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TNO report

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Investigations and real world emission performance of Euro 6 light-duty vehicles

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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 hoger ligt dan op grond van de Euro 6 norm mocht worden verwacht. De Euro 6 norm wordt 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 Euro 5 (180 mg/km) naar Euro 6 (80 mg/km) ligt de praktijk NO_x-emissie van de geteste voertuigen op circa 500 mg/km, d.w.z. hetzelfde niveau als van Euro 4 en Euro 5 dieselpersonenauto's.

In opdracht van het ministerie van Infrastructuur & Milieu heeft TNO onderzoek gedaan naar het praktijkemissiegedrag van Euro 6 personenwagens die zijn uitgerust met dieselmotor. Het onderzoek is een basis voor de emissiefactoren die in 2014 worden vastgesteld. Ook heeft het ministerie aan TNO gevraagd adviezen op te stellen voor maatregelen die resulteren in lage praktijkemissies en in lijn zijn met de emissies in de typegoedkeuringstest.

Bij de uitgevoerde testen gaat het zowel om metingen in het laboratorium op de rollenbank als om metingen met mobiele meetapparatuur (PEMS) op de weg. De geteste voertuigen voldoen op basis van de NEDC typekeuringstest aan de Euro 6 NO_x-norm van 80 mg/km. Echter onder praktijkomstandigheden ligt de NO_x-uitstoot tot wel een factor 6 hoger. Eén getest voertuig presteerde wel goed en haalde onder praktijkomstandigheden 35-95% van de NOx limietwaarde.

Leeswijzer:
Dit onderzoek is gebaseerd op diverse emissiemetingen aan Euro 6 diesel personenwagens. De metingen zijn in 2010 en 2013 uitgevoerd, zowel in een laboratorium als op de weg.
Vervolgens zijn de meetresultaten beoordeeld aan de hand van de toegepaste nabehandelingstechnologie. Tevens zijn de emissiefactoren bepaald en vergeleken met emissiefactoren van oudere voertuigen.
Ook zijn de resultaten van dit onderzoek vergeleken met resultaten van een aantal andere Europese instituten.
Als laatste zijn op basis van deze resultaten aanbevelingen gedaan voor de regulering van praktijkemissies in de toekomstige emissiewetgeving.

Reden tot zorg:
Ondanks een voortdurende aanscherping van de NOx emissienormen van Euro 1 naar Euro 6, zijn de NO_x emissiefactoren[1] van dieselpersonenauto's op de snelweg de laatste 10 jaar ongeveer gelijk gebleven (400 – 600 mg/km). In stadsverkeer is er wel sprake van reductie (van 1000 naar 200 mg/km) maar de NOx emissie ligt nog altijd ver boven de limietwaarde van de typegoedkeuring (80 mg/km). Zie ook Figuur 1.

In 2010 zijn enkele metingen uitgevoerd aan de eerste Euro 6 dieselpersonenauto's. Deze eerder geteste voertuigen uit 'voorserie modellen' (pre-

[1] Een emissiefactor is een op basis van meetdata berekend gemiddelde voor de vloot

Euro 6), die ook leverbaar zijn op de Amerikaanse markt, presteerden beter dan de huidige Euro 6 productiemodellen.

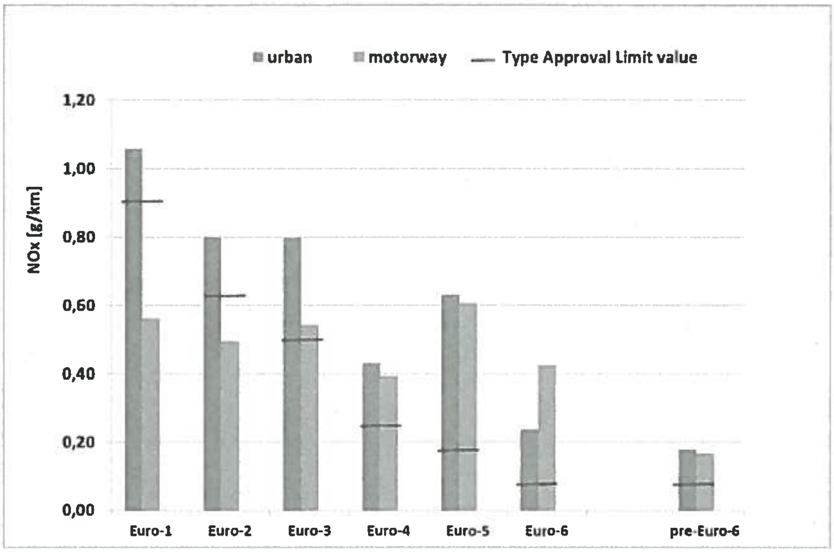

Figure 1: NOx emissiefactoren voor stad en snelweg en limietwaarden bij typegoedkeuring van dieselpersonenwagens

Tot op heden is in Nederland een gering aantal Euro 6 dieselauto's verkocht. Het betreft vooral duurdere voertuigen. Voor kleinere voertuigen wordt namelijk nog geen Euro 6 technologie geleverd. Vanaf 1 september 2014 zullen echter alle nieuwe typen personenwagens en kleine bedrijfswagens moeten voldoen aan Euro 6 emissienormen. Eén jaar later zullen alle voertuigen waarvoor een kenteken wordt aangevraagd aan deze emissienorm moeten voldoen. Vermoedelijk zullen de kleinere Euro 6 dieselvoertuigen, die op dit moment nog niet leverbaar zijn, met goedkopere technologie worden uitgerust. Dit kan leiden tot andere (hogere!) praktijkemissies en bijstelling van de emissiefactoren.

Uit de metingen blijkt dat Euro 5 en Euro 6 voertuigen met benzinemotor in de praktijk wel lage NOx emissies hebben.

Toegepaste nabehandelingstechnologie is van grote invloed:
De NO_x praktijkemissies van Euro 6 dieselvoertuigen variëren zeer sterk. Afhankelijk van de testcondities en het voertuig is de spreiding 10% tot 1000% van de limietwaarde. Dit wordt hoofdzakelijk veroorzaakt door het type, de werking en regelstrategie van de uitlaatgasnabehandelingstechnologie. Beschikbare technologieën zijn EGR (uitlaatgasrecirculatie), SCR (selectieve katalytische reductie) en LNT (Lean NOx Trap). Net als bij Euro 5 dieselvoertuigen wordt bij Euro 6 voertuigen selectief gebruik gemaakt van deze systemen die zorg dragen voor verlaging van NOx-emissies in de uitlaatgassen. De regelstrategie is zodanig dat EGR en SCR systemen tijdens de rijomstandigheden die optreden bij de typekeuringstest functioneel zijn, maar onder praktijkomstandigheden om economische redenen (gedeeltelijk) worden uitgeschakeld.

Bij de geteste voertuigen ging het om duurdere middenklasse of grotere auto's die met EGR en SCR dan wel met LNT waren uitgerust. Goedkopere Euro-6 dieselpersonenauto's uit de compacte klasse of kleiner zijn nog niet of nauwelijks op de markt. Het is waarschijnlijk dat de kleinere en goedkope alsook de middelgrote dieselvoertuigen die in Nederland het hoofdaandeel in het dieselsegment vormen, zullen worden uitgerust met de goedkoopste Euro 6 technologie. Fabrikanten passen dan alleen EGR toe om auto's op de typekeuringstest aan Euro-6 te laten voldoen. Beschikbare systemen als SCR en LNT die onder praktijkomstandigheden een forse NOx-reductie kunnen leveren zullen bij deze modellen naar verwachting niet worden toegepast. Net als Euro 5 voertuigen levert dit vooral een risico van hoge NO_x praktijkemissies op de snelweg. Verwacht wordt dat de praktijk NO_x-emissies van deze kleinere Euro 6 dieselpersonenauto's ook op het niveau van Euro 5 uit zullen gaan komen.

Resultaten emissiemetingen dieselvoertuigen TNO en TUG:
Alle Euro 6 dieselvoertuigen blijken in de typegoedkeuringstest aan de limietwaarde van 80 mg/km te voldoen, maar de doorwerking daarvan in de praktijk blijkt beperkt. Dit komt vooral tot uiting in meer praktijkgerichte metingen. Op de rollenbank is dit de CADC-test en op de weg in testen in het stadsverkeer, op de buitenweg en op de snelweg. Ook hier valt de NO_x praktijkemissie het meest op, die is gemiddeld 400-500 mg/km (5-6 keer limietwaarde). In de testen op de openbare weg (stad, buitenweg, snelweg) zijn gemiddelde NO_x emissies van 550 – 800 mg/km gemeten, dit is 7 – 10 keer de limietwaarde van de typegoedkeuringstest. Verder valt op dat de spreiding onder de verschillende voertuigen zeer groot is (wel tot een factor 10). Slechts één dieselvoertuig met EGR in combinatie met LNT technologie presteerde naar verwachting.
Voor de emissiecomponenten CO, THC en PM is er voor alle technologieën geen sprake van praktijkemissies die hoger zijn dan de emissies in de typekeuring.
De resultaten van dit onderzoek worden bevestigd door externe bronnen en metingen van de Technische Universiteit in Graz. Alhoewel het aantal gemeten voertuigen beperkt is, is het niet de verwachting dat het beeld zal veranderen als er meer testresultaten beschikbaar komen. Een en ander betekent dat de NOx praktijkemissies van Euro 3,4,5 en 6 voertuigen niet wezenlijk verschillen.

Resultaten literatuuronderzoek:
Vier Europese bronnen met emissieresultaten van Euro 6 voertuigen zijn geraadpleegd. Het betreft publicaties van de volgende organisaties: ADAC (D), AECC(B), JRC(I) en TOI(N). De resultaten van deze studies komen redelijk tot goed overeen en stroken in grote lijnen met de praktijkmetingen van TNO en TUG. Bij een omgevingstemperatuur van 25 °C bedraagt de NOx praktijkemissie van dieselvoertuigen 400-500 mg/km (5-6 keer limietwaarde). Voor de emissiecomponenten CO, THC en PM is er geen sprake van overschrijding.

Eisen voor praktijkemissies in toekomstige Euro 6 wetgeving:
Vanaf 1 september 2014 moeten alle nieuw ontwikkelde personenwagens voldoen aan de eisen van fase 1 van Euro 6. Deze wetgeving bevat nog geen specifieke eisen over de emissies in de praktijk en dwingt dus niet af dat dieselauto's het ook in de praktijk goed doen. Lage praktijkemissies voor NOx kunnen wel worden afgedwongen door aanvullende wetgeving met NOx emissies die in de praktijk moeten worden gehaald. Zolang dit niet gebeurd is er geen perspectief op lage praktijkemissies voor NOx van dieselpersonenauto's.

Op dit moment wordt in Brussel gewerkt aan de tweede fase van Euro 6, waarin dergelijke emissie-eisen voor de praktijk worden gedefinieerd. In aanvulling op de typekeuringstest in het laboratorium moet het voertuig voor fase twee Euro 6 ook op de weg met mobiele testapparatuur (PEMS) worden beproefd. Het is de verwachting dat door het stellen van praktijkeisen NOx-emissies aanzienlijk zullen dalen. Bij Euro-VI vrachtwagens heeft de invoering van een nieuwe testmethode met mobiele meetapparatuur op de weg ook tot een aanzienlijke daling van de NOx-emissies geleid.

De Europese Commissie is voornemens om de tweede fase van Euro-6 in september 2017 in werking te laten treden. Vanuit de auto-industrie zijn er echter wensen voor uitstel naar een latere datum.
De voertuigtechnologie is echter beschikbaar om voertuigen aan fase twee eisen van Euro-6 te laten voldoen. Dit kan worden gerealiseerd door effectieve toepassing van EGR in combinatie met SCR of LNT systemen. Reeds in 2010 zijn metingen verricht aan pre-Euro 6 dieselvoertuigen, waarbij goede NOx prestaties werden vastgesteld. Vermoedelijk is een optimalisatieslag van kosten de reden geweest dat de huidige Euro 6 voertuigen in de praktijk slechter presteren.

Summary

Results of a vehicle emission test program on behalf of the Dutch Ministry of Infrastructure & the Environment show higher real world NO_x emissions of Euro 6 diesel passenger vehicles than would be expected on basis of the Euro 6 Type Approval emission levels. The Euro 6 type approval limit value comes into force in 2014 and it aims at a substantial reduction of pollutants of passenger cars and light commercial vehicles.
In spite of the tightening of the Euro 5 NO_x limit value (180 mg/km) to Euro 6 (80 mg/km) real world NO_x emissions of tested Euro 6 vehicles are approximately 500 mg/km and they are equal approximately to Euro 4 and Euro 5 diesel passenger vehicles.

On behalf of the Dutch Ministry of Infrastructure and The Environment TNO investigated real world emission performance of Euro 6 diesel passenger cars. The results of the test program are the basis of the determination of Dutch emission factors. Furthermore the Ministry requested TNO to define measures for low real world emissions which are in line with type approval emissions.

The vehicle emission tests are carried out in a laboratory on a chassis dynamometer as well as on the road with a portable emission measuring system (PEMS). All these Euro 6 diesel passenger cars comply with the NO_x type approval limit values of 80 mg/km. However real world NO_x results are approximately 6 times higher. Only one vehicle performed under real world conditions well below (25-75 mg/km) the NO_x limit value.

Structure of the study:
This study is based on emission test results of diesel passenger cars. In 2010 and 2013 the tests were carried out in a laboratory and on the road. The test results are reviewed on the basis of the applied aftertreatment technologies. Furthermore Euro 6 emission factors are determined and compared with former emission factors.
All test results are compared with test results of a number of European research institutes. Finally on basis of these results recommendations for low real world emission test procedures are made for future legislation.

Cause for concern:
In spite of the continuous tightening of the NO_x type approval-limit values from Euro 1 to Euro 6, last decade the NOx emission factors on the motorway have been more or less stable (400-600 mg/km). However there is a reduction in city traffic (from 1000 – 200 mg/km) but this still is more than the type approval limit value of 80 mg/km.

