CITA SET II Project

Sustainable Emission Test for diesel vehicles involving NO_x measurements

Final Report

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Table 1 - Document history.

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v.01.00	6/01/2019	All	

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1. Introduction

1.1. Introduction to the SET II project

Although, the PTI emission test requirements have been updated in recent years. They have not kept pace with the developments in vehicle technology and the associated type approval procedures, as well as the increased emphasis on nitrogen oxides (NOx) and particulate matter (PM) with respect to air quality and human health. On 18th September 2015, the Environmental Protection Agency (EPA) in the USA issued a notice of violation of the Clean Air Act. This incidence evoked some questions by politicians e.g. are high NOx emissions polluters able to be detected during PTI and are major malfunctions of NOx emission-control systems able to be detected during the PTI? Clearly, there is a danger that current PTI emission testing in Europe will lose its effectiveness. Which is why, there is a clear need to update the PTI exhaust emissions test in light of today's technology now.

CITA has already conducted previous work on this topic:

- The TEDDIE (TEst(D)DIEsel) project (2011) was funded by the European Commission Directorate-General for Mobility and Transport (DG MOVE) and members of CITA. As the name suggests, this project concentrated on diesel engines.
- The SET project (2015) looked for the correlation between a tailpipe emission test and EOBD check as well as applicable thresholds for both petrol and diesel vehicles.

1.2. Objectives and Approach of the project

The ultimate aim of this new CITA Study: SET II (Sustainable Emission Test for diesel vehicles involving NO_X measurements) is to develop new methods for the inspection of emissions of nitrogen oxides (NO_X), from M1/N1 diesel vehicles < 3.5 ton, suitable for use in a regulatory regime. NO_x comprises of a mixture of nitrogen oxide (NO) and nitrogen dioxide (NO_2). These methods should assess NO_X aftertreatment functions to an appropriate level to ensure the system is functioning correctly, is practical for implementation in the current PTI regime and is cost beneficial. Both, existing and future tools should be commercially available from a number of suppliers at a competitive price.

The starting point for this work is based on inspection methods being introduced and availability of suitable equipment. Therefore a comprehensive international review of the legislation, procedures, instruments and research relating to emission testing during PTI, will evaluate all possible NOx test procedures, including those not so evident or currently available in a European PTI centre e.g. chassis dyno tests and remote sensing. A basic EU PTI takes into consideration that emission testing should be relatively short, simple and pragmatic. Some States with a large volume PTI scheme may consider implementing more expensive equipment, such as emissions tests on a chassis-dynometer. The analysis will define the next steps for the laboratory tests on the test procedures and the large scale measurement (field tests) in different EU Member States.

1.3. Project Partners

A consortium, led by CITA, was been assembled in 2016 to provide the required services and resources for this project. The project is supported by a variety of different CITA members, from both full and corporate members, 21 in total, from the following 10 countries: Austria, Belgium, France, Great Britain, Germany, Republic of Croatia, Serbia, Spain, Sweden and The Netherlands.

SET II project technical executives:

Name	Project Partner	Country
Andrej Prosenc	ÖAMTC	Austria
Antonio Multari	MAHA	Germany
Antonio Sánchez Gonzalez	Veiasa	Spain
Celestino Pérez Rodríguez	ITVASA	Spain
Dennis Ipenburg	RDW	The Netherlands
Enrique Taracido	SYC	Spain
Eva Morger	Bilprovningen	Sweden
Georges Petelet	CAPELEC	France
Gerhard Müller	TÜV SÜD Auto Service GmbH	Germany
Gunter Gessner	DEKRA	Germany
Hans-Jürgen Mäurer	DEKRA	Germany
Helge Schmidt	TÜV NORD	Germany
Henk Bussink	RDW	The Netherlands
Ismael Herrera	Certio ITV	Spain
John Stephenson	DVSA	Great Britain
Juan Ramón González Rojo	Grupo Itevelesa	Spain
Klaus Schulte	AVL	Austria
Macarena Fernández Rivera	Veiasa	Spain
Manuel Krimshandl	TÜV SÜD Auto Service GmbH	Germany
Milan Coran	AMSS-CMV	Serbia
Olivera Djordjevic	AMSS-CMV	Serbia
Pascal Buekenhoudt	GOCA	Belgium
Ralph Schröder	FSD	Germany
Roger Eggers	TÜV NORD	Germany
Salvador Esquius	Applus+	Spain
Thomas Nilsson	Opus Bilprovning AB	Sweden
Thomas Ost	DEKRA	Germany
Thomas Pettersson	Opus Bilprovning AB	Sweden
Tobias Stoor	Bilprovningen	Sweden
Tomislav Škreblin	CVH	Croatia
Walter Lukesch	AVL	Austria

Table 2- SET II project technical executives.

2. Understanding the context

2.1. PTI emission tests in Europe

Although, the PTI emission test requirements have been updated in recent years. They have not kept pace with the developments in vehicle technology, as well as the increased emphasis on NO_x emissions and particulate matter (PM). Although NO is not harmful to health at concentrations typically found in the atmosphere, NO_2 is associated with a range of environmental and human health problems. For decades PTI in Europe has continued to test tailpipe emissions, which essentially requires the following:

- For vehicles with spark ignition engines, the measurement of the CO concentration in the exhaust with the engine at idle and high idle, as well as lambda (*i.e.* the normalised air/fuel ratio) at idle for lambda-controlled vehicles.
- For diesel vehicles, the measurement of exhaust opacity during a so-called 'free acceleration' test.

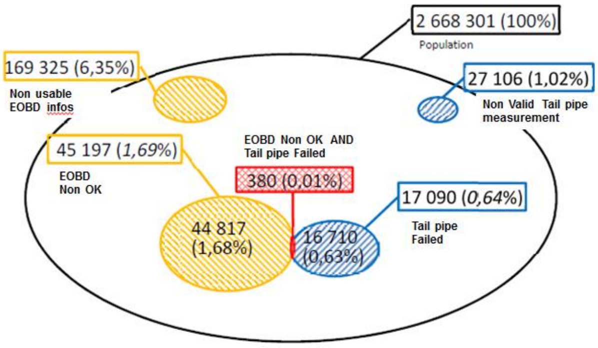
A more detailed description of the test procedure, pass/fail criteria and test equipment for vehicles with spark ignition engines as well as for diesel vehicles can be found in the TEDDIE study (CITA, 2011). The measurement of NO, NO_2 or NO_x is not currently required. The danger is that the current PTI emission test in Europe has lost its effectiveness.

Even with the most recent PTI Directive 2014/45/EU of 3 April 2014 (European Union, 2014) no NO_x measurement and no significant tightening of the emissions thresholds limits is foreseen. This Directive is the latest revision, and includes amendments to the emission tests, which were to be implemented by the Member States, by May 2018. A discussion of the requirements for emissions testing is presented below.

- For vehicle emission classes up to and including Euro 5 and Euro V the tailpipe test is the default method of exhaust emission assessment. On the basis of an assessment of equivalence Member States may authorise the use of EOBD. For vehicles as of emission classes Euro 6 and Euro VI a tailpipe test or an EOBD test can be used.

  Although the content of the assessment of equivalence is not clear, the studies from UTAC OTC in France (UTAC OTC, 2013a) and CITA (CITA, 2015) focused on the comparison between both test methods.

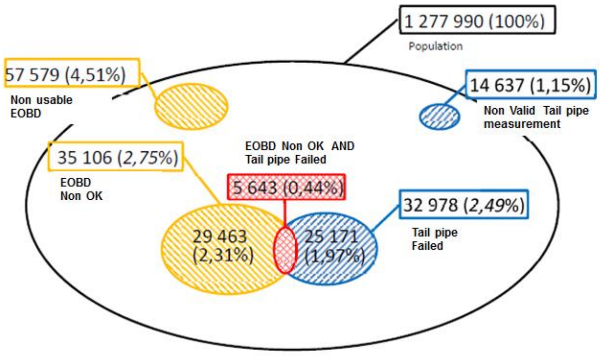
  In France petrol passenger cars with a first registration date after 1/1/2002 and diesel vehicles after 1/1/2004 or 1/1/2007 (depending on max authorised mass and number of seats) are also tested (since 2008) via both, the tailpipe test as well as an EOBD test (UTAC OTC, 2013b). They also have a program for measuring the emissions of heavy duty vehicles since 2011. The EOBD test is limited to the evaluation of the MIL and the data trouble codes. UTAC OTC (UTAC OTC, 2013a) published the results of the comparison between the tailpipe tests and the EOBD interrogation during the PTI of light vehicles in France in the period January – June 2013. They had quite a signinificant sample of 2.668.301 diesel vehicles and 1.277.990 petrol vehicles, most of them were Euro 3 and Euro 4 vehicles.



Note:
Overlapping between non usable EOBD info and no tail pipe measurement result is not part of the study
Dimensions of population are not related to dimension of drawings

Figure 1 - Comparison of the opacity tailpipe tests with EOBD. (Taken from UTAC OTC, 2013a)

For the diesel vehicles, Figure 1, 0.64% were rejected based on the opacity test, and 1.69% based on the EOBD test. Only 0.01% were rejected for both tests. Furthermore, 6.35% could not be evaluated by the EOBD system and 1.02% by the opacity test. Similar results were noted for petrol vehicles, Figure 2, where only a small amount of the sample were rejected for both, tailpipe as well as for EOBD (0.44%). Also 2.49% did not achieve the exhaust gas measurement and 2.75% the EOBD test. From the sample petrol vehicles 1.15% could not be evaluated by the tailpipe test and 4.51% by the EOBD. Note that the status of the Readiness Codes, (RCs) is not taken into account in France (UTAC OTC, 2013b).



Note:
Overlapping between non usable EOBD info and no tail pipe measurement result is not part of the study
Dimensions of population are not related to dimension of drawings

Figure 2 - Comparison of the 4-gas analyse tests with EOBD. (Taken from UTAC OTC, 2013a)

CITA undertook the SET Project (CITA, 2015) with the aim of assessing possible approaches for in-use vehicle testing and to adapt vehicle inspection techniques to new and stricter pollutant emission thresholds. There were six countries involved (Belgium, France, Germany, The

Netherlands, Spain, Sweden) and more than 3.000 vehicles were tested in the field over one year. Most of them were Euro 4 and Euro 5.

The data retrieved was analysed in order to compare EOBD read out (fault codes, RC Status, status information) versus the tailpipe emission test (CO, k values[1] for particulate matter [PM]). One of the main conclusions was that EOBD and tailpipe emission testing are complimentary. There is no clear correlation between an emissions test and EOBD check for either petrol or diesel vehicles. It is therefore, recommended that for Euro 4 or later vehicles, both an emission test and an EOBD check should be performed. The combination of EOBD information and tailpipe measurement will have the best benefit and ability to detect most of the emission behaviours affecting failures on modern passenger cars.

- Despite the progress of engine technology, emission limit values in the Directive 2014/45/EU have only been tightened for Euro 6 and Euro VI diesel engines, by introducing a new limit of 0.7 m^{-1}.

Outcomes of the German project 'Emission 2010' (VdTÜV and DEKRA, 2010) and the TEDDIE study (CITA, 2011) suggested adjusting the mandatory emission limit values for vehicles to current vehicle technology conditions, as from Euro 2 (and Euro II). The project 'Emission check 2020' suggested more severe limits for Euro class engines than introduced by directive 2014/45/EU (VdTÜV and DEKRA, 2013). The use of the so called emission reference values on each vehicle identification plate of diesel powered vehicles will probably not be introduced by each Member State because the Directive set some threshold limits where this information is not available or requirements do not allow the use of these reference values.

During this SET study (CITA, 2015), the threshold emission values of the Directive were evaluated for each emission class. To define suitable thresholds, the accuracy of measurement devices as well as the level of gross pollutants today were taken into account and in order to finally compile a precise recommendation, a cost-benefit analysis was included.

The outcome was that periodical inspection may be enhanced with more adequate limits for newer and cleaner vehicles (Euro 5, Euro V, Euro 6 and Euro VI vehicles);

- For petrol vehicles:
  - For Euro 3 vehicles, the current limit is suitable.
  - For Euro 4 or later vehicles, a revised limit of 0.1% CO should be used for the fast idle test. A stricter limit of 0.05% CO could be introduced for Euro 4 or later vehicles, but some Member States might require new equipment to test to this level. The current limit is suitable for the two speed, idle/high idle test.

