.6
Constant speed 120 km/h	342	40,016	46,387	12.4
Constant speed 140 km/h	906	20,262	14,735	39.0
Reference trip(s)	858	32,821	15,641	36.8
City trip(s)	811	59,372	16,640	34.6
Highway trip(s)	913	24,412	14,618	39.3
Average of all dynamic real-world tests	865	27,084	15,506	37.1

Vehicle O1

Vehicle O1 has in all trips relatively low pre SCR NO_x emissions. Also during the dynamic trips the pre SCR emissions are lower than the other tested vehicles. To achieve average NO_x emissions of 80 mg/km in dynamic real world operation an AdBlue tank between 10 and 15 liter is needed, or the range should be between 15.000 and 24.000 kilometer. This characteristics are equal or even better than the specified characteristics. During the reference trip the actual range is more or less comparable with the needed range, i.e. the reduction ensures an average post SCR NO_x emissions of approximately 80 mg/km. The actual range of the average of all dynamic trips is 19% higher, this means the NO_x reduction should be approximately 1.19 times higher than the actual performance to achieve an average NO_x emissions of 80 mg/km. This is the result of high speed driving on the German highway and the trips with a sportive driving style.

During chassis dynamometer and constant speed tests up to 120 km/h the results are impressive, especially during the constant speed test of 80 km/h. At a constant speed of 80 km/h an AdBlue tank of approximately 0.4 liter is needed, or the range can be extended from 15.000 to ±625.000 kilometer in order to achieve average NO_x emissions of 80 mg/km in real world operation. The actual range is shorter, i.e. the actual emissions are lower than 80 mg/km.

Table 34: Estimated size of AdBlue tank to low NO_x emissions and estimated range on AdBlue tank of vehicle O1

	NO _x pre SCR	Actual range with specified tank capacity	Range with specified tank capacity for reduction to 80 mg/km	Needed tank capacity for reduction to 80 mg/km NO _x with specified range
	[mg/km]	[km]	[km]	[L]
<i>Specified range with AdBlue tank: 15.000 km</i>				
<i>Specified AdBlue tank capacity: 15 liter</i>				
NEDC cold start	102	107,620	361,737	0.6
NEDC hot start	144	72,593	123,672	1.8
WLTC hot start	351	25,858	29,255	7.7
Constant speed 80 km/h	93	87,120	626,079	0.4
Constant speed 120 km/h	285	32,713	38,759	5.8
Constant speed 140 km/h	432	23,323	22,541	10.0
Reference trip(s)	456	21,548	21,131	10.6
City trip(s)	614	16,489	14,870	15.1
Highway trip(s)	409	20,580	24,117	9.3
Average of all dynamic real-world tests	606	17,913	15,086	14.9

D Additional tables for RDE evaluation

Table 35: Trip characteristics of the TNO reference trip with hot start and regular driving style

Reference trip	Trip distance	Average speed	Average acceleration	Average Relative Positive Acceleration
Vehicle	[km]	[km/h]	[m/s ²]	[m/s ²]
E6	73.1	49.0	0.43	4.82
H7	73.5	47.0	0.42	4.68
K2	76.5	49.8	0.43	4.85
L1	73.3	49.9	0.35	3.49
M1	73.2	47.5	0.44	4.80
N1	72.4	52.4	0.46	5.35
O1	73.4	55.8	0.37	4.16

Table 36: NO_x results per road area for vehicle K2

NO _x emissions in mg/km during TNO reference trip	Average			EMROAD			CLEAR		
	urban 0 - 60 km/h	rural 60 -90 km/h	motorway >90 km/h	urban 0 - 45 km/h	rural 45 -80 km/h	motorway >80 km/h	urban 0 - 60 km/h	rural 60 -90 km/h	motorway >90 km/h
K2_regular	117	45	369	78	61	407	67	168	
K2_sportive	1173	663	869	892	790	901	497	570	
K2_regular	100%	100%	100%	-33.3%	35.6%	10.3%	-42.7%	-	
K2_sportive	100%	100%	100%	-24.0%	19.2%	3.7%	-57.6%	-	