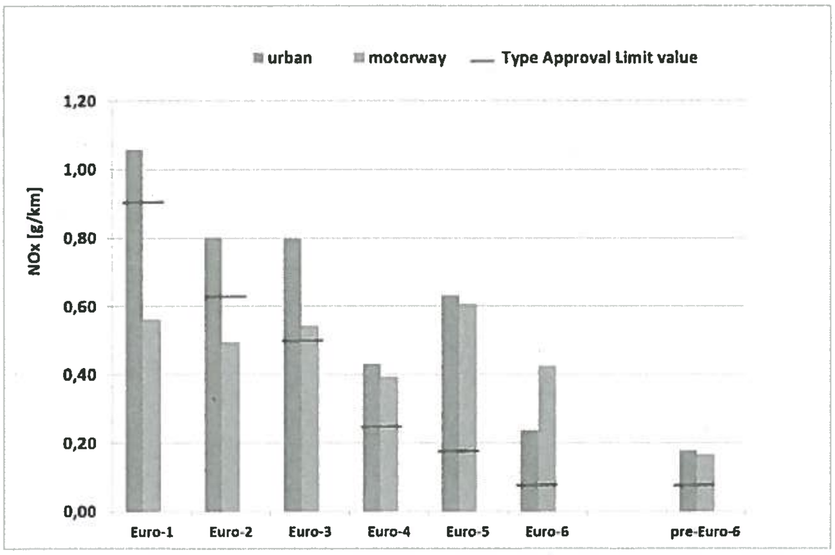

Figure 2: NOx emission factors in the city and on the highway and type approval limit values of diesel passenger cars.

In 2010 some emission tests were carried out on the first Euro 6 diesel passenger cars. These pre Euro 6 vehicles which were available for the US-market performed better than the current Euro 6 production models.

Up to 2013 only a few Euro 6 diesel vehicles were sold, and mainly in the upper market segment. Small new diesel vehicles are still not equipped with Euro 6 technology. However, they must comply to type approval values in 2014 and all new vehicles must comply one year later. Presumably, the smaller diesel vehicles will be equipped with cheap technology. This may lead to different (higher!) real world emissions and adjustment of current Euro 6 emission factors.

The test results of Euro 5 and 6 petrol vehicles certainly show low real world NO_x emissions (< 80 mg/km).

Applied exhaust aftertreatment technology is a key element:
Real world NO_x emissions of Euro 6 diesel passenger cars vary very strongly. Dependent on the test conditions and vehicle technology the spread is 10% to 1000% of the limit value. This is mainly caused by the type, the functionality and the control strategy of the exhaust after-treatment technology. Available technologies are EGR (Exhaust Gas Recirculation), SCR (Selective Catalytic Reduction) and LNT (Lean NOx Trap). Euro 5 as well as Euro 6 vehicles make selective use of these technologies which take care of NO_x reduction in the exhaust gases. During type approval tests the control strategies are active and effective, but during real world operation the systems can be (partly) switched off.

In this test program the selected vehicles are classified in the upper segments and equipped with EGR and SCR or LNT technologies. The small Euro 6 diesel vehicles are still not on the market. These smaller and middle segments will be the bulk of the total fleet of diesel vehicles and probably they will be equipped with cheaper technology. Manufacturers only apply EGR-technologies, SCR and LNT technologies which are able to produce low real world NOx emissions probably will not be applied widely. Like with Euro 5 diesel vehicles this is a risk for high NO_x

emissions on the motorway. It is expected that real world NO_x emissions of small Euro 6 vehicles will be on the same level as the real world NO_x emissions of Euro 5 diesel vehicles.

Vehicle emission test results of TUG and TNO:
All Euro 6 diesel vehicles comply with their NOx type approval limit values of 80 mg/km but the effect of the applied technologies under real world conditions is restricted. This is measured in tests which are more related to daily use. On the chassis dynamometer this is the CADC-test and on the road tests are performed in the city, rural roads and motorways. Again the real world NO_x emissions are on average 400-500 mg/km. In road tests on public roads (city, rural, motorway) average NO_x emissions of 550 – 800 mg/km are measured, this 7-10 times the type approval value. Furthermore, the spread of the different vehicles is huge (up to 10 times). Only one vehicle with EGR and LNT technology performed under real world conditions below the type approval limit value of 80 mg/km.
For all technologies CO, THC and PM real world emissions are below their type approval limit values.
The results of this test program are confirmed by literature and the test results of the Technical University of Graz (TUG). Although the number of tested vehicles is low it is not expected that these emission factors will change in case of more available test results. This means that real world NOx emissions of Euro 3,4,5 and 6 vehicles not really differ.

Results literature research
Four European sources with emission test results of Euro 6 vehicles have been investigated. It concerns publications of ADAC (D), AECC(B), JRC(I) en TOI(N). The results of these studies agree reasonably with the real world test results of TUG and TNO. At ambient temperatures of 25 °C the real world NO_x emission of diesel passenger cars are 400-500 mg/km (5-6 times of the type approval limit value). The CO, THC and PM real world test results do not exceed the type approval limit values.

Requirements for future Euro 6 emission legislation:
On September 1st, 2014 all new vehicle types must comply with Euro 6 stage 1 regulation. This regulation does not contain specific requirements for real driving emissions (RDE) and does not force manufacturers to achieve low real world emissions. However, low real world NO_x emissions can be reached with appropriate legislation with real world NO_x emission requirements. As long as this legislation comes not into force low real world NO_x emissions of diesel cars will probably not be realized.
Currently stage 2 of Euro 6 legislation is under construction in Brussels which will contain requirements for real world emissions. In addition to chassis dynamometer tests vehicles will be tested on the road with PEMS equipment. It is expected that real world emission requirements will lead to lower real world NO_x emissions of diesel passenger cars.
In case of Euro VI trucks the enforcement of new test methods with mobile test equipment has led to a strong reduction of real world NO_x emissions.

In September 2017 the European Commision resolves the enforcement of phase 2 of the Euro 6 legislation but the automotive industry prefers to postpone this. However, the Euro 6 phase 2 technology is already available. Low real world NOx emissions can be reached by application of EGR technology in combination with

SCR or LNT technology. In 2010 lower NO_x emissions were already measured. Presumably an optimization of costs of aftertreatment technologies causes the worse performance of Euro 6 vehicles in real world operation.

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Appendices
A TNO chassis dynamometer test results
B Determination of emission factors

1 Introduction

1.1 Background

To minimize air pollutant emissions of light duty vehicles the Euro emissions standards were introduced in 1992. The Euro emissions standards becoming more stringent in the course of time. Currently produced light duty vehicles needs to comply with the Euro 5 standard. The Euro 6 standard will become mandatory in 2014. The standards apply for both spark ignition engines and for compression ignition engines and includes the following gaseous and particulate emissions:
- CO (carbon monoxide)
- THC (hydrocarbons)
- NO_x (nitrogen oxides)
- PM (particulate mass)
- PN (particulate number)

As a result of the Euro emissions standards the pollutant emissions decreased a lot during the type approval test the past decade. However, some emissions under real driving conditions differ a lot from type approval emissions. The real driving NO_x (nitrogen oxides) emissions of diesel vehicles are currently the largest issue with regard to pollutant emissions. The ambient NO_2 concentration exceeds the limits at numerous road-side locations in The Netherlands.

TNO performs emission measurements within the "in-use-compliance program for light duty vehicles" on behalf of the Dutch Ministry of Infrastructure and the Environment. Whereas in the early years, 1989-2000, many standard type approval tests were executed, in recent years the emphasis has shifted to the gathering of real world emission data on various nonstandard driving cycles. In the current program multiple Euro 6 diesel passenger cars are tested.
TNO develops annually updated vehicle emission factors based on the performed emission measurements, emission factors represent real world emission data for various vehicle types and different driving conditions. Vehicle emission factors are used for emission inventory and air quality monitoring. TNO is the sole supplier of primary data for this purpose in The Netherlands.

The emission factors for NO_x emissions of Euro 5 diesel passenger cars were a lot higher than expected, see Table 1. The NO_x emission factors of Euro 5 are in most cases even higher than Euro 4.

Table 1: Emission limits and emission factors for diesel passenger cars

Emission standard	Emission limit NO_x [g/km]	Emission factor NO_x [g/km]		
		City	Rural	Highway
Euro-1 (1993)	0.97*	0.73	0.45	0.56
Euro-2 (1996)	0.7*	1.02	0.55	0.5
Euro 3 (2000)	0.5	0.89	0.55	0.54
Euro 4 (2005)	0.25	0.51	0.38	0.39
Euro 5 (2009)	0.18	0.63	0.34	0.61
Euro 6 (2014)	0.08			

*NO_x + HC

In this report the first results of Euro 6 diesel passenger are discussed. Preliminary Euro 6 emission factors, used in previous years for prognoses are in between 0.08 g/km (80 km/h speed limit motorway) and 0.22 g/km (heavy congestion).

1.2 Aim and approach

The objective of this research is to assess the real world emission performance of Euro 6 diesel passenger cars and to provide emission factors for this category.

In order to obtain a more comprehensive understanding of the emission performance, both measurements of TNO and TU Graz are evaluated as well as the available public data.

Emission measurements are performed with Euro 6 compliant vehicles (early models). Both chassis dynamometer and PEMS (Portable Emissions Measurement System) measurements are performed. On the chassis dynamometer various real driving cycles are used.

1.3 Structure of the report

The project contains a literature survey, an experimental test program and an emission modelling program.
Chapter 1 describes the introduction, the aim and the approach. In chapter 2 the applied vehicles, testing methodologies and emission reduction technologies are described. In chapter 3 the emission reduction technologies are reported. In chapter 4 the available public data are described. In chapter 5 the experimental results are given and in chapter 6 the determination of the emission factors is reported.

2 Method

Available public data or publications are investigated and several Euro 6 vehicles are tested. These measured test results are the basis for the determination of the emission factors.

2.1 Tested vehicles

The tested vehicles are early models because Euro 6 is not yet mandatory (will become mandatory in 09-2014). Only compression ignition (diesel) vehicles are tested due to the fact that there are no expected direct issues with spark ignition (gasoline) vehicles regarding NO_x emissions.

2.1.1 *TNO tested vehicles*

The tested vehicles by TNO are either provided by the official Dutch importers or by private owners. In all cases the vehicles have exceeded the minimum requirement of 3.000 driven kilometres. TNO tested Euro 6 compliant vehicles in 2010 and in 2012/2013.
Table 2 shows the tested vehicles, the character indicates the brand, the number indicates a specific vehicle.

Table 2: TNO tested vehicles

Vehicle ID	-	veh: H2	veh: H3	veh: A2	veh:E4*	veh: H4	veh: H6	Veh: E6	Veh: J1	Veh: J2
Engine Power class	[kW]	>150	>150	>150	100 - 125	125 - 150	100 - 125	100 - 125	100 - 125	100 - 125
Engine capacity class	[cm3]	>2000	>2000	>2000	1750 - 2000	1750 - 2000	1750 - 2000	1750 - 2000	1750 - 2000	1750 - 2000
Odometer	[km]	2354	16634	9466	±9400	10965	28376	26200	20100	11616
Fuel	-	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Inertia	[kg]	1700	1930	2040	1590	1590	1470	1590	1590	1590
Emission class	-	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6	Euro 6
Type	-	Sedan	Sedan	Sedan	Sedan	Station	Station	Sedan	MPV	MPV
Vehicles class	-	M1	M1	M1	M1	M1	M1	M1	M1	M1
Date	-	2010	2010	2010	2010	2012	2013	2013	2013	2013
Emission technology		EGR + SCR	EGR + LNT	EGR + SCR	EGR + LNT	EGR + SCR	EGR + LNT	EGR + SCR	EGR	EGR
Remark	-	Prototype or for USA market	Prototype or for USA market	Prototype or for USA market	Prototype or for USA market	Production vehicle	Production vehicle	Production vehicle	Production vehicle	Production vehicle

*Three identical vehicles

The tested four vehicles in 2010 were prototypes or were meant for the USA market, all these vehicles are relatively large. In 2012 and 2013 five production vehicles are tested, also this vehicles are relatively large vehicles. The two vehicles of brand H are of the same model but with a different engine. The two vehicles of brand J are identical model and types. Furthermore the availability of Euro 6 compliant vehicles are still very scarce, especially for the compact cars .

2.1.2 *TUG tested vehicles*

TUG IVT is within Europe, besides TNO, the second party with an substantial test program for real world emissions of passengers cars. The PHEM emission model is used to generate the HBEFA emission factors, from this data, for a number of European countries, such as, Germany, Switzerland, Austria, and Sweden. The last years, with the availability of Euro 6 vehicles, these vehicles were incorporated in the test program. The current status is given in the table below:

Table 3: Available instantaneous emission data on Euro 6 diesel passenger cars at TUG.

Vehicle ID	Vehicle make and model	Rated power [kW]	Lab
D6_v01	Prototype from US market	180	TUG/chassisdyno
D6_v02	Prototype from US market	180	TUG/chassisdyno
D6_v03	Serial production EU6	180	TUG/chassisdyno
D6_v04	Serial production EU6	110	TUG/chassisdyno
D6_v05	Serial production EU6	125	TUG/PEMS

2.1.3 *Other parties*

JRC is the third party with a test program for real-world emissions. However, there seems to be no systematic program for in-service conformity. Both the selection of vehicles as the test cycles are not controlled, to ensure a proper comparison between vehicles and Euro-classes, needed for emission inventories. The program seems designed to validate methodology rather than vehicles.

Other parties like ADAC, AECC and TOI have tested the same kind of vehicles as TNO and TUG. These test programs are limited, yet consistent. ADAC has a long-running program of vehicle testing for consumers. The TOI program is designed to provide insight in real-world emission of new technology.

2.2 Test methods and test cycles

Both chassis dynamometer and PEMS (Portable Emissions Measurement System) measurements are performed in various test cycles.

2.2.1 *Chassis dynamometer testing*

The vehicles are tested according to the official test procedure (UNECE Reg 83) and by using different driving cycles with warm or hot start conditions. The following regulated emissions were measured: CO (carbon monoxide), THC (total hydrocarbons), NO_x (nitrogen oxides), PM (particulate mass) and PN (particulate number). Additionally CO_2 (carbon dioxide) is measured. Table 4 gives an overview of the used measuring methods.