[1] Absorption coefficient, a reading from an opacity measurement that would give the same results no matter what tester or chamber length is used. The opacity percentage is through the Beer Lambert equation transformed into an absorption coefficient.

- For diesel vehicles
  - For Euro 3 vehicles, the current limit is suitable.
  - For Euro 4 vehicles, because some are fitted with DPFs whereas others are not, the limit should be the plate value, but maximum 1.0 m^{-1}.
  - For Euro 5 or later vehicles, a general limit is practical to apply to all diesel vehicles. It is recommended that a limit of 0.2 m^{-1} is used in the future.

Enhancing the periodical inspection of pollutant emissions in Europe as defined in the project has a benefit of between 7 and 12 times higher than the cost.

Since the introduction of the diesel particulate filter (DPF), opacity testing from Euro 5 onwards is no longer efficient, as the correlation between the opacity and produced particulate matter (PM) is proven to be very poor (CITA, 2011).

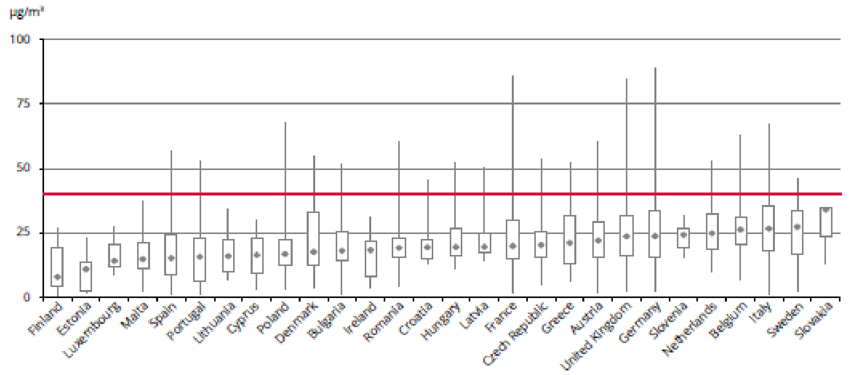
Although the EU Directive 2014/45/EU (European Union, 2014) has no testing of other pollutants foreseen, the EU has a clear position about NO_x:

> *"Possibilities for improving test cycles to match on-road conditions should be closely examined in order to develop future solutions, including the establishment of test methods for the measurement of NO_x levels and of limit values for NO_x emissions."*

2.2. NO_x emissions are a particular problem in EU

On September 18th, 2015, the Environmental Protection Agency (EPA or USEPA) issued a notice of violation of the Clean Air Act to Volkswagen AG, Audi AG, and Volkswagen Group of America, Inc. (United States Environmental Protection Agency [EPA], 2015). The notice of violation alleges that four-cylinder Volkswagen and Audi diesel cars from model years 2009-2015 include software that circumvents EPA emissions standards, for certain air pollutants. This incidence evoked some awareness of NO_x emissions by European politicians.

NO_x emissions are a particular problem in the EU. A large proportion of the Member States are failing to comply with the annual average ambient limit value for NO_2. In 2013 nineteen of the 28 EU Member States recorded an exceedance of the annual limit at one or more of their monitoring stations (European Environment Agency [EEA], 2015). See also Figure 3. In addition, many European cities continuously exceed the limits the European Commission has set for pollutants in urban areas. These cities are running the risk of treaty violation proceedings. (European Environment Agency. (2015).



Notes: The graph is based on the annual mean concentration values (calculated from hourly data) for each Member State. For each country, the lowest, highest and median values (in µg/m³) at the stations are given. The rectangles give the 25 and 75 percentiles. At 25% of the stations, levels are below the lower percentile; at 25% of the stations, concentrations are above the upper percentile. The limit value set by EU legislation (equal to the WHO AQ guideline) is marked by the red line.

Figure 3 - Attainment of annual mean NO_2 values for 2013 for all EU Member States. (Taken from EEA, 2015)

Diesel vehicles are, known to be high emitters of NO_x. The road transport sector emits around 40% of Europe's NO_x emissions. Of the emitted NO_x from vehicles, around 80% comes from diesel-powered vehicles, for which the proportion of harmful NO_2 in the NO_x is far higher than the proportion found in the emissions from petrol vehicles (EEA, 2015).

The fact that diesel vehicles have such an influence in Europe has several reasons (Hooftman, Messagie, Coosemans, & Van Mierlo, 2014):

1. The combustion process, by means of a direct diesel injection in an excess of oxygen (O_2), inherently produces high levels of the NO_x pollutant.

2. Diesel technology has historically known advantages such as the fuel economy, which is better compared to petrol technology due to higher combustion efficiencies and the benefit of the fuel cost in Europe, as diesel fuel has historically been cheaper than petrol fuel, which is an important incentive for the vehicle owner (The International Council on Clean Transportation [ICCT], 2014).

3. In addition to the Belgian study (Hooftman et al., 2014), diesel car power has inexorably increased over the last 20 years (Carslaw, 2013). Petrol cars, on the other hand, had a relative stable evolution of their car power over the same period as can be seen in Figure 4. The link between car power and NO_x emissions is clear.

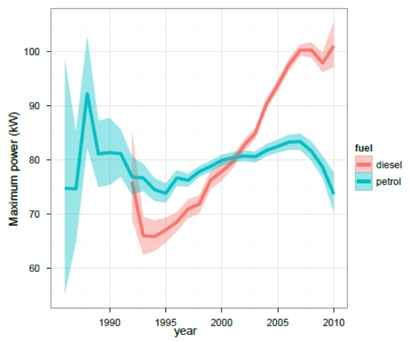


Figure 4 - diesel car power has increased over the last 20 years. (Taken from Carslaw, 2013).

4. An advantage at type-approval level is to be noticed, as different emission limits have been applied according to the fuel type and higher NO_x levels have been allowed for European diesel vehicles.

In the U.S. there is a fuel-neutral approach. For Europe, this explains the significantly higher market share for diesel passenger cars (53 %), while markets such as the U.S. (0.8 %) and Japan are only marginally populated by light-duty diesel vehicles (ICCT, 2015). Figure 5 show the EU market share of diesel vehicle for some notable countries. In the aftermath of the Dieselgate scandal, sales of new diesel cars dropped significantly. In 2011–2012, about 55 % of newly registered cars in the EU were powered by diesel fuel, an all-time high. Since then, the market share of diesel has slowly decreased, to 49 % in 2016, but diesel shares continue to vary by member state (ICCT, 2017).

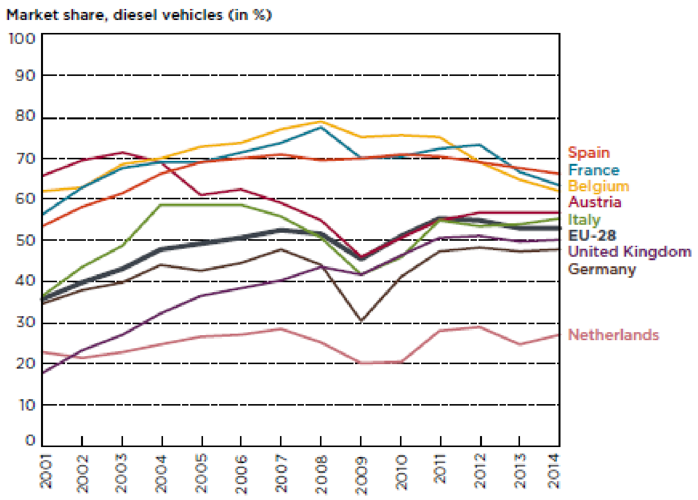


Figure 5 - Diesel vehicles market share in EU. (Taken from ICCT, 2015)

2.3. NO_x emissions under real driving conditions

The transport sector has considerably reduced its emissions of air pollutants in Europe over the past decade (EEA, 2015).

Recently, since the EPA notice of violation of the Clean Air Act (EPA, 2015), there has been increasing public attention on the current vehicle type approval emissions procedure. It is clear that both the on-road emissions and fuel consumption from European cars are significantly higher than the official type approval measurements. The fuel consumption on the road, and hence the CO_2 emissions, can be 20 to over 40% higher than the official measurements (Tietge, Diaz, Mock, German, Bandivadekar, and Ligterink, 2016). The differences are even higher for NO_x emissions, in particular for diesel vehicles.

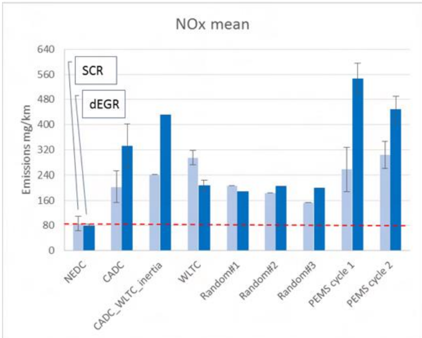


Figure 6 - NO_x Emissions from Chassis Dyno and PEMS Tests. (Taken from Andersson et al., 2014)

Two (2) Euro 6 Vehicles, with both, different NO_x aftertreatment systems, were tested and discussed in the SAE paper 2014-01-2826 (Anderson et al., 2014). One vehicle had a SCR system and the other one a dual-EGR system. The NO_x emissions from on road tests with PEMS and different chassis dynamometer tests are showed in Figure 6. During the NEDC type approval cycle both vehicles showed mean NO_x emissions to the Euro 6 limit of 80 mg/km. For all EU type approval limits, see Annex 1. On the other hand the emissions levels on other, more severe driving cycles as well as on the two PEMS routes had emissions levels of two to almost seven times more.

In Figure 7 the NEDC test cycle is compared with the more representative Common Artemis Driving Cycle (CADC) (Katsis, Ntziachristos & Mellios, 2012). The driving cycle consists of three parts: an urban, a rural and a motorway part. The CADC is deemed to be much more in line with the real usage of an engine. The diesel NO_x emission trends per Euro emission standards are given for each cycle. What is noticeable from Figure 7 is that despite the positive trend for the NEDC type approval results, the levels of NO_x emissions in more real usage conditions of the engine have been almost the same over the years between pre-Euro 1 and Euro 5 engines.

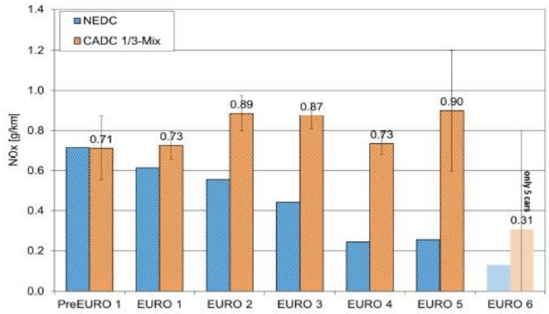


Figure 7 - The evolution of light-duty diesel NO_x emission for the NEDC (blue) and the CADC 1/3-mix (orange) over the subsequent Euro emission standards. (Taken from Katsis, Ntziachristos, & Mellios, 2012).

Figure 6 and Figure 7 show that Real-life measurements of NO_x emissions from diesel vehicles can be, from two to seven times higher under real driving conditions. Petrol vehicles broadly meet the 'Euro' standards under real driving conditions. Several studies have shown this discrepancy between the NEDC cycle and real driving situations. An overview of some public studies on more stringent NO_x testing based on our literature research is produced. The Table 3 show that Euro 6 diesel vehicles exceed the legal NO_x emissions by a factor up to seven when tested under more real driving conditions based on dyno-tests or PEMS measurements.

Portable emissions measurement systems, also known as PEMS are certified mobile measurement equipment for the regulatory on-road emission testing and will help to address the gap between legislative and real-world NO_x emissions since the European Union has recently agreed a Real Driving Emission (RDE) test procedure for M1/N1. The new RDE procedure will measure emissions of NO_x, and at a later stage particle numbers. The new protocol requires the real driving emissions from cars and vans to be lower than the legal limits multiplied by a 'conformity factor'. This factor expresses the ratio of on-road PEMS emissions to the legal limits. PEMS main limitations are the reduced range of pollutants that can be measured during a test compared with laboratory testing, as well as the additional mass (30–150 kg) the PEMS kit adds to the vehicle, which can affect the fuel consumption and hence measurements of the different pollutants. Furthermore, the lower repeatability of measurements encountered when testing, owing to real-world sources of variability, can be challenging to ensure consistency of measurements between different vehicles tested (EEA, 2016).