Table 4: Measurement principles

Component	Analyse
CO	NDIR, Non Dispersive Infrared
HC	Heated Flame Ionization Detection HFID
NO_x	Chemo Luminescence (CLA)
CO_2	NDIR
PM	Gravimetric
PN	Condensation Particle Counter (CPC) with Volatile Particle Remover(VPR)

For the tests regular diesel is used, not reference fuel, the influence of reference fuel on emissions is expected to be relatively small and in addition under real world conditions there is also no reference fuel applied.

Road load settings were for each vehicle provided by the manufacturer. If necessary also a chassis dynamometer 'test mode' was activated in order to avoid problems with start stop, ESP, etc. In some cases the manufactured was present during the tests.

Used driving cycles

The following driving cycles are used to assess the emission performance of the Euro 6 vehicles:

- NEDC (New European Driving Cycle)
  The NEDC (see Figure 3) is used for the official type approval, 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). Officially the NEDC begins with cold start. The emission results of the NEDC with cold start are used to check whether the vehicle complies with the Euro 6 limit and to check if the vehicle is technically in good condition. Some vehicles are additionally tested over a NEDC with a hot start to gain more information about the emission performances.
  The NEDC pattern is not dynamic and does not look like real world driving. The largest part (in time, not in distance) of the NEDC is urban driving, this is a disadvantage for heavy and high-powered vehicles. The NEDC is relatively short (±11 km), as a result the cold start effect is quite large. During the cycle the engine loads are very low, engine efficiencies at low engine loads are mostly not optimal.

- CADC (Common Artemis Driving Cycle):
  The CADC (see Figure 4) is a cycle which represent real world driving better than the NEDC, however, the CADC is not part of the official type approval procedure.
  The cycle consists of an urban, rural and motorway part. For the motorway part there are two possibilities, a maximum speed of 130 km/h or 150 km/h. In this report the results of the CADC with 130 km/h motorway part are reported.
  A cold and hot start are both possible with the CADC, in this report the CADC with hot start is for most tested vehicles shown. In the most recent tests also CADC's with cold start are performed, during these tests a second urban part is driven directly after the motorway part, the result is a CADC with a cold and hot urban part.
  The CADC is more dynamic and reach higher speeds than the NEDC.
  The cycle is a lot longer than the NEDC (±45 km), hence the relative cold start effect is not very large on the total emission.

- WLTC (Worldwide harmonized Light duty driving Test Cycle):
  The currently European used type approval procedure and test cycle (NEDC) for light duty vehicles are not worldwide accepted and produce emission results (in particular CO_2 and NO_x) that do not correspond very well to real world emission results. An important point of discussion of the current procedure is

the driving cycle. Currently a new worldwide harmonized type approval procedure for light duty vehicles is under development which involves a new driving cycle.
The WLTC (see Figure 5) consists of four parts: low, medium, high and extra high. When the cycle is approved as part of official legislation it most likely begins with a cold start. In this program the WLTC is mostly performed with a hot start and in some cases with a cold start.
The cold start effect is lower than with the NEDC because of the length of cycle (±45 km). The WLTC is more dynamic and reach higher speeds than the NEDC, however, it is less dynamic than the CADC.

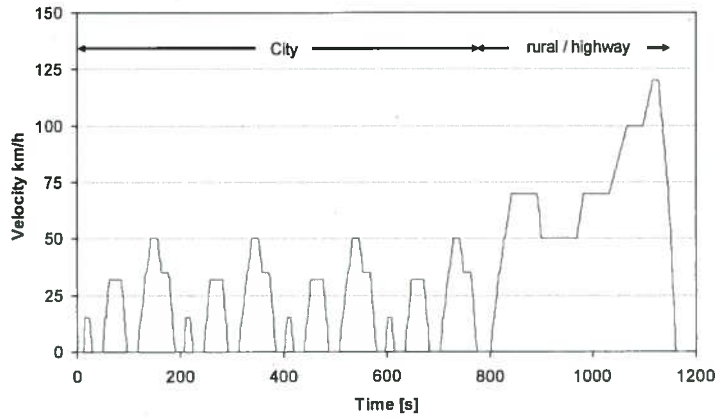

Figure 3: NEDC (New European Driving Cycle)

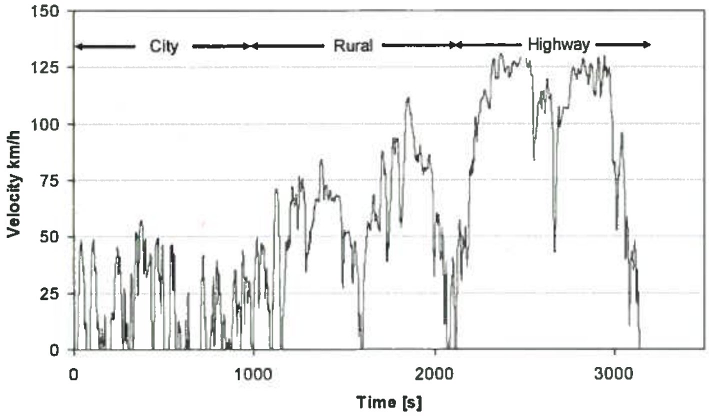

Figure 4: CADC (Common Artemis Driving Cycle)

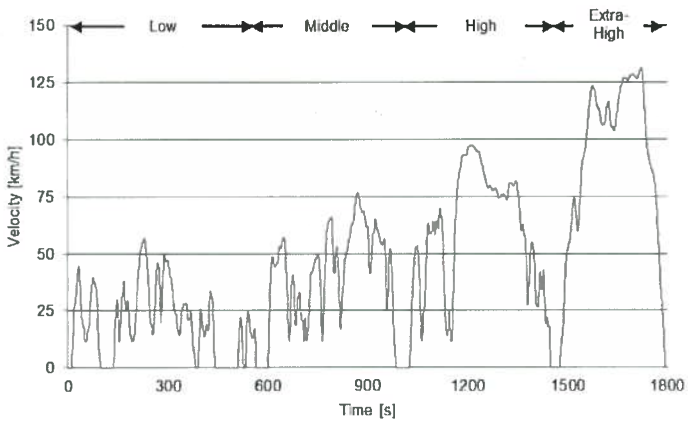

Figure 5: WLTC_v5 (Worldwide harmonized Light duty driving Test Cycle)

2.2.2 *PEMS testing*

With two Euro 6 vehicles (E6 and J1) measurements with PEMS (Portable Emissions Measurement System) are performed. PEMS tests are performed on the road under real world conditions. With the PEMS equipment of TNO it is possible to measure CO, CO_2, HC and NO_x emissions in g/km. The vehicle is fully loaded during PEMS tests because two persons are needed (1 driver, 1 engineer) and the equipment (including generator) weighs approximately 200 kg.

All kind of driving patterns are possible with PEMS. In order to be able to compare tests with each other, TNO always drives a 'reference trip'. The reference trip consist of urban, rural and highway driving. Additionally some other trips are driven: constant speed, urban driving and highway driving, see table below for details.

Table 5: PEMS trips

Trip type	Length [km]	Duration [s]	Average speed [km/h]
Reference	72	5000-6000	43-51
Constant speed	Several	300-450	50,80,100,120,130,140,150
Urban	25,5	3600-4100	23-27
Highway	90	3450-3650	89-91

2.3 Vehicle emission factors

Emission factors for Euro 6 will be preliminary. However, new emission factors are needed as the current factors, based on the expectation of successful emission control in combination with the Euro 6 emission limits, are no longer tenable with the currently available measurements. The new emission factors are larger than the current estimates, but will probably be slightly lower than the values of next year when a substantial group of Euro 6 vehicles and models can be measured. The expectation is based on the experiences with the introduction of Euro 4 and the introduction of Euro 5. In both cases the initial expectations were not met, and the NO_x emissions remained at more or less the same levels as before.

The current estimates for the diesel Euro 6 NO_x and NO_2 emission factors are given in the table below. The table contain both the emission factors for SRM1 (including motorway average) and the SRM2 (the detailed motorway emission factors).

Table 6 Preliminary emission factors for the air-quality model (SRM1 and SRM2)

[mg/km]	emission estimate	NOx	NO_2
urban	Congested	379	119
	Normal	237	71
	free-flow	252	69
rural	Normal	202	53
motorway	Average	425	129
	Congested	377	132
	80 km/h	260	76
	100 km/h control	387	122
	100 km/h	394	123
	120 km/h	437	131
	130 km/h	468	138

Advanced NOx reduction technologies are needed to comply with the Euro 6 NOx limit value. To provide better understanding of these technologies the most common used reduction technologies are identified and shortly described in chapter 3.

3 Emission reduction technologies

3.1 Petrol vehicles

The Euro 6 emission limit values for light duty vehicles with spark ignition engines (petrol engines) are equal to Euro 5 limit values. Euro 5 petrol vehicles show already good real world (pollutant) emission performances. The three-way catalyst in combination with an accurate air-fuel control is the mainstream technology with very high reduction rates of CO, THC and NO_x emissions. The last few years engines with direct fuel injection are often used to obtain higher engine efficiencies (and lower CO2 emissions). The disadvantage of direct fuel injection is the possibility of higher PN emissions which will possibly require extra emission reduction technologies like a gasoline particle filter (GPF).

3.2 Diesel vehicles

The Euro 6 emission NO_x limit values (80 mg/km) for light duty vehicles (class M1) with compression ignition engines are more stringent than the Euro 5 limit values (180 mg/km). Under real world conditions the NO_x emissions of Euro 5 diesel vehicles are often much higher than during the type approval test. Particulate emissions and CO and HC emissions of Euro 5 diesel vehicles are under control under real world conditions as a result of the applied DPF (diesel particulate filter) and oxidation catalyst.

To reduce NO_x emissions different technologies can be used. The mainstream applied reduction technology for Euro 5 is EGR (exhaust gas recirculation).
To comply with the Euro 6 limit more advanced technologies are needed. The following technologies are most used in combination with EGR:
- Improved EGR (cooled low and high pressure EGR).
- Reduced engine compression ratio in combination with high pressure EGR.
- SCR (selective catalytic reduction) in combination with high pressure EGR.
- LNT (Lean NO_x Trap) in combination with high pressure EGR.

Active (engine) control is needed for NO_x reduction with EGR, SCR and LNT systems. The NO_x reduction strongly depends on the engine and EGR maps and SCR and LNT control.

Improved EGR (Exhaust Gas Recirculation)
NO_x emissions are mainly produced at high pressures and temperatures during the combustion. With EGR (cooled) exhaust gas is recirculated back to the combustion process. Due to the recirculated exhaust gas there is less oxygen available for combustion, as a result the combustion (peak) temperatures lowered, hence NO_x emissions decrease. The efficiency of EGR depends on the EGR rate (the amount of recirculated exhaust gas) and its temperature. The possible EGR rate depends on various parameters (such as engine load) and needs to be controlled precisely. The disadvantage of EGR is the increase of the PM emissions (engine out) and increase of fuel consumption and the possible contamination of the inlet trajectory. A higher EGR rate causes lower NO_x emissions but also higher engine out PM emissions. Due to higher engine out PM emissions the DPF needs to regenerate (combustion of the stored particles in the DPF) more often.

For Euro 5 vehicles 'high pressure' cooled EGR is most often used. With high pressure EGR the exhaust gases are guided and cooled from upfront the exhaust turbine to the inlet trajectory of the engine.

To comply with the Euro 6 limit small diesel vehicles can be equipped with an advanced or improved EGR system without application of NO_x aftertreatment systems. Improved EGR is the combination between cooled low and high pressure EGR. With low pressure EGR the exhaust gases are guided from after the exhaust turbine and DPF to upfront the inlet turbine (ambient pressure). The advantages of low pressure EGR are better cooling possibilities (enables higher EGR rates and operation at higher engine load conditions), less contamination (because of the filtered exhaust gas) and better mixture with the fresh air. However, there is a risk of condensates within the EGR- and intercooler with strongly cooled EGR, the condensates can possibly cause maintenance problems. Also the combination with high pressure EGR is still needed for proper reaction on engine load variations.

Reduced engine compression ratio
As mentioned in the previous paragraph high pressure and temperature during the combustion cause high NO_x emissions. By reducing the engine compression ratio peak combustion temperatures and pressures are lowered and the ignition delay will increase, hence less NO_x emissions are produced.
The compression ratio is typically lowered from 17-18,5 to ±14.0. The disadvantage of lowering the compression ratio is a decrease in engine efficiency (and thus higher fuel consumption) and the HC/CO control will become more challenging. Combination with EGR is needed to fulfill the Euro 6 limit.

Injection timing
The timing of the fuel injection in the cylinder has a substantial influence on the NO_x emissions. A delayed injection will reduce the engine efficiency, but, at the same time it will yield a reduction of the NO_x formation and emission.

SCR (selective catalytic reduction)
A SCR system is the combination between a catalyst and the injection of urea upfront the catalyst. Above ±190°C the urea is converted to ammonia (NH_3) which reacts with NO_x in the SCR-catalyst. The catalyst converts NO_x and NH_3 into N_2 and H_2O. However, the temperatures of diesel exhaust gases are relative low and the SCR catalyst needs a temperature of approximately 190 to 500°C to work properly, therefore the vehicle needs to be warmed up before the SCR system is working properly. Short trips in the city with low engine loads are therefore not optimal for a SCR system, hence the combination with EGR is necessary to comply with the Euro 6 limit values.
The AdBlue (urea + water) is stored in a separate tank in the vehicle and needs to be refilled during service intervals.

LNT (Lean NO_x Trap)
The Lean NO_x Trap (or LNC, Lean $NO_{x,}$ Catalyst) reduces NO_x emissions by a frequent cycle of NO_x storage and release due to catalytic reaction by applying periodic lean and rich air/fuel mixtures. During lean air/fuel mixture period NO_x is stored, when the Trap reach the max capacity a rich mixture is used to convert the NO_x emissions into N_2 en O_2. .

The LNT needs to have a temperature between approximately 250-400°C to work properly. Dependent of the NO_x conversion rate and the specifications of the catalyst an increase in fuel consumption of 1 to 4% is possible. With dynamic engine loads and a cold engine the LNT performs not very efficient. Most ideal conditions are static or low engine loads and a warm engine. The combination with EGR is necessary to comply with the Euro 6 limit values.

4 Investigations of public data

Four external publications of Euro 6 real world emissions were found and investigated.

4.1 ADAC test results

ADAC tested 7 Euro 6 vehicles [ADAC 2011]. In Figure 6 it is shown that all Euro 6 vehicles comply in the NEDC Type Approval test with the NOx limit of 80 mg/km. However a NEDC test with hot start results in higher NOx emissions, some vehicles emit 350 mg/km. Furthermore these vehicles emit on the highway 150 – 1100 mg/km (average appr. 500 mg/km).
ADAC states: "Euro 6 diesel vehicles must also effectively reduce NOx and NO_2 emissions in off-cycle conditions (i.e. CADC test cycle)".

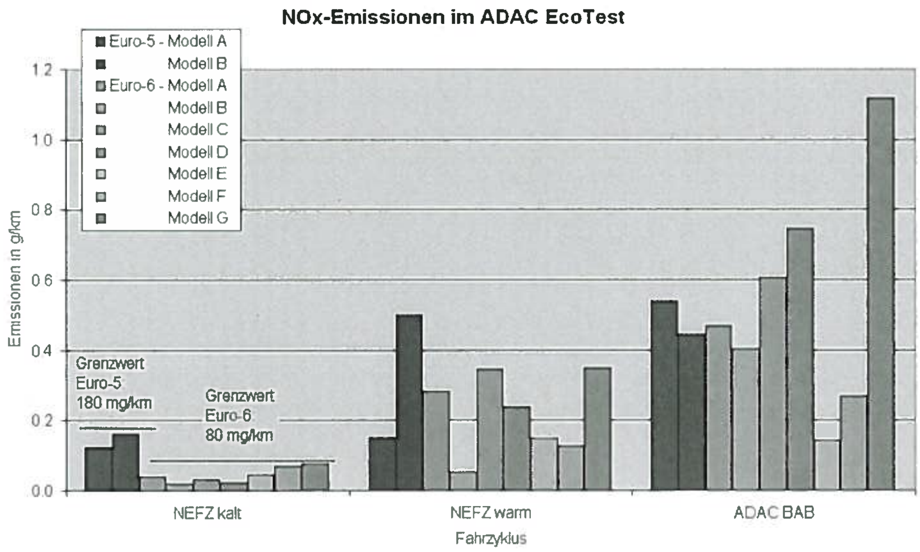

Figure 6: ADAC Ecotest results Euro 5 and 6 vehicles

4.2 TOI test results

The Institute of Transport Economics in Norway tested 2 Euro 6 vehicles [TOI 2013] in an urban test cycle. This Helsinki test cycle has a length of 7,8 km and a duration of 23 minutes and a maximum vehicle speed of 60 km/h. The tests were performed at -7 °C and + 23 °C and started all with a cold and hot engine.

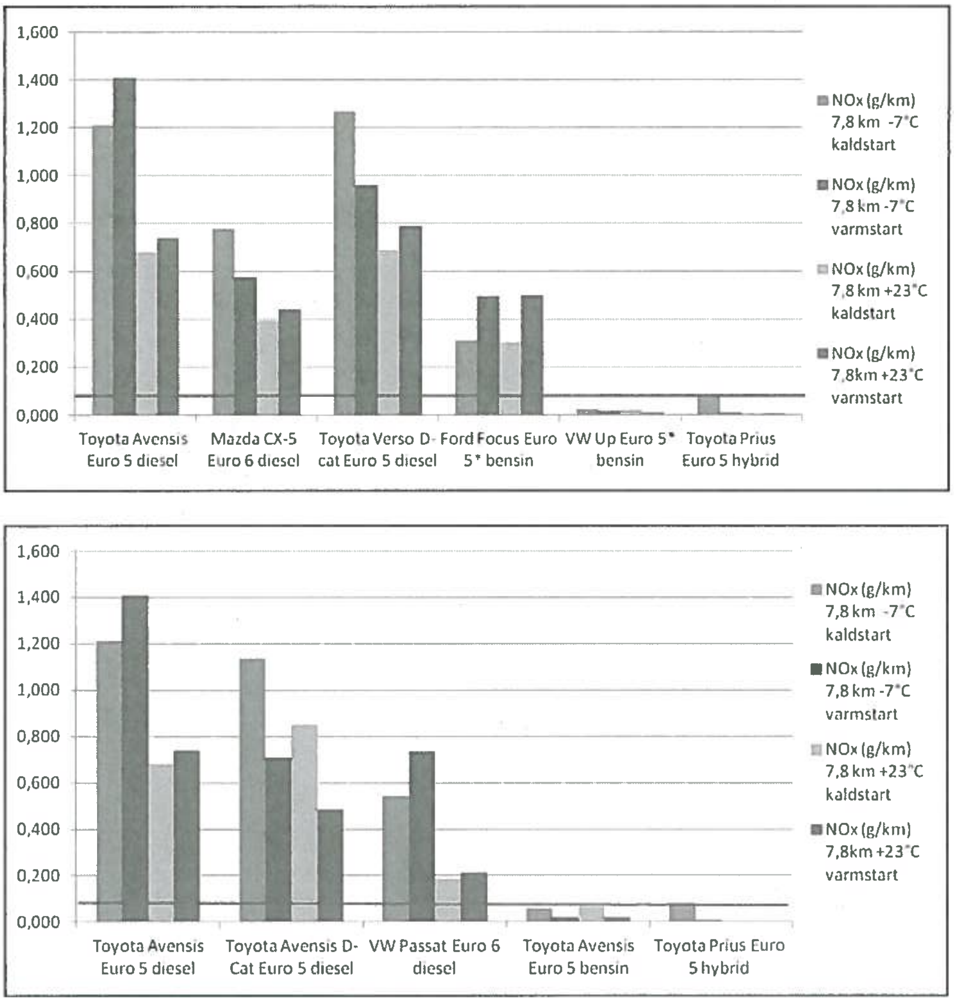

Figure 7: Emissions of NOx from six light vehicles tested with the Helsinki city cycle at -7°C and +23°C with cold and warm engine start (Source: TOI-Norway)

The results of the two Euro 6 vehicles of Figure 7 show NO_x emissions of approximately 180 – 780 mg/km. On average the real world NO_x emissions in urban conditions are 400 – 500 mg/km.

4.3 AECC test results

AECC, the Association for Emissions Control by Catalyst, conducted a test program to compare the newly developed World-harmonized Light vehicles Test Cycle (WLTC) with the current European regulatory New European Drive Cycle (NEDC) and the cold-start Common Artemis Driving Cycle (CADC) [AECC 2013a] . Vehicle engines and aftertreatment technologies were selected to cover a wide range of future systems. Six European commercially available passenger cars were chosen: three Euro 5 Gasoline Direct Injection cars, two Euro 6 Diesel cars and a Euro 5 non-plug-in gasoline hybrid car. Investigations on the test temperature were also conducted by comparing emissions at 25°C and at -7°C. The study isolated cycle-to-cycle effects on emissions for each vehicle by normalizing the test mass in all tests to the draft WLTP (World-harmonized Light vehicles Test procedure) Global Technical Regulation (gtr).

NOx emissions measured on NEDC, CADC and cold-start WLTC are shown in Figure 8. Some NOx emissions results on NEDC are slightly above the regulatory limit. However, as described earlier in Figure 5, vehicles inertia used in this test campaign was higher than the value used at type-approval. This may explain the impact on NOx emissions on NEDC. Except for vehicle C, NEDC and WLTC are very similar in terms of NOx emissions. Nevertheless, both the Artemis CADC and WLTC highlight some increase in NOx emissions Page 5 of 10

on the lean GDI car (vehicle C) compared to the regulatory NEDC.
The Artemis CADC also highlights the higher NOx emissions in real-world of current diesel cars (vehicles E and F). This is in line with other measurements and is being addressed by the European Commission developing real-driving emissions provision for the second stage of the Euro 6 legislation.

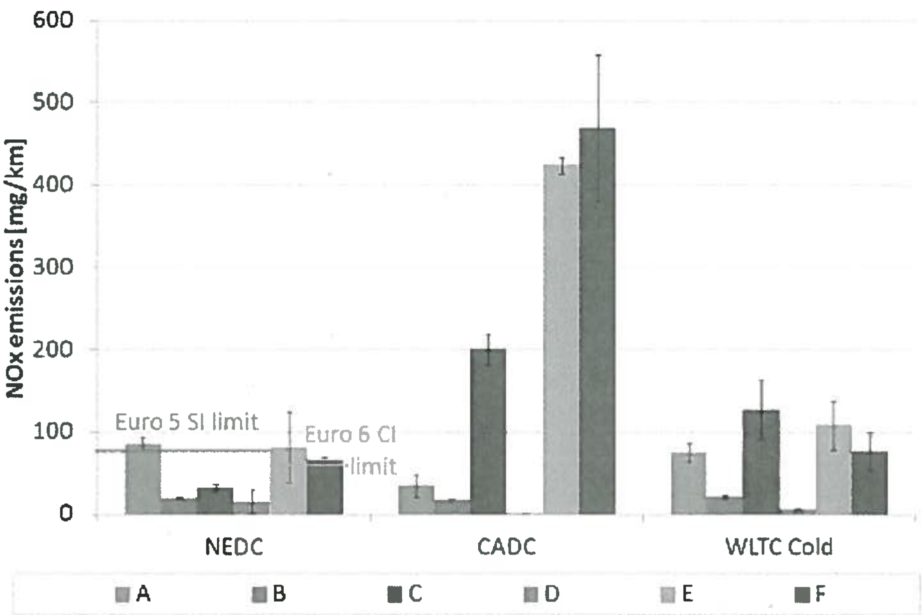

Figure 8: NOx emissions @ ambient temperature 25 °C (Source AECC)

Influence of ambient temperature on NOx Emissions:
As illustrated by Figure 9, NOx emissions of all vehicles increased when cars were tested at -7°C. However, the influence is the largest on diesel cars, which can emit 800 to 1000 mg/km of NOx on NEDC and WLTC. This is more than ten times the NEDC Euro 6 limit value of 80 mg/km and highlights that without a regulatory limitation of Diesel NO_x emissions at low temperature as is currently being investigated by the European Commission, NO_x emissions at low temperatures may not be controlled.

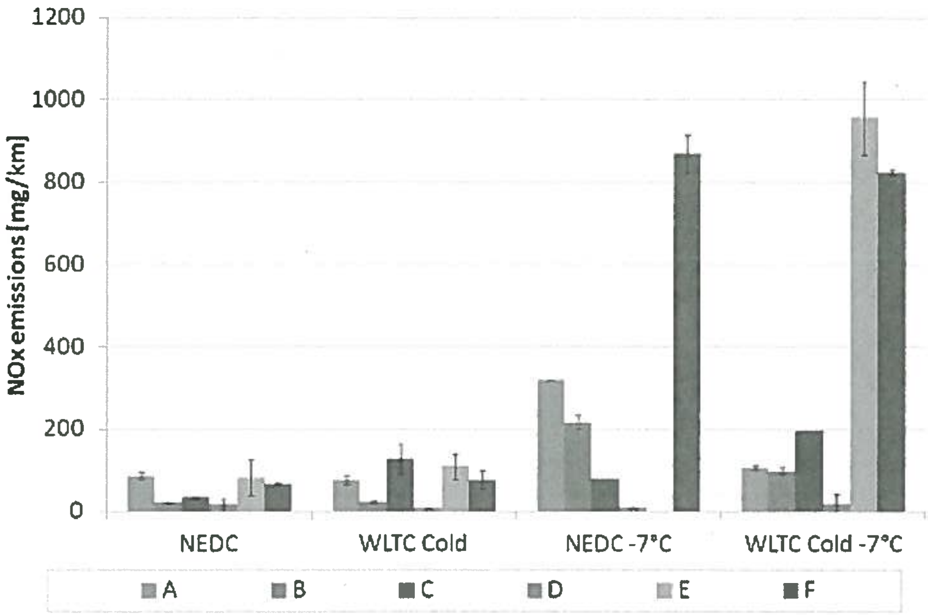

Figure 9: NOx emissions at 25°C and -7°C on NEDC and CADC (Source AECC)

One of the AECC conclusions is:
CADC emissions results highlighted some higher NO_x emissions from diesel vehicles and somewhat higher NH_3 emissions from stoichiometric gasoline cars. As high NO_x emissions have also been reported for modern diesel cars in real-driving conditions, this tends to confirm that CADC is closer to real-world driving than NEDC or even WLTC. There was little difference for other emissions though, including CO_2.

In a second publication [AECC 2013b] four Euro 6 diesel vehicles were investigated. See vehicles 12, 13, 14 and 19 in Figure 10 up to Figure 13. From these test results it is shown that CO, THC and PM emissions of the Euro 6 vehicles are below all limit values. However the NO_x emissions of three vehicles in the CADC test cycle, which represents real world conditions, are 25 – 572 mg/km and three samples exceed the limit values.