Conformity Factor (CF) is the ratio of measured emissions to the regulated emission limit (CF>1 indicates an exceedance). Nevertheless, a small number of vehicles met the legal limit in real-life conditions. This proves that the existing technologies are able to meet the existing limits under more real-life conditions.

Study	N° of Euro 6 Diesel tested	Type of measurement	NO_x CF	N° of vehicles reaching the legal limit
AECC, (Favre et al., 2013)	2	Dyno Artemis CADC	6 - 7	0
TNO, (Ligterink et al., 2013)	16	Dyno	2.5	1
AECC, (May et al., 2013)	4	Dyno	7 - 10	1
Ricardo UK – AECC (Andersson et al.,(2014)	2	Dyno PEMS	2 - 6	0
TNO, (Kadijk et al., 2015b)	7	PEMS	5.2	0
ICCT, (Franco et al., 2014)	15	PEMS	7	1
Baden Württemberg, (Scholz et al., 2015)	3	PEMS	4.2	0
Emission Analytics, (Molden, 2015)	25+	PEMS	4.5	3

Table 3 - Summary of public domain data sources on more stringent Euro 6 diesel NO_x testing.

The EU confirmed these values in their EEA publication “Explaining road transport emissions - A non-technical guide” as seen in Figure 8. (EEA, 2016).

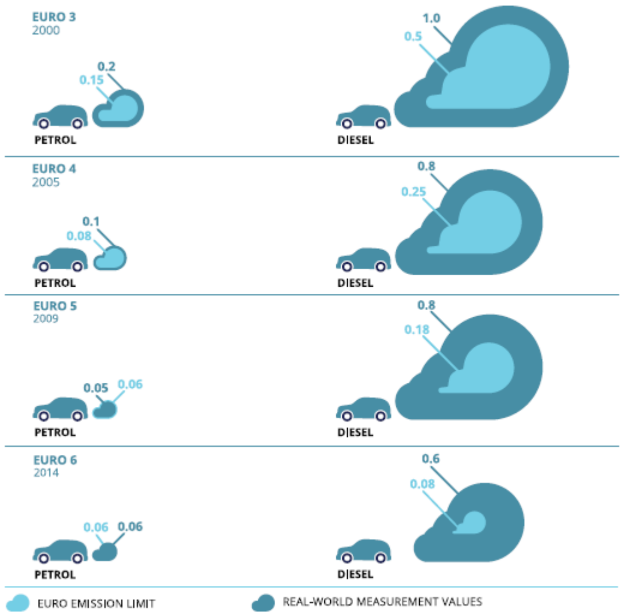


Figure 8 - Comparison of NO_x emissions and standards for different Euro Classes. Nitrogen emissions in g/km. (Taken from EEA, 2016)

Such differences are attributable to a variety of factors (Transport and Environment [T&E], 2013), given the fact that the current laboratory test cycle used in Europe is not very representative of how people drive their cars in real life. The test cycle is unrealistic and undemanding. Furthermore, current legislation affords manufacturers a number of flexibilities, as presented in Figure 9, which enable them to optimise vehicles for the testing procedure. The lack of transparency in these testing procedures and the fact that vehicle manufacturers have an increasingly stringent pressure to lower the CO_2 limits of their vehicles as fiscal incentives on lowest-emitting cars exist, will not help to close the gap.

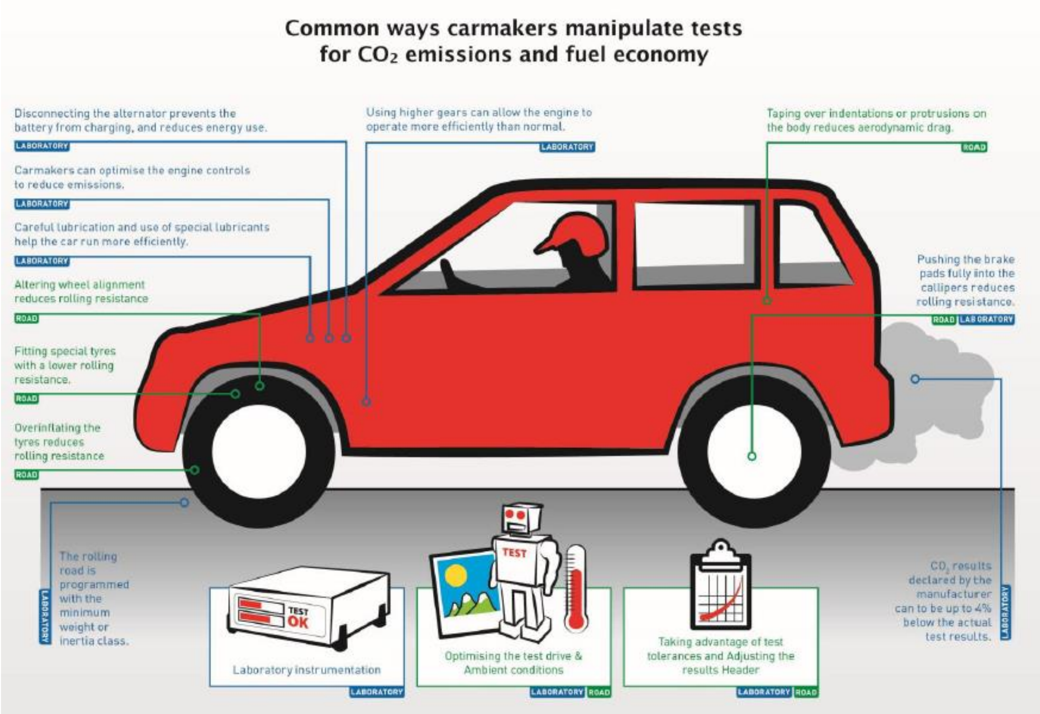


Figure 9 - Common ways car manufacturers manipulate tests for CO2 emissions and fuel economy. (Taken from T&E, 2013)

Carslaw, Williams, Tate & Beevers (2013a) pointed out another issue why urban ambient concentrations of NO_x have not decreased as much as anticipated. The vehicle power and NO_x emissions are closely correlated. Moreover, the power of diesel vehicles has increased by about 50% over the past 2 decades while that of petrol cars has remained almost constant.

It is clear that changes to vehicle technology, driving conditions and driver behaviour have become more important and detrimental to increased vehicle NO_x emissions.

2.4. NO_x emissions testing should be a part of PTI

Anyon, Jones, Real & Jamieson (1996) described the influence of age, mileage and maintenance on vehicle emissions. As expected, the emissions increase the more the vehicle is driven, gets older and is less maintained. Regular maintenance of the vehicle leads to a 10 % to 25 % decrease of the emissions in comparison with a poorly maintained vehicle. However, the distribution of this reduction is not uniform: the repair of 20 % of the vehicles leads to a decrease of 80 % of the emissions. The study took also into account NO_x emissions.

Another study from the National Research Council (2001) pointed out that, typically, less than 10% of the fleet accounts for more than 50% of emissions of any given pollutant. The Texas A&M Transportation Institute (2013) confirmed this "pareto" observation, having an unequal distribution. These studies support the notion, that NO_x measurement during PTI has a potential for emissions reductions through identification and repair of high emitters.

Vehicle owners have little incentive to perform maintenance on their vehicles to keep emissions low (Fung & Suen, 2013). After all malfunction of emission control components do not often affect vehicle drivability, and most harmful pollutants, such as CO, NO_x and HC are invisible. For this reason, a PTI NO_x emission test with the goal of identifying gross-emitters is necessary. PTI should identify gross-emitting vehicles, whose pollutant levels are significantly greater than expected, taking into account vehicle's technology, emission standard and age, and mitigate their impact on air quality by ensuring that they are properly fixed.

High-emitting vehicles can have different causes as listed by Posada, Yang, & Muncrief (2015):

- Improper or incorrect vehicle maintenance or operation can cause early deterioration of engine or emissions control components;
- Ignoring the malfunction indicator lamp (MIL) leads to high emissions since the EOBD system is designed to alert the driver in case of malfunctions that can lead to increased emissions;
- Incorrect vehicle operation, e.g. driving with an overloaded vehicle, can also lead to elevated emissions;
- Tampering or the deliberate modification of a vehicles, engine or emission control device in order to boost the vehicle performance, save costs, or improve vehicle fuel economy. Well known examples are "reflashing" the vehicles electronic control unit, removal of catalytic converter or DPF and removal or blocking the EGR system;
- Vehicles may become gross emitters because of design or manufacture defects such as a defective component or poor durability of components; and
- A disconnect between the design conditions used for developing the emission control system and the conditions that the vehicle experiences during daily use. Lower exhaust temperatures under low-speed urban driving conditions.

Clark, Kern, Atkinson, & Nine (2002) listed some influence factors affecting heavy-duty diesel vehicle emissions. For NO_x emissions, the effects registered are shown in Table 4. Each value represents a specific comparison discussed in the study and is not to be generalised. Vehicle age and use (including work terrain) seems to have an enormous impact on NO_x emissions.

It is clear that today with the current and upcoming EU PTI emission legislation (European Union, 2014), not all gross emitters will be detected. Vehicles as detected by EPA (EPA, 2015), vehicles that have been tampered with, defects not covered by the EOBD system or those specifically related to NO_x emissions, will not necessarily be detected by the current EU PTI regimes.

Influence factor – grade effect	Effect on NO_x emissions
Vehicle class and weight	25 %
Emissions test cycles	300 %
Vehicle vocations or specific use	10 %
Fuel differences	25 %
Exhaust aftertreatment	15 %
Terrain travelled by the heavy duty vehicle	250 %
Vehicle age	250 %
Injection timing variances	200 %

Table 4 - Effect of various factors on NO_x emissions (Created from Clark et al, 2002)

A French study, between end-2011 and mid-2012, tested 312 vehicles (168 were diesel vehicles) after a PTI visit (Pillot, Legrand-Tiger, Thirapounho, Tassel, & Perret, 2014). The diesel vehicles were mainly Euro 3 and Euro 4 vehicles, since vehicles are only submitted for PTI after 4 years. The test consisted of a continuous monitoring of the gas fractions (CO, CO_2, HC and NO_x and in addition O_2 and λ[2]) during an engine cycle composed of four successive steady-state regimes without any load and an engine stop delay. The Non-dispersive infrared analyser [NDIR] was equipped with a software program which displays and analyses the exhaust gas composition and can detect defects in the combustion process and aftertreatment system. More than 130 defects and combinations of defects can be identified based on a comparison to threshold values. Here for a necessary input data e.g. brand and model of the vehicle, vehicle millage, model year, engine technology, fuel injection type and MIL, etc. is needed.

During the NDIR test mentioned above only 25 % of the vehicles were screened without any defect, as can be seen in Figure 10. Some vehicles had multiple defects. The main nature of the diagnosed defects are poor injectors (fuel leakage or bad spray) with a 36 % of occurrence in the diesel sample, Exhaust pipe clogging (36 %), EGR valve malfunction (16 %), Turbocharger defect (16 %) and restricted air intake (5 %). However, only three of the 168 diesel vehicles were rejected using the opacity based emission test.

[2] The Brettshneider equation is the de-facto standard method used to calculate the normalised Air/Fuel Balance ((λ) Lambda) for Inspection Programs. It's derived from a paper written by Dr. J. Brettshneider in 1979. He established a method to calculate Lambda (Balance of Oxygen to Fuel) by comparing the ratio of Oxygen molecules to Carbon molecules in the exhaust.

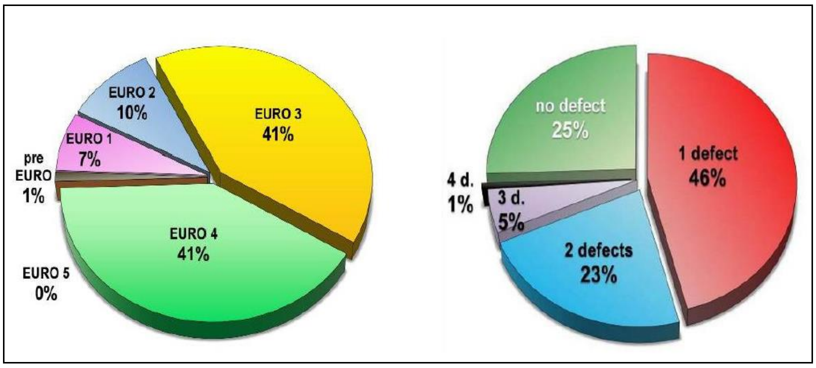


Figure 10 - Distribution of the 168 tested diesel vehicles and defect number from the engine diagnostic. (Taken from Pillot et al., 2014)

Currently several European Union Member States are already considering updating their PTI emission testing schemes (Ministère de l'écologie, du développement durable et de l'énergie, 2015). Therefore, it is the right time to consider the development of a new harmonised procedure applicable for the needs of the current challenges in PTI emission testing.

Norris (2005) and Transport and Environment (2015), both pointed out that in service NO_x testing should consist of a diagnostic check of key systems or components in order to ensure they are functioning correctly throughout the life of the vehicle. Failure of these components or systems would lead to excessive NO_x emissions.

Taking in account all off the above discussions in this chapter, there is a current need for measuring exhaust NO_x emissions during PTI that needs to be updated in light of today's technology and capability of modern measurement devices.

3. Sustainable Emission Test for diesel vehicles involving NO_x measurements

3.1. International review

The international review had a focus on the following topics:

- Technologies for the control of NO_x emissions (annex 2);
- Instruments for measuring NOx during PTI (annex 3);
- PTI test procedures for the test of diesel vehicles involving NO_X measurements (annex 4).

Diesel engines almost always run in a lean environment, it is with an excess of air. Temperature rises when the air is compressed in the cylinders. Currently, when the fuel is injected it will auto ignite due to the suitable temperature and conditions that are created in the cylinders.
Stoichiometric engines emit more engine-out NO_x than lean engines, but these are relatively easy to control with aftertreatment systems. PM and NO_x emissions are a concern for diesel engines and more of a challenge to control, than the HC and CO emissions due to the lean operation.

The major part of the NO emissions are produced during diesel combustion of near-stoichiometric fuel-air mixtures by the oxidation of atmospheric nitrogen. At typical flame temperatures the NO_2/NO ratio for Diesel engines NO_2 can be between 10 % and 30 % of the total NO_x emissions. NO_2 is formed since the produced NO, formed in the flame zone can be rapidly converted to NO_2.

Controlling nitrogen oxides (NO_x) emissions from Euro 6 diesel passenger cars is one of the biggest technical challenges facing car manufacturers. The main technologies for the control of NO_x emissions available for this purpose are:

- inner-engine modifications coupled with exhaust gas recirculation (EGR);
- lean-burn NO_x absorbers (also called lean NO_x traps, or LNTs);
- Selective Catalytic Reduction (SCR).
- Lean NO_x catalysts (also called hydrocarbon-SCR)

The literature review on these technologies is presented in annex 2.

This next section of the review summarises the instruments, which are likely to be suitable for the measurement of NO_x during PTI, including the results of any studies in which the instruments have been tested and compared. The instruments were identified through a review of the literature and through the personal knowledge of the project members. Instruments for measuring NO_x during PTI are described in annex 3. The following types of equipment were investigated:

- Chemiluminescence analyser;
- Non-dispersive infrared absorption spectroscopy (NDIR);
- Non-dispersive ultraviolet absorption spectroscopy (NDUV);
- Electrochemical cells ;
- Zirconia multilayer ceramics;
- Fourier-transform infrared spectroscopy (FTIR).

The importance of a good time response for NO_x emission measurement has already been highlighted in the TEDDIE study (CITA, 2011) and the review shows some difference in a quick and a conventional analyser.

The research for applicable PTI test procedures for the test of diesel vehicles involving NO_X measurements, annex 4, began with those already disclosed in the TEDDIE-study.

The outcome for a new PTI test procedure should involve three different aspects:

1. The vehicle test condition including the use of OBD information as well as a tailpipe emission test: a fixed schedule of vehicle operation, which allows an emission test to be conducted under reproducible conditions and considering the different PTI regimes in Europe. This could be a specific unloaded condition or a loaded condition obtained by a driving cycle. These driving cycles can be divided into loaded steady state and loaded transient cycles, depending on the character of speed and engine load changes.
2. NO_x measurement equipment.
3. Additional equipment, if necessary (measurement of oil temperature, rpm, OBD data, etc.)

The scope of the project should include the precise recommendations to measure NO_x emissions for the European Commission and Member States to amend the PTI Directive 2014/45/EU accordingly. These test procedures could be based upon the evaluation of a certain amount of NO_x air pollutants at a certain load or upon an evaluation of good working NO_x after-treatment systems. The study should evaluate all possible NO_x test procedures; including those not so evident in a European PTI centre, e.g. chassis dyno tests and remote sensing, and all existing NO_x test equipment.

Two different kinds of test procedures with a focus on NO_x emissions and applicable in a European PTI environment have been identified:

- NO_x threshold test procedures.
  An overview of existing NO_X threshold test procedures, completed on a chassis dynometer and their evaluation are described in annex 4. Most of the existing NO_X procedures are done on petrol vehicles, like ASM Acceleration Simulation Mode, IM240, MA31/BAR31, CARB test cycle. The test cycles DT80 and KD147 are the only cycles, as far as we could find, used on diesel vehicles. These test procedures are described in annex 4.
- Component (after-treatment) test procedures.
  The following NOx – abatement component test procedures are described in annex 4:
  - Exhaust gas recirculation (EGR) component tests – “Capelec”;
  - Exhaust gas recirculation (EGR) component tests – “Norris (2005)”;
  - Diagnostic screening test – “Pillot et al. (2014)” – “Spheretech-Bosch”;
  - AVL DiTest rpm ramp for NOx measurement – “Schweiger (2016)”.

The most important test cycles for this study are shortly decribed hereafter. Nevertheless, a detailed description of these and other test cycles are given in the annex 4.

The ASM2050 cycle focuses on the urban part of driving cycles, as urban transport emissions in particular are at the forefront of public and political debate. The driven speeds are therefore between 0 and 50 km/h. The two constant speed points are at 20 and 50 km/h.
In the ASM test for petrol and diesel cars, the vehicle is driven on a basic chassis dynamometer without the use of inertia flywheels. The inertia load normally encountered during accelerations is simulated by applying additional load. The vehicle is driven on the dynamometer at a constant speed, with a steady-state power absorption that is equal to the actual road load of the vehicle (except the rolling resistance) during acceleration. This circumvents the need for flywheels. However, at high speed/high acceleration combinations the required power absorption is too great to be achieved without the engine overheating. This restricts the useable speed/power range.

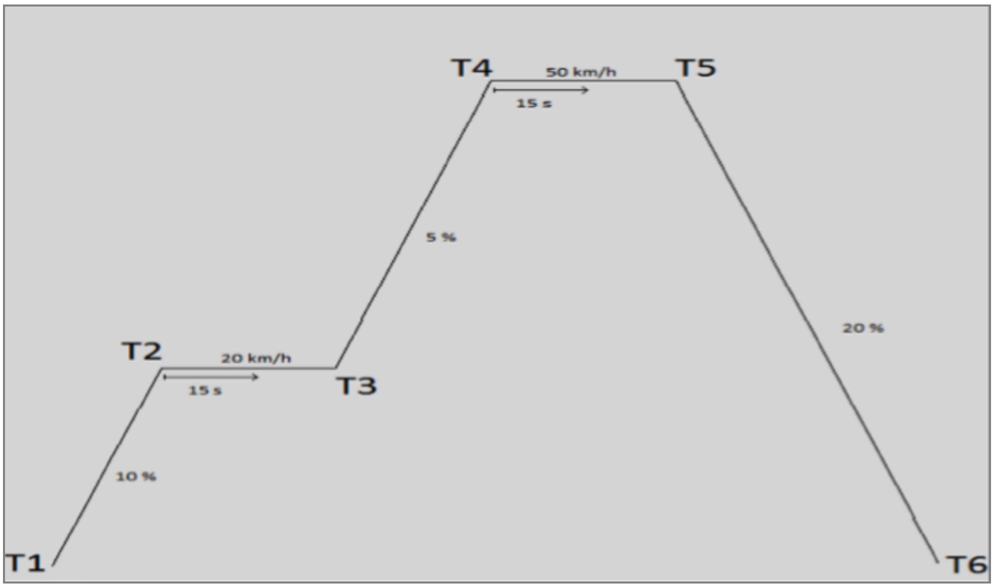


Figure 11 – ASM2050 Test Cycle

There are two variants of the ASM2050. Both are the same as that shown in Figure 11. However, in variant 1 the cycle is driven from point T2 in second gear to the end of the process, whereas, in variant 2 at point T4 you change from second gear to third gear and thus the 50 km/h stage is driven in third gear (Pando, 2016). These variants are further described in the Annex 4.

While the ASM2050 test can be done within closed areas, on the contrary, with the Australia Diesel test a country road has to be avoided. As this method requires a speed of 60 km/h (DT60) or a speed of 80 km/h (DT80). In addition it is a longer test sequence with about 130 seconds for the DT60 and about 290 seconds for the DT80, this also requires an additional longer drive to reach a suitable location where it is allowed to drive the required speed. Furthermore, the method requires much higher requirements for safety standards with respect to a chassis dynamometer; moreover, due to a higher speed on the one hand, a stronger fan is required to cool the engine and, on the other hand, a more powerful test stand.

Considering the prescribed top speed of 83.5 km/h for the Korean Cycle KD147, creates the same problem, which led to the exclusion of the Australia Diesel test. Although the KD147 is around the same time as the DT60 and half the time of the DT80, it is at least twice the test duration of the ASM2050. Also, due to the complex driving profile, the KD147 with its different speed specifications can only be traced on a chassis dynamometer and is not suitable for a public road with other road users. If this were considered for use on a public road, it would require a second examiner to accurately specify the prescribed speeds so that the driver would not be distracted from the road. Furthermore, other road users would influence the process.

After a closer look at the three dynamic processes, the ASM2050 process was selected and tested on different vehicles. The ASM2050 procedure provides for a maximum speed of 50 km/h, which on the one hand, means less risk on the chassis dynamometer and, on the other hand, allows driving within closed areas. With a test duration of approx. 60 seconds, without set-up time of the measuring instruments, the method promises a quick emission test.

Capelec propose the following test conditions:

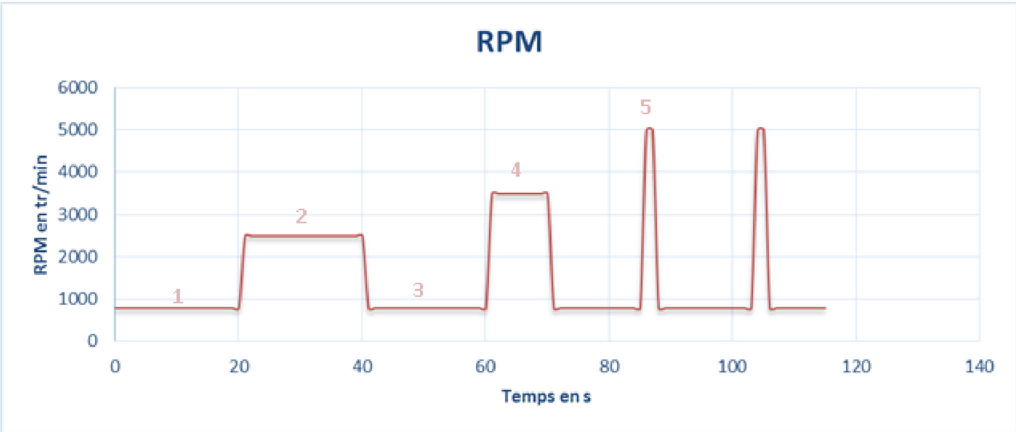


Figure 12 – "Capelec" cycle to test EGR. (reproduced by kind permission of Capelec).

1: 20s at Idle rpm : acquisition of NO_{x1}, rpm and Engine filling ratio ρ_1
2: 20s at Fast Idle rpm (2500 rpm): acquisition of NO_{x2}, rpm and Engine filling ratio ρ_2
3: 20s at Idle rpm: acquisition NO_{x3}, rpm and Engine filling ratio ρ_3
4: 10s at high rpm level (> 3500 rpm): acquisition NO_{x4}, rpm and Engine filling ratio ρ_4
5: 2 free acceleration: maximum pic NO_{x51} and NO_{x52}, rpm, Engine filling ratio pic ρ_{51} and ρ_{52}

During each of the procedural stages the rpm is monitored via OBD. The user will be informed with a colour code regarding live rpm value validating (or not) the rpm for each particular stage. A valid rpm is required in order to validate each stage and each stage transition. In stage 4, a minimum of 5s at 3500 rpm is needed. In case of rpm limited vehicles the procedure will nevertheless go further on to the next stages (possible in stages 4 and 5), with a remark if the rpm was not validated. Evaluations based on the engine filling ratio as well as on the NO_x values are taken into consideration and are described in detail in annex 4.