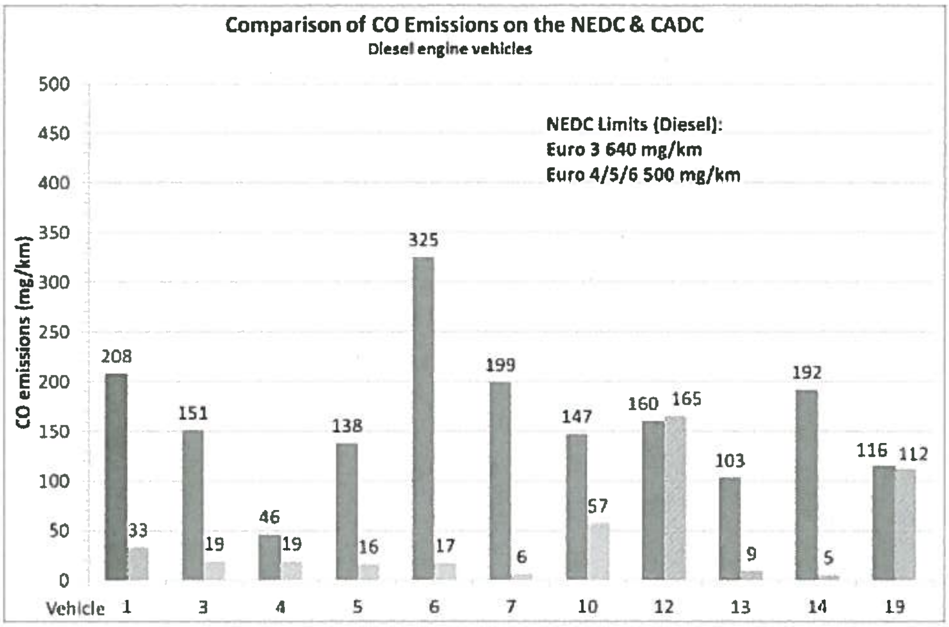

Figure 10: Diesel CO results over full NEDC and CADC tests (Source AECC)

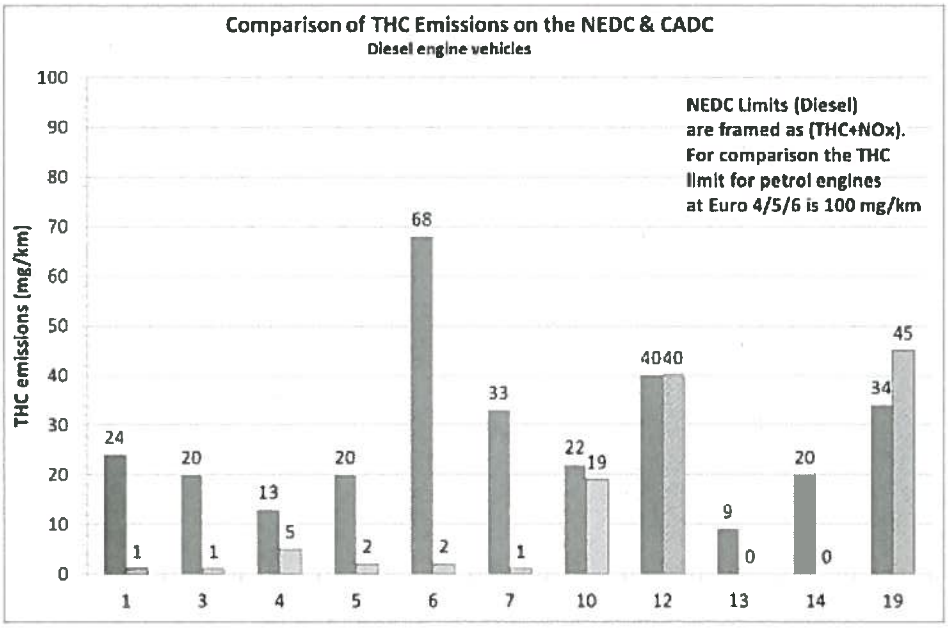

Figure 11: Diesel THC results over full NEDC and CADC tests (Source AECC)

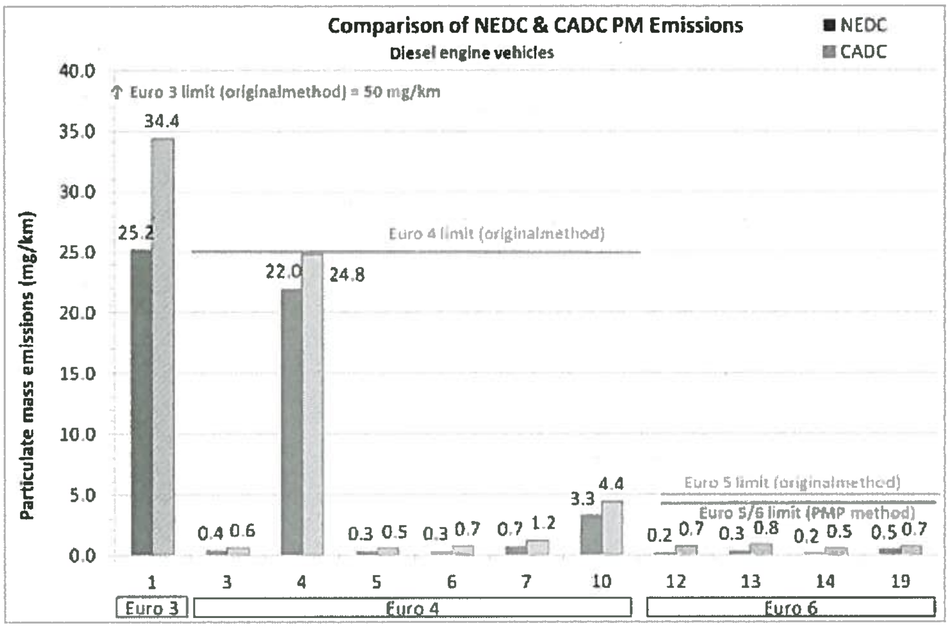

Figure 12: Diesel PM results over full NEDC and CADC tests (Source AECC)

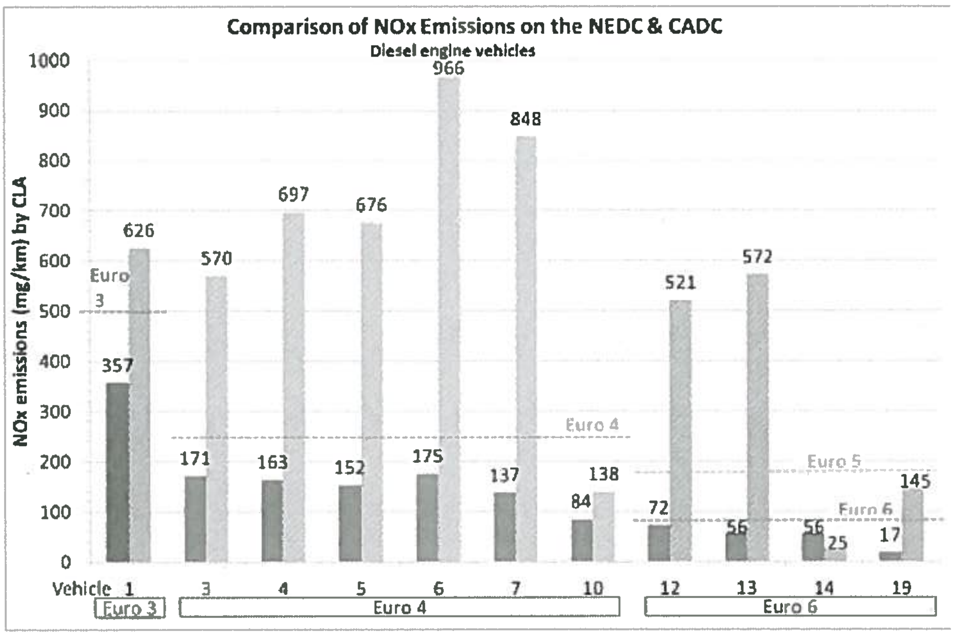

Figure 13: Diesel NOx results over full NEDC and CADC tests (Source AECC)

4.4 Joint Research Centre data

DG-JRC conducted a test program with one Euro 6 diesel vehicle. Laboratory as well as real world tests were performed [JRC 2012]. Real world NO_x emissions exceed the Type Approval limit values.

"The Euro 6 diesel car shows in the laboratory substantially lower NO_x emissions (0.07 +/- 0.004 g/km) than the Euro 4 car9 (0.29 g/ km) and the four Euro 5 cars (0.20 0.04 g/km). More importantly, the Euro 6 car also shows substantially lower on-road NO_x emissions (0.21 +/- 0.09 g/km) than the Euro 4 cars (0.76 +/- 0.12 g/ km) and Euro 5 cars (0.71 +/- 0.30 g/km)".

4.5 Conclusions public data

All public sources [ADAC 2011], [AECC 2013a] , [AECC 2013b] and [TOI 2013] report for diesel Euro 6 vehicles average real world NOx emissions of 400 – 500 mg/km @ 25 °C. For lower ambient temperatures the NOx emissions are even higher.
The other pollutant emissions (CO, THC and PM) do not exceed the Type Approval limit values.

For direct injected gasoline Euro 6 engines PN test results do not comply with future standards. It is expected that Gasoline Particulate Filters are needed to comply with future requirements.

5 Experimental results

In this chapter the test results of the emission measurements of TNO, TUG and from public data are shown.

5.1 TNO results

TNO performed chassis dynamometer and PEMS tests, both results are shown in the following paragraphs. Detailed results are reported in Appendix A .

5.1.1 Chassis dynamometer results

NO_x emissions
Figure 14 up to Figure 16 show the NO_x emissions of the tested vehicles in 2010 and in 2012/2013 over various driving cycles.

Figure 14 shows that the NO_x emissions over the NEDC with cold start are almost in all cases compliant with the Euro 6 limit value (only vehicle E6 is slightly higher). During the CADC test the NO_x emissions are often a lot higher than during the NEDC.

Especially vehicle J1 and J2 have extreme high NO_x emissions in the CADC, the NO_x emissions are 5,7 (J1) and 9,1 (J2) times higher than the Euro 6 limit value, these emissions are comparable to Euro 5 real world emissions. The NO_x emissions during the WLTC are 2,6 and 3,1 times higher than the Euro 6 limit value.
These vehicles have no after treatment to reduce NO_x emissions but work with a lowered compression ratio in combination with EGR.

Vehicle E6 shows betters results than vehicle J1 and J2 during both the WLTC as the CADC, the NO_x emissions are approximately 2,2 times higher than the Euro 6 limit value. This vehicle has SCR aftertreatment.
Vehicle H4 and H6 show very good results on all cycles, only vehicle H4 exceeds the limit during the CADC, however, this is caused by a regeneration of the DPF. It is assumed that these vehicles use a LNT.

In general the 2010 models have better results than the 2012/2013 models.

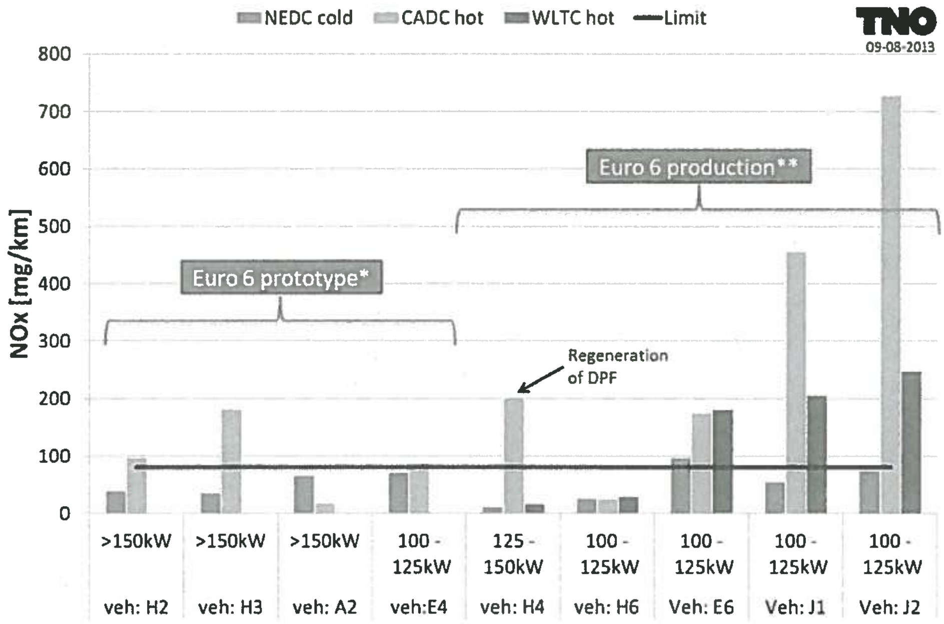

Figure 14: NO_x emissions per driving cycle

Figure 15 and Figure 16 show the NO_x emission results per phase during the NEDC and CADC. In the NEDC the NO_x emissions are in all cases higher in the urban phase than in extra urban phase. In some cases also a NEDC with hot start is performed, it is interesting that vehicle E6, J1 and J2 have higher NO_x emissions during the urban phase with hot start than during the urban phase with cold start. In the CADC this trend is not the same, the urban phase with cold and hot start differ mostly not very much.

Vehicle J1 and J2 show especially during the CADC motorway part extreme high emissions, vehicle J2 exceeds even the 1000 mg/km. Also in the urban en rural phase the emissions are not very good.
Vehicle E6 shows good results during the CADC motorway phase, the SCR system is working properly during the high speeds. The NO_x emissions during the urban phase on the other hand are quit high with more than 400 mg/km.
Vehicle H4 and H6 show very good results on each part of the CADC cycle, only high emissions are shown during the motorway phase with vehicle H4 due to the regeneration of the DPF.