AVL propose the following test procedure:

- Coolant temperature: >80°C
- The engine has to be accelerated within the defined scatter band (red lines of Figure 13). The acceleration from idle speed to approx. 2500rpm should be done constantly within 4 – 11 seconds.
- Keeping the rpm stable at 2500rpm for about 5-6 seconds
- Immediate release of the gas paddle after this 5-6 seconds

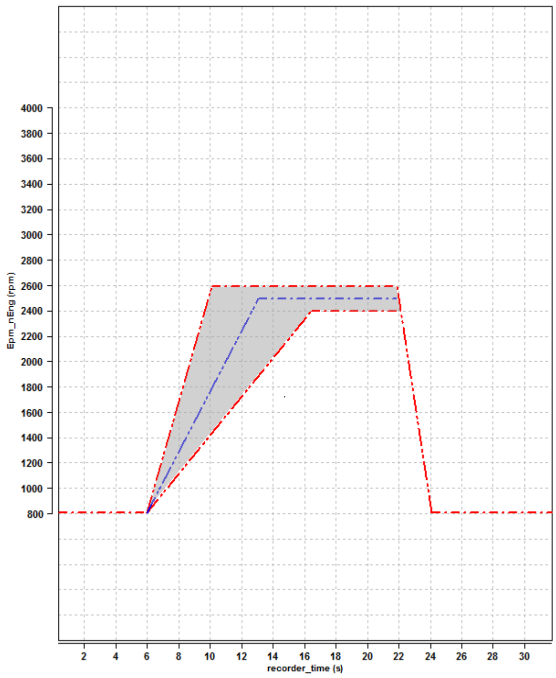


Figure 13 – AVL unloaded idle cycle for NO_x measurement. (Taken from Schweiger, 2016).

The maximum NO_x value, during this idle acceleration is measured.

For the static method, the AVL method was considered. This process can be carried out in a short time, and is very similar to today's emission analysis and is therefore applicable without too much effort.

For completion, Remote Sensing (RSD) and On-road Heavy-duty Emissions Monitoring System (OHMS) are also identified as possible test procedures, but more to assist or facilitate the PTI. Remote sensing is described in the annex 4.

3.2. Lab tests

The outcome of the international review gave some test methods suitable for our research. The objects for the LabTest were the follows:

- ASM2050 and DT80 ➔ Dynometer for engine load simulation
  (DT80 Test method was excluded after the first evaluation, because the DT80 did not offer any greater accuracy or results compared to the ASM2050);
- unloaded test – focus on EGR Valve, created be Capelec and AVL;
- short test ride, approximately 100m acceleration and stopping distance with a mobile measurement device (PEMS) on board.

Three (3) different Labs participated in the study.

- DEKRA;
- TÜV NORD;
- TÜV SÜD.

Ten (10) Different vehicles have been tested under the same conditions (See the vehicle technical description at the annex of each lab). Vehicles were tested with and without a failure simulation.

3.2.1. Capability to detect a failure in the emission control system, mainly the EGR system

The different test methods were evaluated during the lab tests, using different vehicles without any defects affecting the emissions control system and then retested with an installed defect affecting the NO_X emissions to simulate a failure. The ratio between both these situations gives a good idea of the quality of detecting failures in the emission control system. The ratio is calculated as the measurement with the defect divided by the measurement without the defect.

The defects installed are clearly manipulated, and are simulating failure results that could be possible either by aging or by fraud. We do not want to go into a discussion as to whether these failures are realistic or could happen in real life. The goal of these tests was to see if a test method could clearly identify a defect, which when present, would create higher NO_X emissions when driving with the vehicle.

Some of the failures installed were the following:

- Manipulation of the EGR-system by blocking it. Only a small hole (4mm) was open.
- Manipulation of the EGR-system by removing a temperature sensor, so that a part of the recirculated exhaust gas is blowing out into the atmosphere and not entering the intake air of the engine. As a result, the EGR-rate is reduced. (By comparison with the other vehicles, this defect is a relatively small defect).
- Manipulation of the EGR-system by reducing the exhaust tube to the air intake with a simple plate out of metal and with a hole (4 mm) drilled through the middle.
- Disconnecting the mass air flow sensor (MAF) which determines the mass flow rate of air entering the diesel-injected internal combustion engine. Disconnecting the MAF causes the engine to operate with a different composition of air and diesel.
- Disconnecting the EGR valve. It was unfortunately not possible to determine the position of the EGR valve, after disconnecting it.

3.2.1.1. The Loaded tests ASM2050 and DT80

3.2.1.1.1. The influence of load

The DEKRA lab investigated the influence of load for the ASM2050 and the DT80 test cycle.

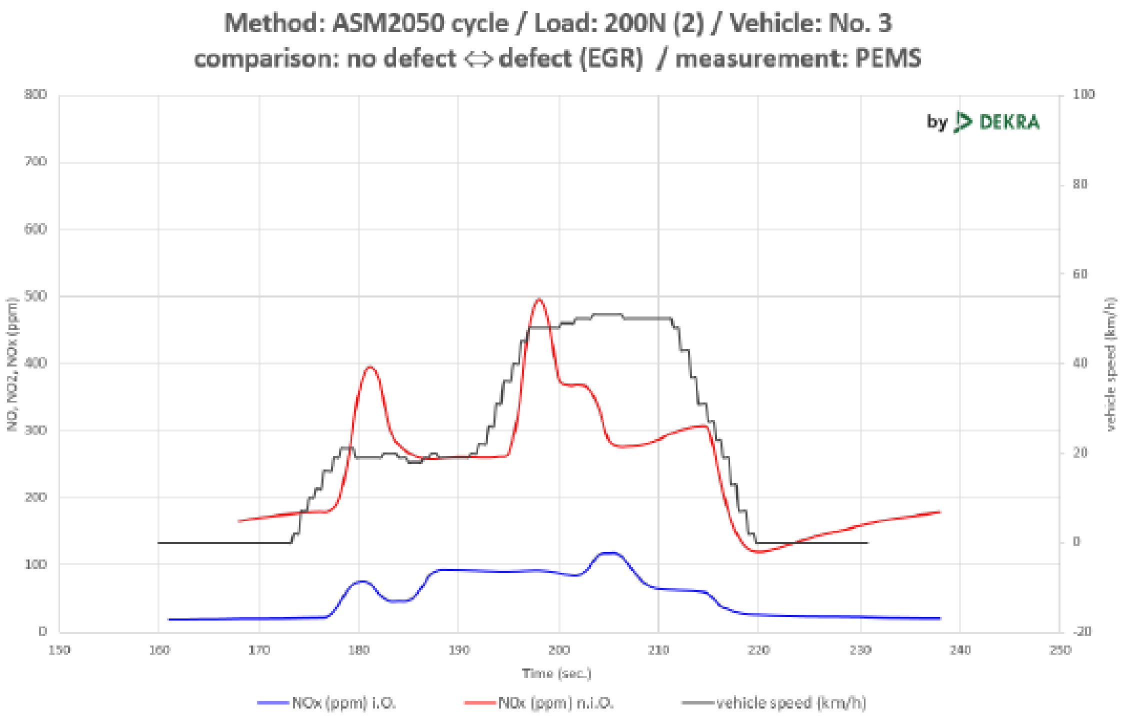


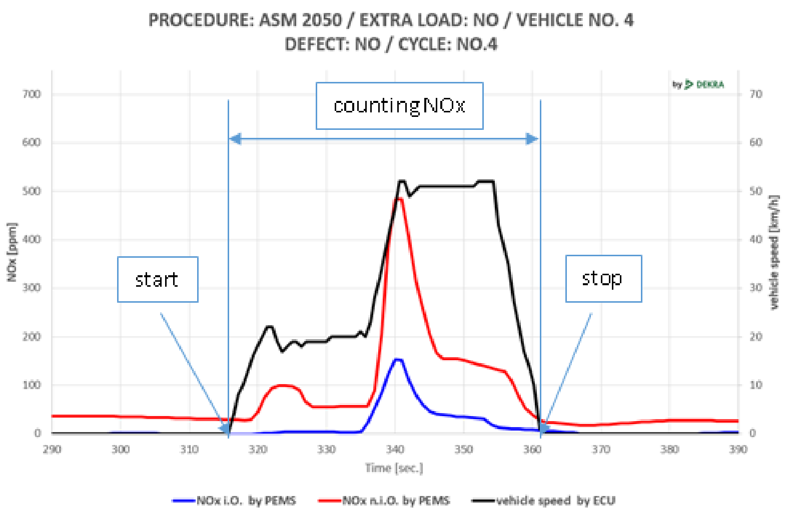
Figure 14 – ASM2050 with (n.i.O.) and without (i.O.) defect.
(n.i.O.= “nicht in Ordnung” = Not OK and i.O.= “in Ordnung” = OK)

RATIO for ASM2050 test cycle	LOAD			
	200 N	400 N	600 N	800 N
Ratio	3,8	4,1	4,3	3,6

Table 5- Ratio ASM2050 test cycle.

The ratio is calculated as the NO_X measurement with a simulated failure divided by the NO_X measurement without the failure.

Dekra measured the NO_X value as an average value over the period as explained in the next graph.
The driving cycles (dyno) are exactly defined in terms of their duration (as well as the vehicle speed and, if applicable, the gear ratio). Thus, the evaluation can be defined exactly in time the measured values relevant for the evaluation were counted as soon as the vehicle speed is > 0 km/h and ends as soon as the vehicle speed has again reached the value 0 km/h. (Figure 15). For the DT80-Cycles the two idle phases (D-E and G-H, each 10 seconds) are recorded. As the triggering rate of every measuring device is constant, it is important, that the number of measuring points is exactly the same for each cycle so that the cycles can be compared with each other.



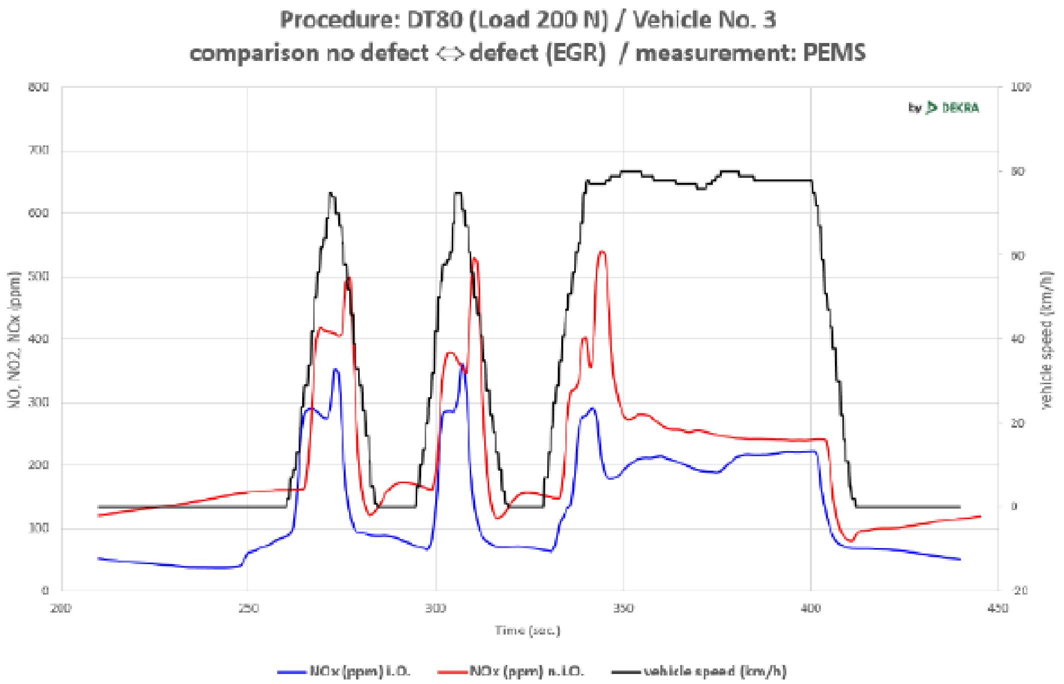


Figure 16 – DT80 with and without defect.
(n.i.O.= “nicht in Ordnung” = Not OK and i.O.= “in Ordnung” = OK)

RATIO for DT80 test cycle	LOAD			
	200 N	400 N	600 N	800 N
Ratio	1,5	1,3	1,2	1,2

Table 6- Ratio DT80 test cycle.

The ratio is calculated as the NO_X measurement with a simulated failure divided by the NO_X measurement without the failure.

It was considered, that these ratios, do not give enough of a significant difference in order to detect failures in the emission control system at low load as well as at higher load.

3.2.1.1.2. The influence of speed (20 km/h versus 50 km/h)

Introduced Failure	Vehicle without failure NO_x (ppm)		Vehicle with introduced failure NO_x (ppm)	
	20 km/h	50 km/h	20 km/h	50 km/h
MAF disconnected	**112,5**	**693,4**	**534,2**	**725,6**
EGR disconnected	**112,5**	**693,4**	**244,1**	**440,5**
EGR disconnected	**31,6**	**358,9**	**335,5**	**707,4**
EGR disconnected	**115,2**	**365,8**	**345,8**	**556,3**

Table 7- NO_x measurments during ASM2050 test cycle of 4 vehicles with and without failures at 20km/h and 50 km/h.

The same overall results for the different test cycles can be found during the TÜV SÜD lab tests, although the TÜV SÜD lab took the peak value of the NO_x measurement.

Test cycle	ASM2050	
	20 km/h	50 km/h
MAF disconnected	**5**	**1,05**
EGR disconnected	**5-10**	**2**
MAF / EGR disconnected	**2**	**1,5**

Table 8- Ratio's TÜV SÜD Lab.

The ratio is calculated as the NO_x measurement with a simulated failure divided by the NO_x measurement without the failure.

3.2.1.1.3. The Comparison of the ASM2050 variants

Two variants of the ASM2050 cycle were described in the literature review (Pando, 2016).
Since vehicles with automatic transmission were also available for testing, a third variant was also added. In variant 1, the cycle is driven from the point T2 in second gear to the end. In variant 2, the second gear changes to third gear at point T4, so that the 50 km/h are driven in third gear. The third variant, which can be run exclusively with automatic transmission equipped vehicles, provides that the test cycle in selector lever position D (Drive) of the transmission is selected throughout the process. Variant 1 and 2 are driven for vehicles with automatic transmission, depending on the equipment, in selector lever position M (manual) and either with the gear knob in the default gear position switched (M1, 2 or M1, 2, 3) or via shift paddles on the steering wheel.

This Evaluation compares the measurement results of ASM2050 M12 (Variant 1), ASM2050 M123 (Variant 2) and ASM2050 A (Variant 3) for each tested vehicle done by the TÜV SÜD lab.

Initially, the individual variants for each vehicle are considered.
On vehicle 1, a NO_X peak value of 250.7 ppm during acceleration to 20 km/h and acceleration to a further 50 km/h a NO_X peak value of 638.5 ppm could be measured when measuring the ASM2050 M12. In the subsequent measurement of the ASM2050 M123 when reaching the speed of 20 km/h, a NO_X value of 357.5 ppm and when reaching the speed of 50 km/h a NO_X value of 458.0 ppm was found. Since the vehicle was equipped with automatic transmission, variant 3, the ASM2050 A, was completed. At a speed of 20 km/h, this resulted in nitrogen oxide peak emissions of 294.8 ppm and at a speed of 50 km/h emissions of 1053.4 ppm.
Vehicle 2 was measured in the same order as vehicle 1. However, variant 3 was not feasible due to the manual transmission. Measurement of the ASM2050 M12 resulted in NO_X emissions of 116.5 ppm during acceleration to 20 km / h and 766.2 ppm in acceleration to 50 km / h. In variant 2, the ASM2050 M123, a NO_X value of 108.0 ppm was found at a speed of 20 km/h and at the speed of 50 km/h an NO_X value of 620.6 ppm.

In the following, vehicle 3, analogous to vehicle 2, was subjected to the ASM2050 procedure. First, the ASM2050 M12 was driven again and it resulted in the acceleration to 20 km/h NO_X emissions of 24.3 ppm in the onward journey to 50 km/h, an output of 420.5 ppm. The ASM2050 M123 emitted 39.0 ppm of nitrogen oxide at 20 km/h and 296.9 ppm at 50 km/h. Again, analogous to vehicle 2, due to the gearbox no ASM2050 A was driven. Finally, vehicle 4 was again started with the ASM2050 M12. For this, an acceleration to 20 km/h resulted in an NO_X value of 125.2 ppm and an acceleration to 50 km/h resulted in an NO_X value of 313.0 ppm. Subsequently, variant 2, the ASM2050 M123, was carried out and produced at a speed of 20 km/h, a NO_X emissions of 123.0 ppm and at a speed of 50 km/h, an output of 297.7 ppm. Since vehicle 4 was equipped with an automatic transmission, the ASM2050 M could be additionally carried out on this vehicle. At 20 km/h, a nitrogen oxide output of 97.3 ppm and at 50 km/h a nitrogen oxide output of 486.8 ppm could be measured.

Comparing the different variants among the individual vehicles, the following result can be derived:
For vehicles with automatic transmission, it is easier to drive the ASM2050 cycle in the usual selector lever position D (variant 3: ASM2050 A). There were no major differences in the NO_X emissions among the individual variants. Only the NO_X value of 1053.4 ppm in variant 3 on vehicle 1 is out of line. For this, the emission class Euro 5 or the built four-wheel drive could be the cause.

Vehicle	M12 (Variante 1) NO_x peak value [ppm]		M123 (Variante 2) NO_x peak value [ppm]		A (Variante 3) NO_x peak value [ppm]	
	20 km/h	50 km/h	20 km/h	50 km/h	20 km/h	50 km/h
1	250,7	638,5	357,5	458,0	294,8	1053,4
2	116,5	766,2	108,0	620,6	-	-
3	24,3	420,5	39,0	296,9	-	-
4	125,2	313,0	123,0	297,7	97,3	486,8

Table 9- Compairison of different ASM2050 test variants.

These findings were confirmed by the TÜV NORD lab. See also annex 5.

3.2.1.2. The Capelec test cycle

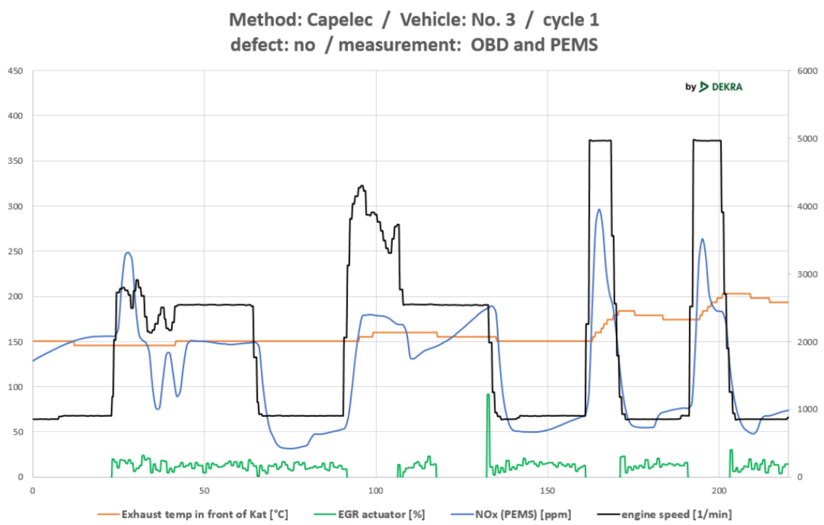


Figure 17 – Capelec cycle with and without defect.

RATIO for Capelec test cycle	NO_x measured via PEMS	NO_x measured via AVL equipment
Ratio	**1,2**	**1,2**

Table 10- Ratio for Capelec test cycle.

The ratio is calculated as the NO_x measurement (Average value) with a simulated failure divided by the NO_x measurement without the failure.

3.2.1.3. The AVL test cycle

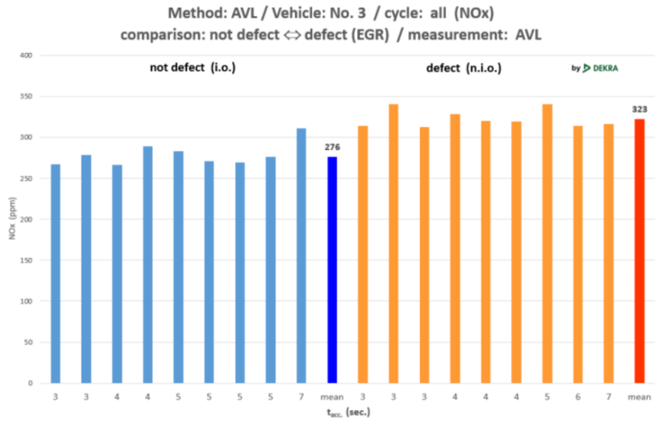


Figure 18 – AVL cycle with and without defect.
(n.i.O.= “nicht in Ordnung” = Not OK and i.O.= “in Ordnung” = OK)

RATIO for AVL test cycle	NO_X measured via PEMS	NO_X measured via AVL equipment
Ratio	**1,2**	**1,2**

Table 11- Ratio for AVL test cycle.

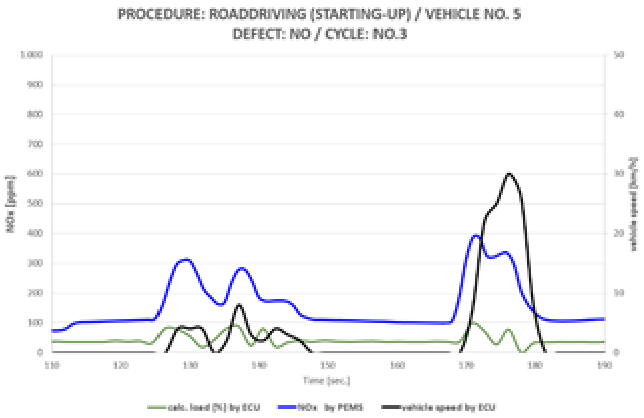
The ratio is calculated as the NO_X measurement (average value) with a simulated failure divided by the NO_X measurement without the failure.

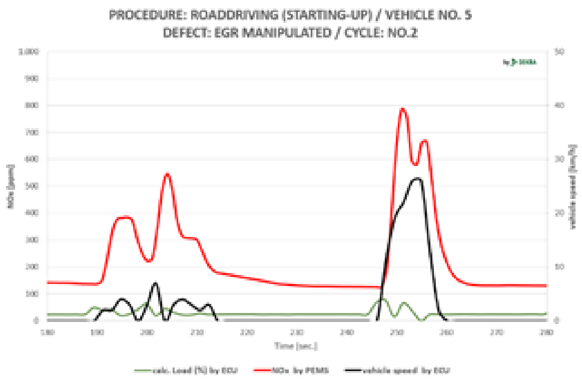
3.2.1.4. The Short Test Drive

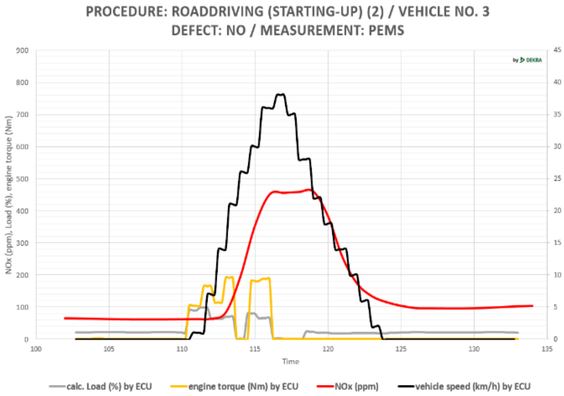
Figure 19 – short test drive – test lane.

Every “cycle” was a short rank (maneuver) for positioning the vehicle in the right direction/change the direction and after this an acceleration up to 30 km/h (target).