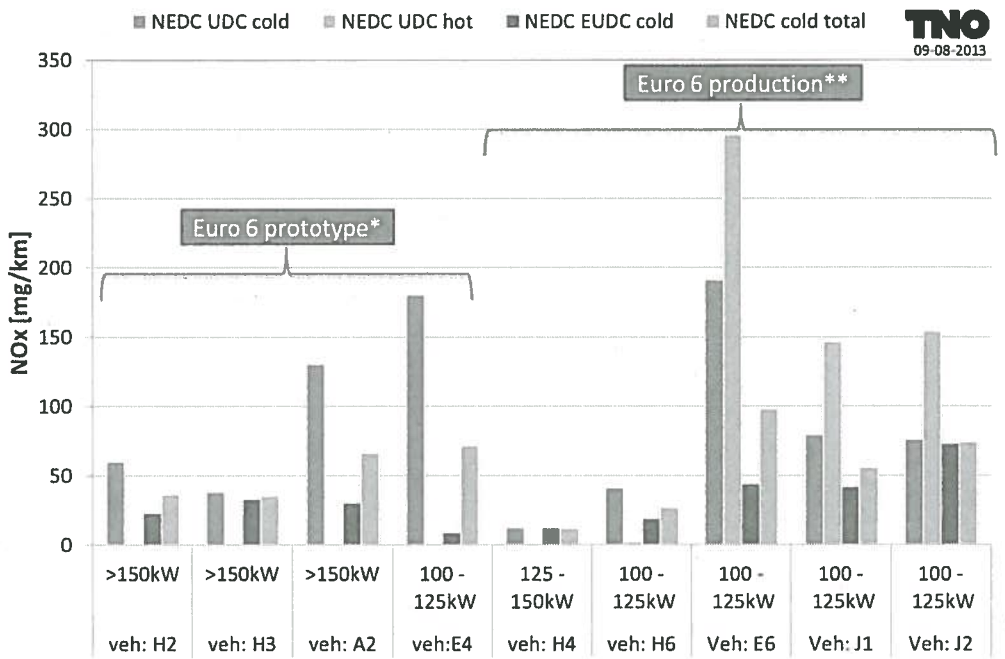

Figure 15: NO_x emissions per phase in the NEDC

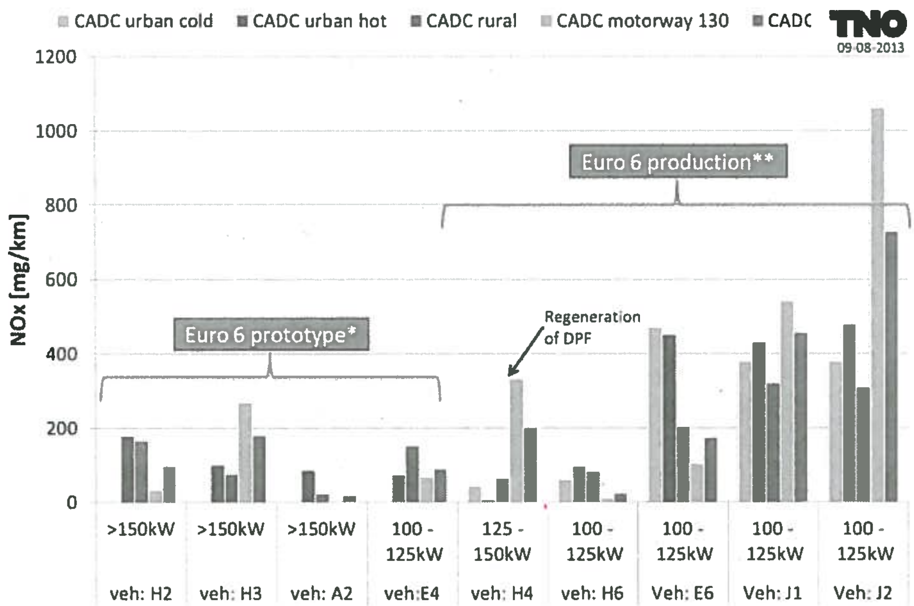

Figure 16: NO_x emissions per phase in the CADC

5.1.2 PEMS test results

With vehicle E6 and J1 PEMS tests are performed. With vehicle E6 all tests were successfully performed. Vehicle J1 shows unusual high g/km emissions, further investigations and tests are needed. Emissions in mass (g/km) of vehicle J1 are therefore not reported in Figure 17 and Figure 18.

In Figure 17 and Figure 18 the NO_x emissions of vehicle E6 and earlier tested Euro 5 vehicles are shown. Figure 17 shows the absolute (mg/km) emissions and Figure 18 shows the relative (%) emissions with respect to the limits.

Figure 17 shows that vehicle E6 is the best vehicle that TNO has tested, the NO_x emissions are especially during high and constant speeds very low (around 80 mg/km) as a result of the SCR system, during urban driving the emissions are still quit high with ±600 mg/km, the same pattern was noticed during the CADC. In the reference trip the emissions are with 400 mg/km the lowest of all tested vehicles but it is still a lot higher than the Euro 6 limit.

Figure 18 shows that with respect to the limit the emissions of vehicle E6 are very high during the urban driving (± 8 times higher than the limit) and during the reference trip (± 5 times higher than the limit). At high and constant speeds the results are around the limit.

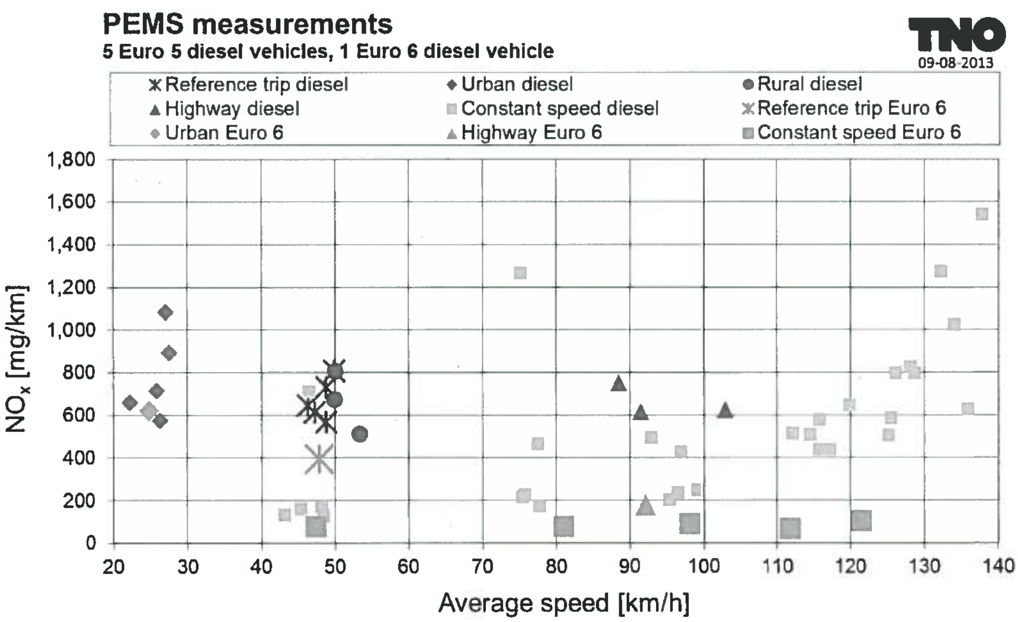

Figure 17: Absolute PEMS results for Euro 5 vehicles and vehicle E6

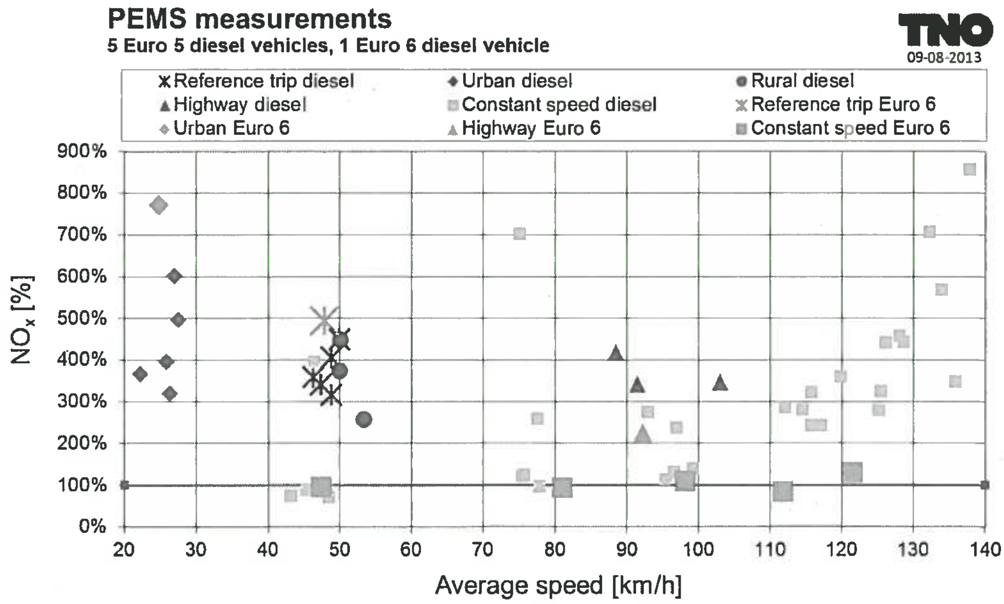

Figure 18: Relative PEMS results for Euro 5 vehicles and vehicle E6

<u>NO_x over CO_2 results</u>

To asses heavy duty vehicles the NO_x over CO_2 (g/kg) results are used by TNO to compare smaller and larger vehicles with each other. When the vehicle has a higher fuel consumption (CO_2 emission), it may emit more NO_x. For light duty vehicles this is not an usual method yet, but TNO does use this method because now the results of the vehicle J1 can also be used.

Figure 19 shows that both the Euro 6 vehicles are better than all Euro 5 vehicles, but compared with a petrol (Euro 5) or heavy duty (Euro VI) vehicle the results are not very good.

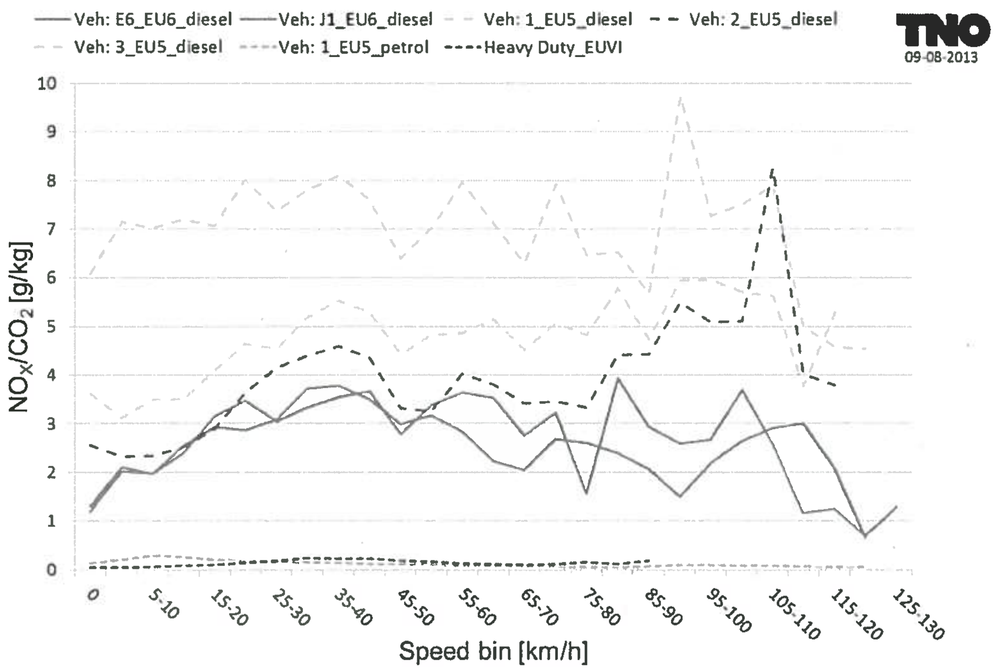

Figure 19: PEMS results binned in NO_x over CO_2

5.2 TUG data and results

The HBEFA3.2 emission factors for Euro 6 passenger cars are compiled by the well-established approach using the TUG IVT emission model PHEM. In the HBEFA3.2 the emission standard Euro 6 will be differentiated between first generation of Euro 6 vehicles (referring to stage Euro 6a and Euro 6b, hereafter and specified as "Euro 6") and vehicles which will enter the market based on more stringent emission regulation expected in 2017 (hereafter and specified as "Euro 6c").

The following chapter describes the data sources and the results for the Beta-version of the HBEFA 3.2 emission factors. Adaptations for the final version may be done in October 2013.

5.2.1 *Emission data available for Euro 6*

The PHEM emission maps for Euro 6 have been generated based on instantaneous emission data available for five vehicles . For this sub-set of the Euro 6 sample the complete data necessary to set up engine emission maps was available (accurate instantaneous emission values and engine speed and engine power data). For the other vehicles measured in the ERMES group at the time of engine map elaboration only bag data was available.

Table 7: Available instantaneous emission data on Euro 6 diesel passenger cars

Vehicle ID	Vehicle make and model	Rated power [kW]	Lab
D6_v01	Prototype from US market	180	TUG/chassisdyno
D6_v02	Prototype from US market	180	TUG/chassisdyno
D6_v03	Serial production EU6	180	TUG/chassisdyno
D6_v04	Serial production EU6	110	TUG/chassisdyno
D6_v05	Serial production EU6	125	TUG/PEMS

With this first set of engine emission maps for Euro 6 diesel cars emissions have been simulated for the CADC and for the ERMES cycle. The engine maps were then calibrated by the ratio of emission levels measured in the CADC on all Euro 6 diesel passenger cars available in the ERMES LDV bag database (Table 7) to the emission levels simulated. In this process the measured emission data also were weighted according to the shares of the used engine types in the available data on new registrations in 2012. For Euro 6 similar sales numbers than for the Euro 5 predecessors were assumed.

Here it has to be mentioned that the Euro 6 vehicles available until the end of the HBEFA3.2 measurement campaign mainly refer to the premium vehicle segment, which adds a certain uncertainty to the resulting fleet emission factors.
In addition uncertainties are related to:

- Shares of NO_x control technologies in the future Euro 6 fleet.
- Level of exploitation of NO_x reduction potential of these technologies in the future fleet (e.g. AdBlue may not be dosed at high engine loads by a yet unknown share of vehicle models if not relevant in the type approval test)

5.2.2 *Assumptions for Euro 6c emission behaviour*

For Euro 6c vehicle technology a real world emission level (in this context defined as 1/3 mix of CADC subcycles “urban”, “road” and “motorway”) has been defined with two times NEDC Euro 6 limits (2*80mg = 160mg) due to a mandatory PEMS test in real drive operation and a emission conformity factor lower than 2. The emission factors for all other regulated pollutants as well the NO_2/NO_x ratio is assumed as identical similar to Euro 6 (first generation) technology.

In the calculation of the emission factors with the model PHEM furthermore the following details have been considered (details see full HBEFA report):

- Updated vehicle parameters (mass, rated power, etc.) to represent the fleet average Euro 6 vehicle from EU27 new car registrations
- Increased market penetration of start stop systems
- Influence of particle filter regeneration on average emission levels.

<u>Results</u>

Figure 20 gives a comparison for NO_x emissions simulated with the calibrated PHEM model for Euro 6 diesel passenger cars in the CADC sub-cycles For comparison also results for Euro 0 to Euro 5 are plotted. Emission factors for the HBEFA are computed for different driving cycles and are reported in the HBEFA report 3.2 . The CADC cycle gives a a picture for a well-known test cycle but is assessed to lead to rather higher emission levels compared to “normal driving”.

The actual data suggests a clear NOx reduction under hot driving conditions due to Euro 6 which is more pronounced for urban driving conditions (~ -65%) than in rural (~-55%) and motorway conditions (~-45%).

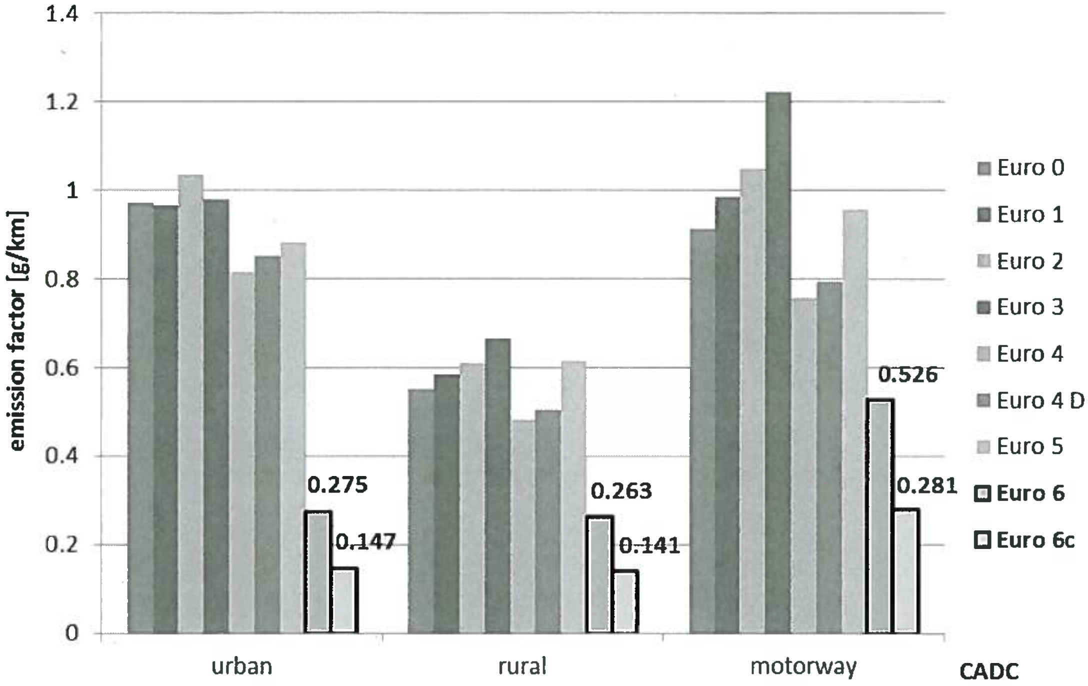

Figure 20: Emissions simulated with PHEM for diesel passenger cars in the CADC under hot start conditions

The NO_2/NO_x ratio found for Euro 6 diesel cars is 35 to 40%. Emission levels of PM, PN and CO is approximately similar to Euro 5. For HC a higher emission level compared to Euro 5 (ca. factor of 3) was calculated, but on very low absolute level compared with the emission limit.

6 Discussion

Both the introduction of Euro 4 and the introduction of Euro 5 followed the same trend. Petrol passenger cars yielding lower real world emission than the emission limits, and the diesel passenger cars, showing some initial reduction at the introduction, have eventually no substantial reduction of the NO_x emissions. Again a new Euro-class is introduced: Euro 6. Some vehicles have low real-world emissions, however, not quite at the level of the emission limit of 80 mg/km. Other vehicles have emissions at the level of Euro 5, showing no significant improvement with the new limit.

There is hope of a reduced NOx emission of Euro 6 diesel passenger cars, however, at the same time the risk there will be no significant reduction. It is possible to optimize the emission control technology such that type-approval test will be below emission limit, and, at the same time, show no appropriate low emissions in other, real-world driving and vehicle usage. Eventually, Real-Driving Emission (RDE) part of later stages of Euro 6 legislation should solve the problem of incompatible results of the official test and other test results. In that case, expected in 2017, the NEDC test alone is no longer the single point of reference for emission control.

The current emission factors for Euro 6 are halfway between the test results and the expected emission risk. The risk manifests itself mainly on the motorway. It is possible that Euro 6 diesel passenger car NO_x emissions are higher than the corresponding Euro 5 emissions. In urban and rural conditions it is expected that Euro 6 emission will remain below Euro 5 emissions, even in the worst case scenario. This is very likely due to the improved fuel efficiency in these conditions, and the closer resemblance of these conditions with the circumstances in the NEDC test.

Different technologies carry different risks. More advanced emission control technologies such as SCR and LNT will yield risk in technology specific circumstances, not directly related to driving behaviour but rather with the trip history, temperature, load variations, and low loads. The most common and important Euro 5 emission control technology is EGR. This technology is relatively inexpensive and likely to be implemented in common compact cars, which dominate the Dutch vehicle fleet. The associated risk with EGR is at high load. Hence, at the moment it is foreseen that in particular these compact cars on the motorway carry a large risk of high NO_x emissions. It is already shown that EGR technology is capable of reaching Euro 6 emission limits on the NEDC.

The results are limited, as the number of available vehicle models is limited, and the analyses of the emissions is preliminary. Based on current results, emission modelling will have to undergo a transition from so-called "proportional models" associating emissions with power, velocity, and CO_2, towards "risk modelling" identifying the emission control strategy and its associated risks. Only for EGR the traditional "proportional" approach will hold also for Euro 6. Despite these limitations, the statistical analysis underlying the approach combined with appropriate test cycles for real world driving still yields robust results for emission factors.

In Figure 21 the historical and current NOx emission factors of diesel passenger cars are shown. In urban traffic it is clear that diesel passenger cars perform better in time, their NOx emission factor is reduced from 1,06 to 0,24 g/km. However this is more than the Euro 6 Type Approval limit value of 0,08 g/km. The NOx emission factors on the motorway show a different trend, they have a constant level of 0,40 – 0,60 g/km (5-7 times the Type Approval limit value).
In time the NOx Type Approval limit values are more than 10 times reduced (from 0,90 to 0,08 g/km). However the emission factors on the motorway didn't decrease significantly and the urban emission factors only reduced 4 times (from 1,06 to 0,24 g/km). These numbers show clearly that the gap between Type Approval NOx emissions and real world NOx emissions increase; this gap is caused by selective use of NOx reduction systems which can be easily managed by advanced control systems of the vehicle. In the past emission factors and Type Approval limit values were at the same level, currently the emission factors are far higher than the Type Approval limit values.

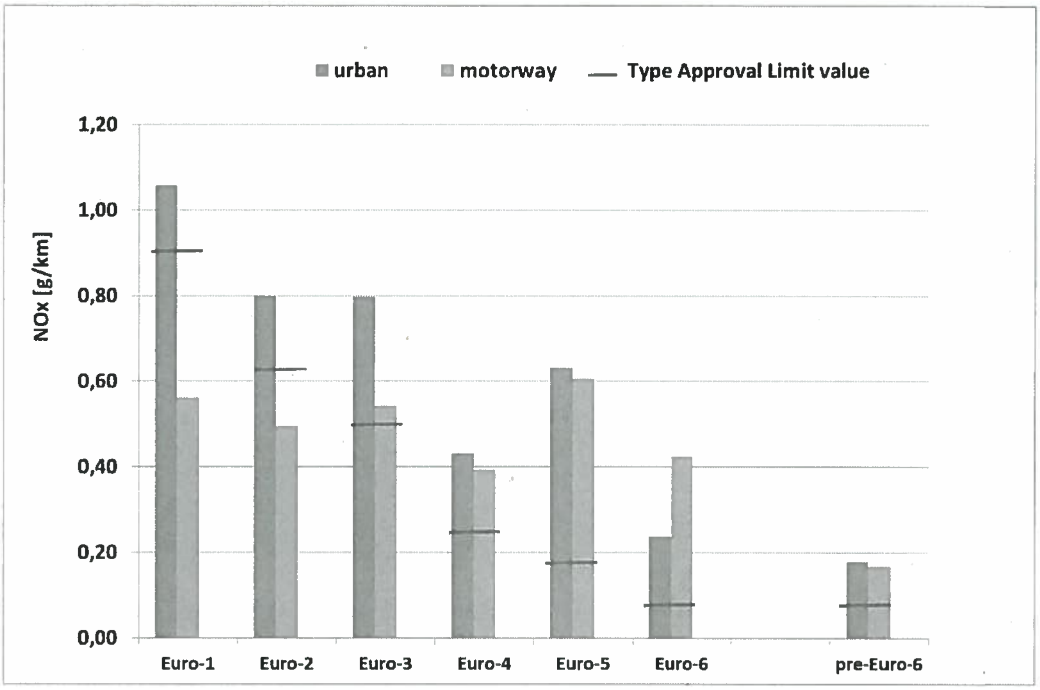

Figure 21: NOx emission factors and Type Approval limit values of diesel passenger cars

7 Conclusions

- The range of NO_x emissions of Euro 6 diesel passenger cars in real-world tests is very large. In some cases the emissions are one-tenth of the emission limit value, in other cases tenfold the emission limit value.
- The results from TNO are confirmed by other tests and emission modelling in Europe. In particular the emission factors from TNO are in line with the preliminary results from TUG.
- Different emission reduction technologies exist, each with their own risk of high emissions. Some of these risks can already be quantified from the limited testing on the available models.
- It is not to be expected that the real-world NO_x emissions of Euro 6 diesel passenger cars will be close to emission limit value of the NEDC test.
- The lower emission limit values from Euro 3 to Euro 4 and Euro 5 has not led to a decrease in real-world NO_x emissions on diesel passenger cars. This experience over the last ten years gives little hope for Euro 6 in the absence of an improved test procedure, or real-driving emission legislation.
- It is likely that the simplest and cheapest emission control technology will be used in compact cars, which are the bulk of the Dutch sales. This signifies a risk of high NO_x emissions similar to Euro 5, in particular on the motorway.

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9 Signature

Delft, 5 December 2013

[redacted]

[redacted]
Project Leader

[redacted]

[redacted]
Author

A TNO chassis dynamometer test results

Compliance with the Euro 6 limit value:
TNO tested vehicles in 2010 and in 2012/2013. The upcoming tables show the emission results over different driving cycles of the five tested vehicles in 2012 and 2013. The tested vehicles in 2010 were prototypes or were meant for the USA market, there these results are less relevant than the tests of 2012 and 2013.

The Table 8 up to Table 12 show that almost all vehicles are compliant with the Euro 6 limit value for each emission type during the NEDC with cold start. The following vehicles exceeding the limit:

- 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 during the cycles other than the NEDC with cold start the CO, PM and PN (except vehicle H4) emissions are all lower 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 CO_2 emissions during the NEDC with cold start are in all cases higher than during the type approval test, the deviation varies between the 3 and 17%. This deviation is considered as a problem but it is not further addressed in this report as it is not a 'pollutant' emission.

Table 8: Results vehicle H4

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

*Type approval value
**Regeneration of DPF

Table 9: Results vehicle H6

Emissions vehicle **H6**	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot	WLTC cold	WLTC hot
CO	[mg/km]	500	88	62	82	83	x	43
CO2	[g/km]	109*	112	108	119	118	x	110
NOx	[mg/km]	80	27	16	28	26	x	25
THC+NOx	[mg/km]	170	53	54	77	76	x	77
PM	[mg/km]	4.5	0.0	0.1	0.1	0.1	x	0.0
PN	[#/km]	6.0E+11	2.6E+09	4.E+10	4.8E+09	4.1E+09	x	1.6E+10
Fuel consumption	[l/100 km]	4,1*	4.18	4.03	4.46	4.40	x	4.11

*Type approval value

Table 10: Results vehicle E6

Emissions vehicle **E6**	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot	WLTC cold	WLTC hot
CO	[mg/km]	500	124	4	5	2	x	3
CO2	[g/km]	127*	149	131	142	140	x	129
NOx	[mg/km]	80	98	201	177	175	x	182
THC+NOx	[mg/km]	170	135	206	180	176	x	183
PM	[mg/km]	4.5	0.1	0.0	0.6	0.6	x	0.0
PN	[-/km]	6.0E+11	2.9E+09	2.E+08	2.8E+09	1.9E+09	x	4.4E+08
Fuel consumption	[l/100 km]	4.9*	5.57	4.88	5.31	5.22	x	5.00

*Type approval value

Table 11: Results vehicle J1

Emissions vehicle **J1**	Unit	Limit (Euro 6)	NEDC cold	NEDC hot	CADC cold	CADC hot	WLTC cold	WLTC hot
CO	[mg/km]	500	372	6	57	20	x	5
CO2	[g/km]	119*	127	112	151	149	x	119
NOx	[mg/km]	80	55	85	447	456	x	205
THC+NOx	[mg/km]	170	100	99	473	477	x	214
PM	[mg/km]	4.5	0.2	0.0	0.1	0.1	x	0.1
PN	[#/km]	6.0E+11	4.7E+11	3.E+09	5.5E+07	3.1E+07	x	4.3E+06
Fuel consumption	[l/100 km]	4.60*	4.76	4.17	5.62	5.54	x	4.45

*Type approval value

Table 12: Results Vehicle J2

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

*Type approval value

B Determination of emission factors

The national emission factors are the representative emission per kilometre for different vehicle categories, and different road types and congestion levels. They are derived from emission measurements, and scaled and weighed to the representative situation. Current data on Euro 6 diesel vehicles will not be representative for the Euro 6 vehicle fleet in 2015 or later. The number of makes and models are very limited. Hence current emission factors for Euro 6 diesel vehicles are preliminary and they will be adjusted to the future sales distribution of different technologies.