Figure 20 – Short test drive: prepared vehicle with PEMS equipment







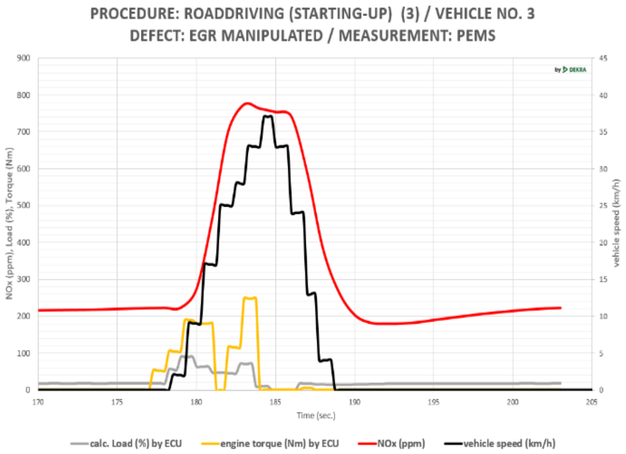


Figure 21 – Short test drive : Tests with and without defect.

During this short vehicle trip is the vehicle accelerated for a short time and a load is put on the engine. Repeatability and a safe method to do such a short trip is a key question.
The "load" (in %) for this tests (short vehicle trip) was taken out of the OBD and in the graphs declared as "load (%) calculated by ECU"). This is very easy and comfortable. Of cause this "load" is not measured, but calculated by the engine management out of different parameters (mostly intake air mass, temperature, and others, ...). Unfortunatelly it is not defined/standardized and for this not clear how the load is calculated out of the OBD and what parameters are included.
The investigated vehicles are too less, but different values for different vehicles/manufacturers are to be seen. The load out of the OBD is a very rough quantitatively information.

RATIO for SHORT TEST DRIVE test cycle	PEMS	AVL
Ratio	**1,8**	**1,8**

Table 12- Ratio for short test drive test cycle.

For the evaluation of each test drive the mean NO_X value over the cycle was taken. The Ratio is approximately 1,8 taking in account the variety of load and dynamic conditions, it might differ, but it is significant to be recorded

Also for very low vehicle speed (< 10 km/h) a significant higher mean NO_X value was measured.

3.2.1.5. Resume

Test cycle	Ratio
ASM Method	**4**
DT80	**1,5**
unloaded	**1,2**
Short test ride	**1,8**

Table 13- Summary ratios in function of the different test cycles.

The ratio is calculated as the NOX mean measurement with a simulated failure divided by the NOX mean measurement without the failure.

The same overall results for the different test cycles can be found during the TÜV SÜD lab tests. Although here the peak value was taken.

Test cycle	AVL	ASM2050	
		20 km/h	50 km/h
Euro 5 / Euro 6	**1,2**	**3**	**2**
MAF disconnected	**2**	**5**	**1,05**
EGR disconnected	**1,2-1,5**	**5-10**	**2**
MAF and EGR disconnected	**1,5**	**2**	**1,5**

Table 14- Ratio's TÜV SÜD Lab.

The ratio is calculated as the NOX measurement with a simulated failure divided by the NOX measurement without the failure.

There is only one test method that gives a significant ratio difference; and thus is able to detect errors in the emission control system, related to NO_x emissions. It is clear that for lower ratios the impact of other test conditions is important, as otherwise a change in these conditions will be in the range of both tests results (failure or no failure).

3.2.2. Comparison of test procedures

When comparing the identified potential test methods, not only was the ability to find a failure in the emission system evaluated. The following were evaluated as well:

- Time and investment needed;
- Overall accuracy of the method;
- Applicable for all vehicle types.

Time and investment are two significant parameters in the matter of costs for implementing such a change. A more decentralised system may have a singnificant interest in the cost of the equipment and the cost of the test, due the potentially low volume of vehicles inspected. Centralised systems may be in a better position to justify these costs due to the increased volume of vehicles they inspect. However, on the other hand, inspection time may be more important to them. Inspection time is related not only on the labour cost for organisations with a centralised system, also the lead time of an inspection is quite important. The lead time for each zone in the periodic technical inspection production chain can in some cases be less than 5 minutes. So tests with a test time of more than 5 minutes can be quite costly for these organisations.

Criteria	Spheretech	Capelec	AVL	DT 80	ASM2050	Short Test Ride
Ability to detect failures of different emission systems	X	X	X	XXX	XXX	XX
Over all accuracy of method	X	X	X	XX	XX	X
Applicable for all vehicles	XX	XX	XX	XXX	XXX	XX
Time and Investment needed	XXX	XXX	XXX	X	XX	XX
XXX = very positive **XX** = positive **X** = partially positive						

Table 15- compairisant of test methods – general findings.

3.2.3. Discussion of the Lab test results

Although the DT80 cycle was only used as a test cycle for diesel vehicles at the begining of our study, we have achieved better results with the ASM2050 cycle in the ability to detect errors in the emission control system. Furthermore, these loaded tests have a sufficient accuracy and good repeatability. The DT80 Test method was excluded after the first evaluation, because compared to the ASM2050, the DT80 is not offering more accuracy or better results.

Four wheel drive vehicles present challenges for loaded tests, where double rollers have to be installed in order to test these vehicles. During the lean NO_X trap generation, extreme high emissions on NO_X (up to 10 times higher) can be measured. We could alternatively measure at 4000 ppm instead of 300 or 400 ppm for several seconds.

It can be clearly stated that already an acceleration of 20 km/h provides a higher level of information about nitrogen oxide emissions in faulty vehicles, than the other evaluated methods. Thus, the focus for future field tests could be on an acceleration of 20 km/h. After an applicable number of further measurements, it can then be decided whether the acceleration to 20 km/h provides sufficient information or the second phase with an acceleration up to 50km/h is still needed.
Furthermore, the results provide the insight that there is no significant difference between the variants to drive the ASM2050. Consequently, it is not relevant for further investigations to shift from second gear to third gear before acceleration to 50 km/h. Again, due to the small measurements, this statement should be checked in further field trials.

The difference between Euro 5 and Euro 6 from all ASM2050 variants were also calculated. The Euro 5 emission class has average NO_X emissions of 301.0 ppm at 20 km/h and average emissions of 716.5 ppm at 50 km/h. The average emission of the Euro 6 vehicles, combined with the driven variants 1, 2 and 3, is 90.5 ppm at 20 km/h and 368.7 ppm at 50 km/h.

The unloaded tests only have a ratio of 1.2 between a vehicle with and without a failure in the emission system. The evaluations show that it is possible to differentiate between vehicles with different emission classes and thus also between fully functional after-treatment systems and faulty vehicles with a typical combustion or with non-functioning exhaust aftertreatment systems. In order to be able to make a valid statement about the measuring method, only the small difference between the emitted nitrogen oxides between an acceptable vehicle and a defective vehicle was observed so could be criticised. For these low ratio's it is important to known the impact of other test conditions. These unloaded test's (AVL, Capelec, Spheretech) are working but, with a less significant indication for failure at the engine system. Furthermore, the Capelec test is focusing on the EGR function and thus less suitable for the other aftertreatment systems.

By comparing the emission Euro 5 class with the Euro 6 (average values of three vehicles) it can be deduced that with the AVL method there is a minimal significant difference in higher nitrogen oxides in a Euro 5 vehicle compared to a Euro 6 vehicle. The Euro 5 had an average NO_X emission of 131.5 ppm. The average emissions of the Euro 6 were 112.5 ppm. Since the emission class Euro 5 provides for a higher limit value for the individual vehicles compared to the emission class Euro 6, it needs to be investigated by further field tests whether the difference from Euro 5 to Euro 6 is constant at this level.

Due to the few lab measurements, these unloaded test methods should be further investigated in detail during the field tests. Despite the small difference in the individual measurement results, the unloaded test method in terms of simplicity to implement into today's PTI regime. These tests could be a future cheap and quick alternative.

The short test ride with a PEMS emission measurement during a 50m to 100m acceleration and stopping distance, has shown to work. However, sufficient safe space is needed within the PTI stations locality. Today not all PTI inspection procedures in Europe have a driving test in their regime. Furthermore, repeatability is a challenge. Based on the engine load and OBD data a reference relation can be calculated. The application of the PEMS measurement device is pending on the vehicle type. Mostly the PEMS can be installed at the trunk, but not for all vehicles.
The equipment is not that much more expensive when compared with the loaded test benches.

Finally, it is important to get information about the installed aftertreatment system and since temperature is significant for the level of concentration and the efficiency of the system in general, a minimum temperature has to be defined. Additional information related to the aftertreatment system could perhaps be obtained via the OBD system. On board measurement systems also seem to be accurate and reliable but these sensors are not defined by type approval so there is no guarantee that this information is always available.

In summary the following information would be required:

- Information about the aftertreatment systems installed (EGR/LNT/SCR);
- Temperature of the SCR catalyst
- NOx-sensor values
- Urea injection rate
- Activity of EGR valve
- Regeneration phase

3.3. Field tests

3.3.1. Field test setup

Fourteen (14) PTI organisations took part on the field test:

Project Partner	Country	Equipment
AMSS-CMV	Serbia	CAPELEC
Applus+	Spain	CAPELEC
Applus+	Spain	MAHA
Bilprovningen	Sweden	AVL
Certio ITV	Spain	CAPELEC
CVH	Republic of Croatia	MAHA
FSD	Germany	MAHA
General de Servicicios ITV, S.A.	Spain	CAPELEC
General de Servicicios ITV, S.A.	Spain	MAHA
Grupo Itevelesa	Spain	MAHA
ITVASA	Spain	AVL
Opus Bilprovning AB	Sweden	AVL
RDW	The Netherlands	AVL
SYC	Spain	MAHA
TÜV NORD	Germany	SPHERETECH
Veiasa	Spain	MAHA

Table 16- SET II project: Field test partners.

Seven hundred thirty five (735) tests were analysed. The distribution of these tests in relation to the test method can be found in Table 17.

Test Method	Equipment	# tested vehicles
AVL/CAPELEC	AVL	259
AVL/CAPELEC	Capelec	254
Spheretech	Spheretech / Bosch	9
ASM2050	MAHA	213

Table 17- SET II Distribution of the field tests in function of the analysed test method.

3.3.2. AVL Test Method

The output values of the AVL devices were used for the evaluation. Only complete data sets were used for the evaluation that met all of the following conditions:

a) All speeds are> 0
b) All averaged NOx values are> 0 ppm
c) The free acceleration is > 3000 rpm

A few vehicles were tested several times. These vehicles were isolated cases and treated as follows in the AVL procedure: if all the necessary measured values were available, the first measurement was used for the evaluation. The remaining measurements for this vehicle were exluded. The first measurement was used to corolate with all of the other vehicles for which there was only one measurement.

In the AVL method, there are no evaluation criteria so far. For this reason, the measured NO_X values were put into ratio and illustrated in the diagram (Figure 22). Each point in the diagram represents a vehicle.

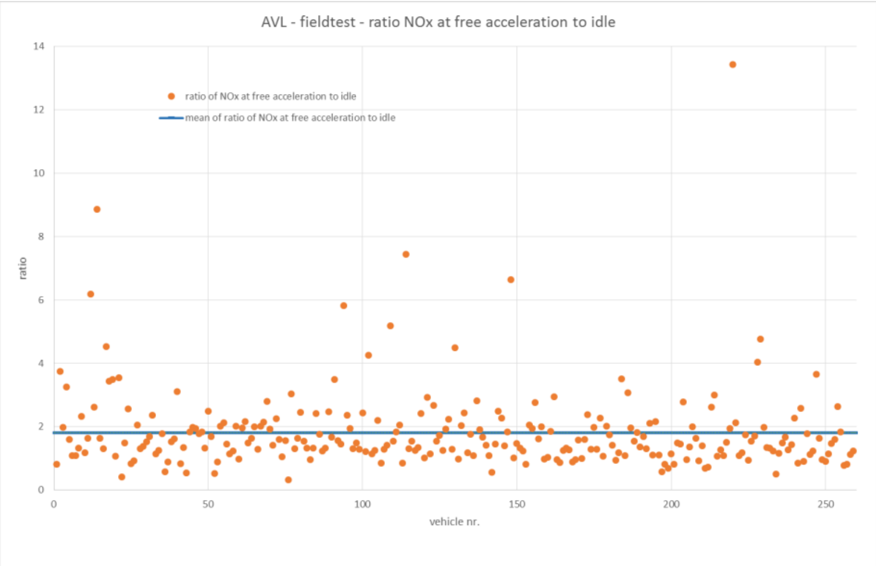


Figure 22 – The ratio of NO_X [ppm] at free acceleration to NOx [ppm] at idle and the associated mean.