A second restriction, apart from the representativeness of the current Euro 6 vehicles for the future fleet, is the performance of the emission reduction technology in real-world circumstances. There is a clear discrepancy between the emissions in the laboratory and the emissions during the on-road tests, for some vehicles. So far, the influences of all on-road conditions are not fully understood. For example, road surface, precipitation, temperature, additional weight, steering, and wind all affect the engine load and emissions. Only in part these are characterized during the trip. However, correcting them to a standard effect for the Dutch situation is only in its preliminary stages and it will require much more research.

The third restriction to be placed on current results is the apparent "incidental emissions". With limited emission control the NO_x and, in a lesser extent, CO are proportional to the fuel consumption and CO_2 emission. Traditionally, the limited HC emissions only occurred at sudden drops in the engine loads, e.g., braking, and high loads, e.g. long periods of accelerations. With the introduction of advanced emission control, such as LNT for Euro 6, NO_x emissions occur in batches. A repetition of the same test will not yield the same emission result as an emission burst or batch may not occur. A proper functioning LNT will yield such batches but with very little NO_x emission. See Figure 22.

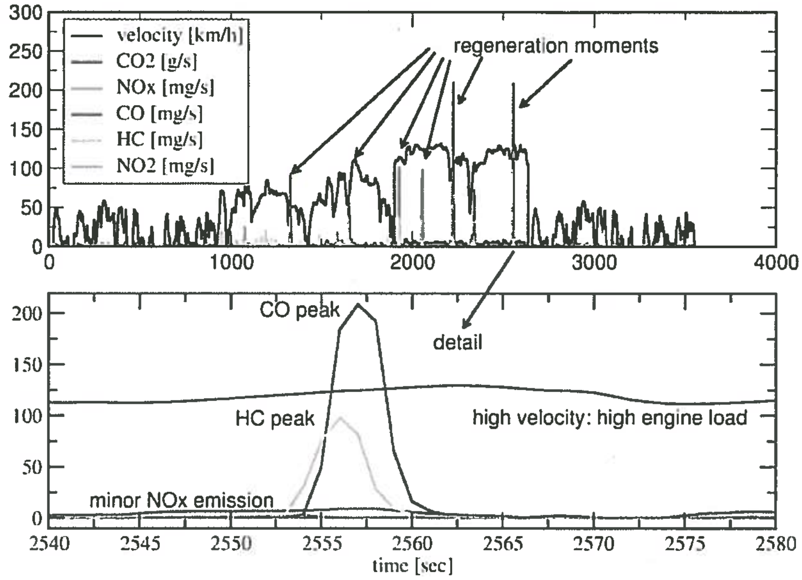

Figure 22: Typical regeneration moments at high velocities. A peak of CO and HC with limited NO_x emissions.

The LNT NO_X emission control is not always as successful as show in Figure 22. Another case under similar circumstances, i.e., motorway driving shows a succession of regenerations which keeps the average NO_x emission around 0.5 g/km. See Figure 23.

The normal regeneration of the LNT is not a problem for the emissions. However, with different vehicles with LNT and several hours of test data, higher emissions occasionally occur. In some case the LNT fails to regenerate altogether yielding, eventually high engine-out values for the NO_x emissions. See Figure 24.

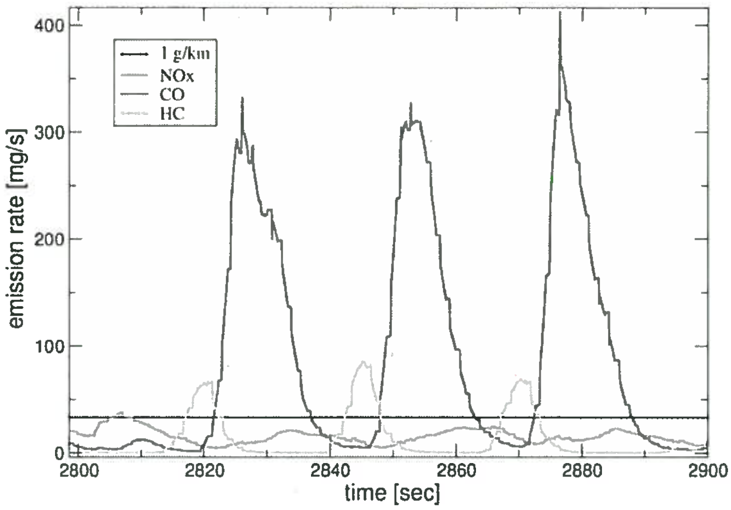

Figure 23: LNT emission control during motorway driving yielding a fast succession of regenerations with still substantial NO_x emissions.

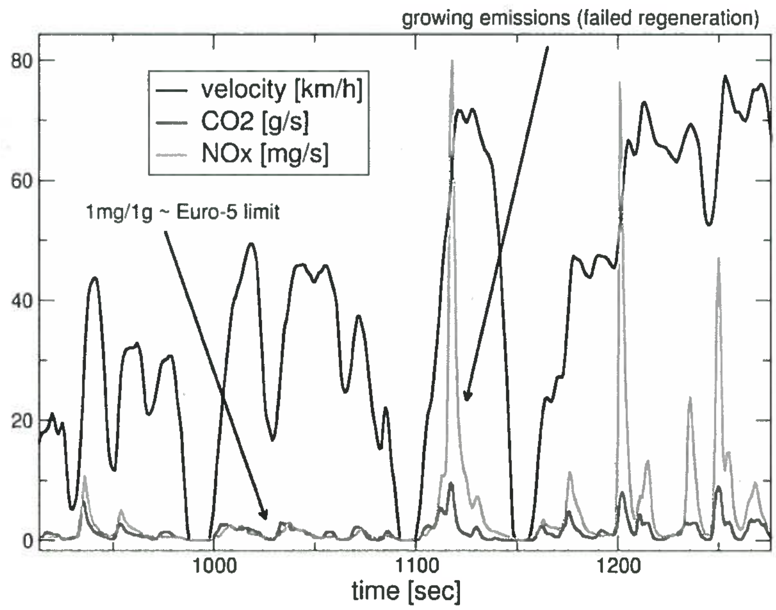

Figure 24 During rural driving NO_x emissions may grow occasionally due the delayed or failed regeneration of the trap.

More traditional technology, such as EGR, yield not only higher emissions but also more constant emissions. The emissions is expected to grow with the CO_2 emission.

In principle there are three types of failures of NO_x emission control: SCR fails if the exhaust-gas temperature is too low, which is at the start and in urban driving with a lot of idling. The LNT fails when engine out emissions increase without the possibility to regenerate. This seems most common in high dynamic rural driving. The last technology EGR has the highest NO_x emissions at high load. High load typically corresponds with motorway driving. In the last case the NO_x emissions increases by all standards: g/km, g/hr, and g/kg CO_2. Depending on the technology, the derived emission factors follow a certain pattern. LNT can achieve very low NO_x emission factors on the motorway, compared with urban and rural emissions. The same holds for SCR.

Given the variations of the result with technology and with tests the emission factors are determined from the average of the real-world chassis dynamometer tests. The results are given in Table 13.

Table 13: Emission factors for Euro 6 based on the average of the tests

[mg/km]	emission factors	NOx	CO	HC	NO2
		[mg/km]			
urban	Congested	234	79	54	47
	Normal	147	46	32	29
	free-flow	163	60	38	30
rural	Normal	128	57	30	22
motorway	Average	164	104	33	41
	Congested	199	73	42	45
	80 km/h	104	86	33	26
	100 km/h control	137	97	29	35
	100 km/h	150	100	31	37
	120 km/h	189	110	36	43
	130 km/h	215	116	38	47

The current emission factors are only a first estimate based on the test results. There is a substantial risk the emission will be much higher. Both the spread, i.e. standard deviation, of the results as the difference between maximal value and the mean are an indication for the values that may occur. We define risk as the average of the standard deviation and the maximal value:

$$\text{Risk [\%]} = \tfrac{1}{2} (\text{stdev[\%]} + \text{maximal deviation [\%]})$$

Using the highest value only for the risk will be overly conservative, with very worst case assumptions. Using the standard deviation only will yield a result dominated by the make-up of the current test program, i.e., the availability and selection of vehicles. Combining both worst case assumptions yield a robust result incorporating both the spread and the extremes.

We find the risk for urban and rural emission to be around 120% extra emissions, for motorway the risk is much higher: the additional emissions are around 300%, yielding up to 0.72 g/km NO_x emissions are possible for Euro 6 diesel vehicles.

Table 14: The estimate of the worst case emission factors for Euro 6 based on the spread in the results per test.

[mg/km]	emission risk	NOx	NO2
urban	Congested	523	190
	Normal	326	114
	free-flow	342	108
rural	Normal	275	83
motorway	Average	686	218
	Congested	554	219
	80 km/h	416	126
	100 km/h control	637	209
	100 km/h	639	209
	120 km/h	684	220
	130 km/h	720	229

These worst case emission factors are confirmed by the PEMS results. There are only two vehicles tested, but the average emission factors from these two Euro 6 cars yields emission factors close to the current Euro 5 emission factors. Furthermore, the emissions on-road of one vehicle are apparently larger than under similar circumstances on the chassis dynamometer in the laboratory.

The initial estimates of the emission factors, must be conservative, as the underlying data is limited. The estimate is based on the following analysis of emission factors based on the individual tests:

$$EF_{estimate} = EF_{average} + 0.25*STDEV + 0.25*(EF_{max}-EF_{average})$$

The experience from Euro 5 would lead to worst case emission factors, as there no discernible overall reduction from Euro 4 to Euro 5. The worst case emission factors follow the same trend from Euro 4 onwards. On the other hand, the lowest emissions, on the official, NEDC tests and also in real-world tests (CADC, WLTC), have gone down. Also with Euro 5 there was only one vehicle which performed in real-world tests comparable with the emission limit. With Euro 6 more brands and models show emissions which follow, in part, the trend of the emission limits. Hence, for the 2014 Dutch national emission factors a conservative estimate will be slightly lower than the worst-case risk. The emission factors are therefore set halfway between the average results and the risk results. The emission factors are given in Table 15. As can be seen the motorway emission factors are much higher above the average emission factors, due to the high risk associated with EGR technology, which is less likely to function in real-world conditions.

The emission factors are in line with the preliminary results of TUG for HBEFA 3.2. The reduction from Euro 5 to Euro 6 is slightly smaller in the proposed TNO emission factors than in the HBEFA emission factors. The difference is explained by three main differences between Dutch emission factors and HBEFA emission factors. First, the driving behaviour is different. In the Netherlands the congestion is typically high and speed limits on the motorway are strict. Second, the compact, fuel-efficient cars dominate the sales in The Netherlands. The Dutch diesel passenger car fleet is different from other European countries. Third, particular choices in testing and modelling are different from other approaches. The Dutch emission factors are part of the calibrated air-quality model. The approach is kept as much the same as possible to allow for historical comparison, retain the calibration, and allow for trend analyses.

Table 15: Euro 6 diesel emission factors, proposed for the 2014 Dutch national air-quality model.

[mg/km]	emission estimate	NOx	NO2
urban	congested	379	119
	Normal	237	71
	free-flow	252	69
rural	Normal	202	53
motorway	Average	425	129
	congested	377	132
	80 km/h	260	76
	100 km/h control	387	122
	100 km/h	394	123
	120 km/h	437	131
	130 km/h	468	138

The current emission factors are in line with the common strategy to estimate emission factors based on the ratio between emission limits and measurement data from earlier Euro-classes. In this case Euro 5. The reduction of the NO_x emission limits from Euro 5 to Euro 6 is from 180 mg/km to 80 mg/km. Applying the same reduction on the Euro 5 emission factors, for which more than sufficient evidence exists yields extrapolated Euro 6 emission factors which are slightly higher (up to 25%) than the current factors in the urban situations, and lower (down 40%) in the case of motorway driving:

Table 16: The Euro 6 emission factors based on the reduction of real-world emissions proportional to the reduction of the emission limit

[mg/km]	Euro 5 extrapolation	NOx	NO2
urban	congested	476	148
	normal	281	86
	free-flow	257	77
rural	normal	153	45
motorway	average	269	87
	congested	447	149
	80 km/h	186	61
	100 km/h control	228	74
	100 km/h	234	75
	120 km/h	258	80
	130 km/h	272	83

The overview of the tables is shown in Figure 25. The larger the spread in the data the larger the risk. The actual emission factors are set halfway between the risk and the average value.

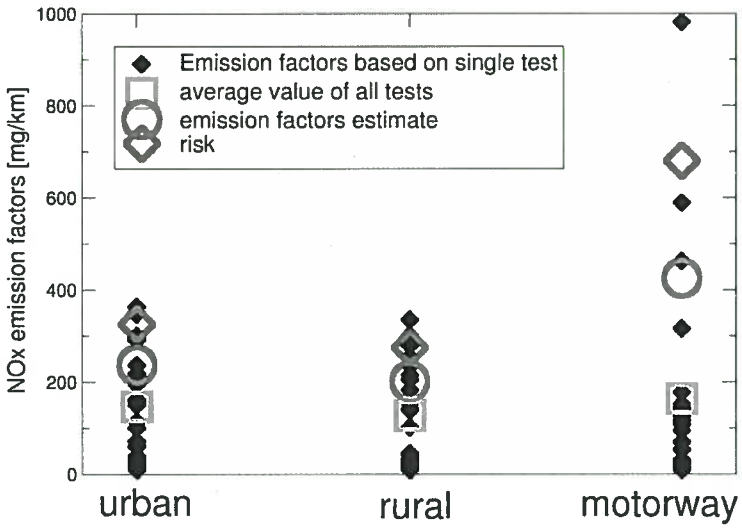

Figure 25: visualization of the emission factors in the different tables. The spread in motorway emission is large, yielding a substantial risk for high emissions, comparable to Euro 5.