As expected the NO_X concentration increases during the acceleration phase. Alarmingly there are a few vehicles exceeding the average ratio significantly. The ratio of the high idle measurements was on average lower, with hardly any vehicles exceeding the average values compared to the acceleration phase.

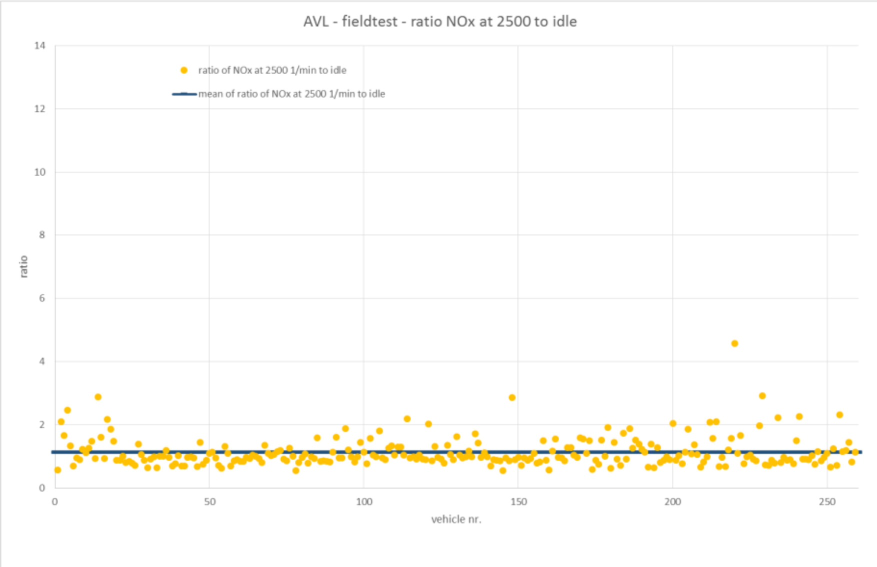


Figure 23 – The ratio of NOx [ppm] at ~ 2500 [1 / min] to NOx [ppm] at idle and the associated mean.

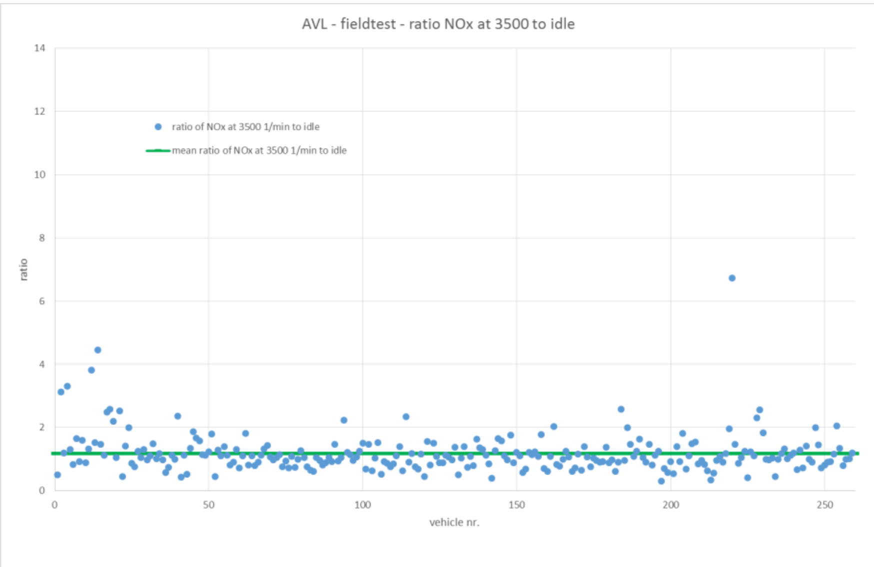


Figure 24 – The ratio of NOx [ppm] at ~ 3500 [1 / min] to NOx [ppm] at idle and the associated mean.

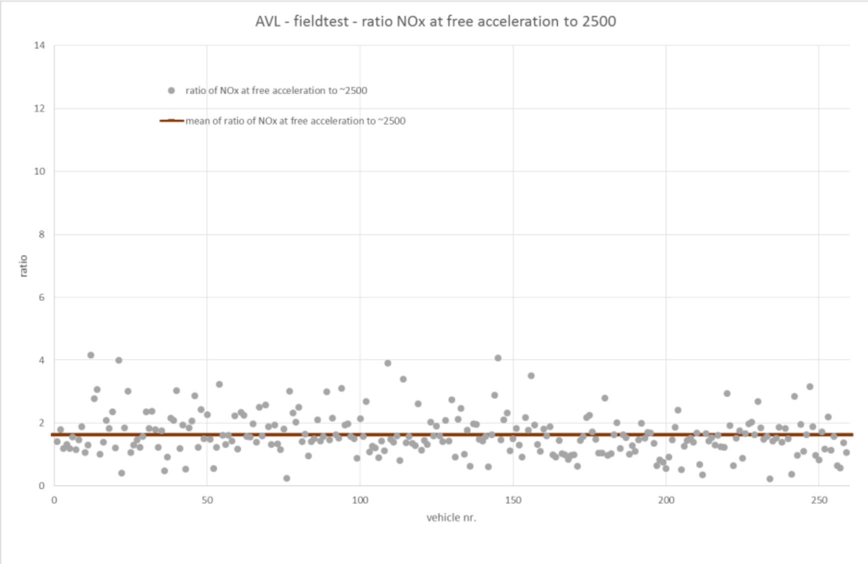


Figure 25 – The ratio of NOx [ppm] at free acceleration to NOx [ppm] at ~ 2500 [1 / min] and the associated mean value.

For almost all vehicles measured with the AVL method, the Euro classes were available. The following diagrams show a NO_X ratio at different speeds (ratio free acceleration to idle) and are divided into their Euro classes. For the free acceleration the mean of the 2 accelerations (NO_X peaks) were taken, and for the idle part the mean value of the idle part. The digits of the X-axis is the serial number of the vehicles (every dash means a vehicle).

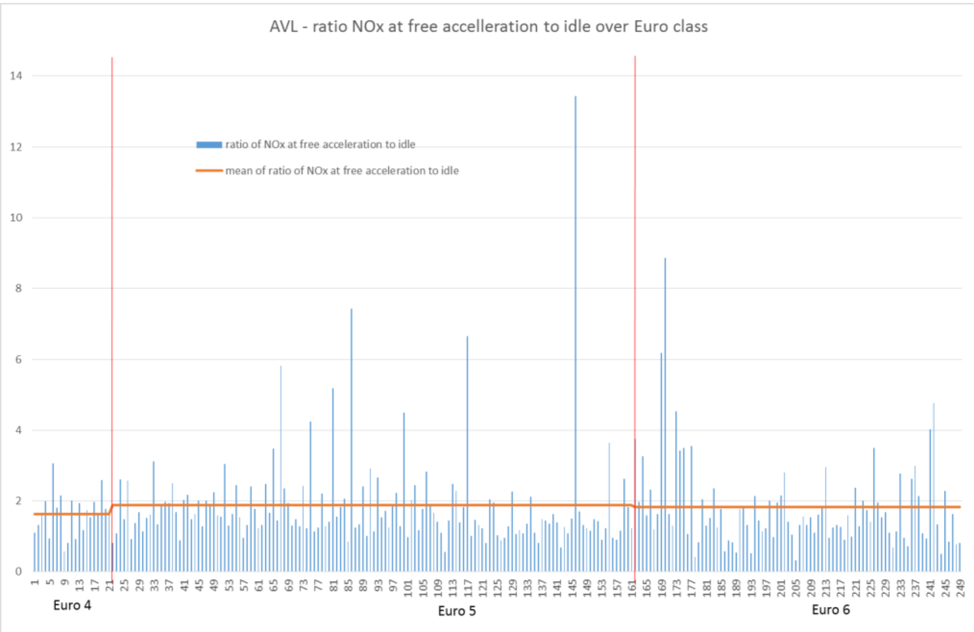


Figure 26 – The ratio of NOx [ppm] at free acceleration to NOx [ppm] at idle and the associated mean are distributed among the Euroclasses.

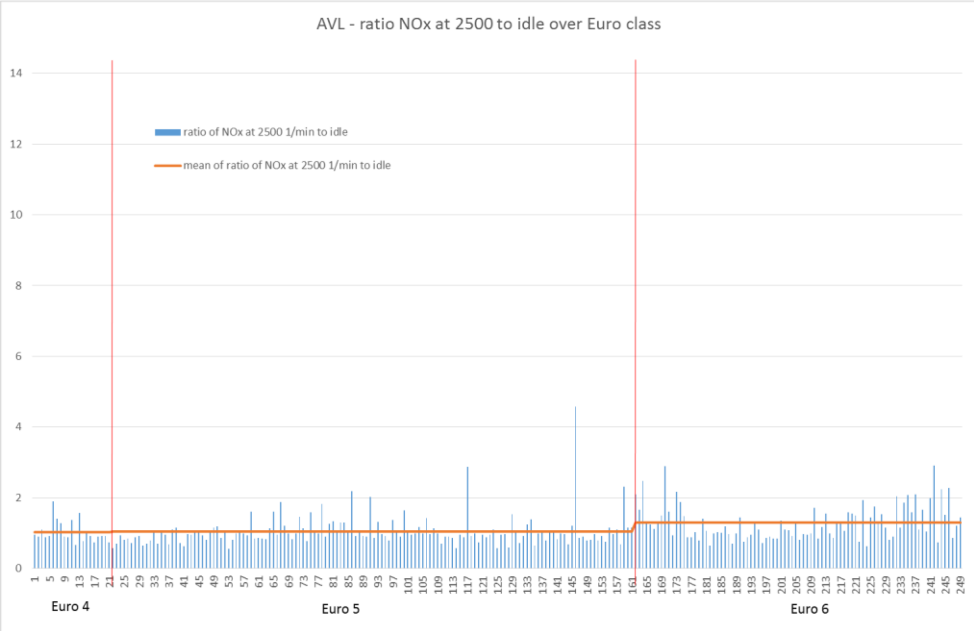


Figure 27 – The ratio of NOx [ppm] at ~ 2500 [1 / min] to NOx [ppm] at idle and the associated mean are distributed among the Euroclasses.

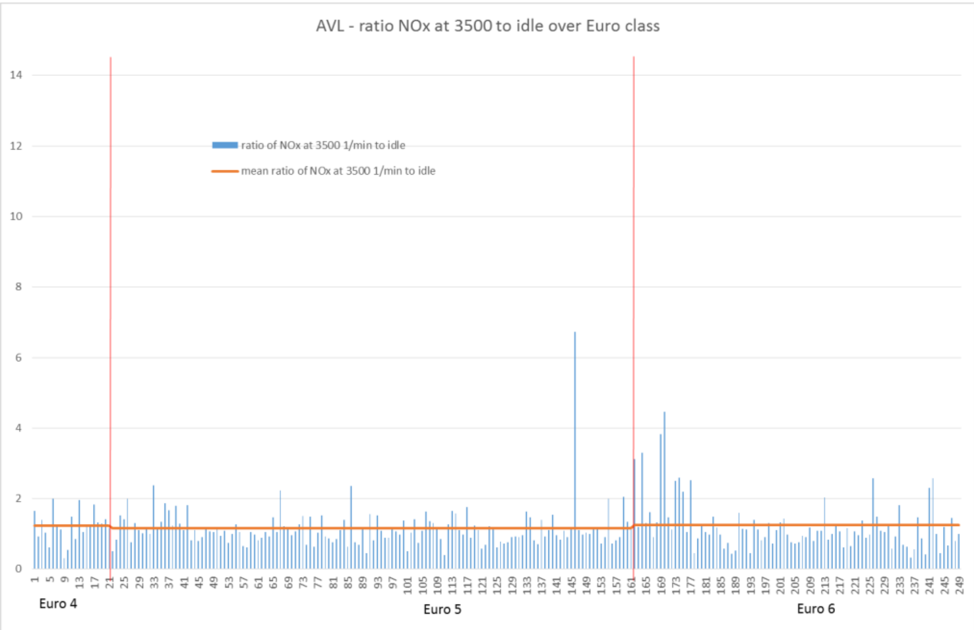


Figure 28 – The ratio of NOx [ppm] at ~ 3500 [1 / min] to NOx [ppm] at idle and the associated mean are distributed among the Euroclasses.

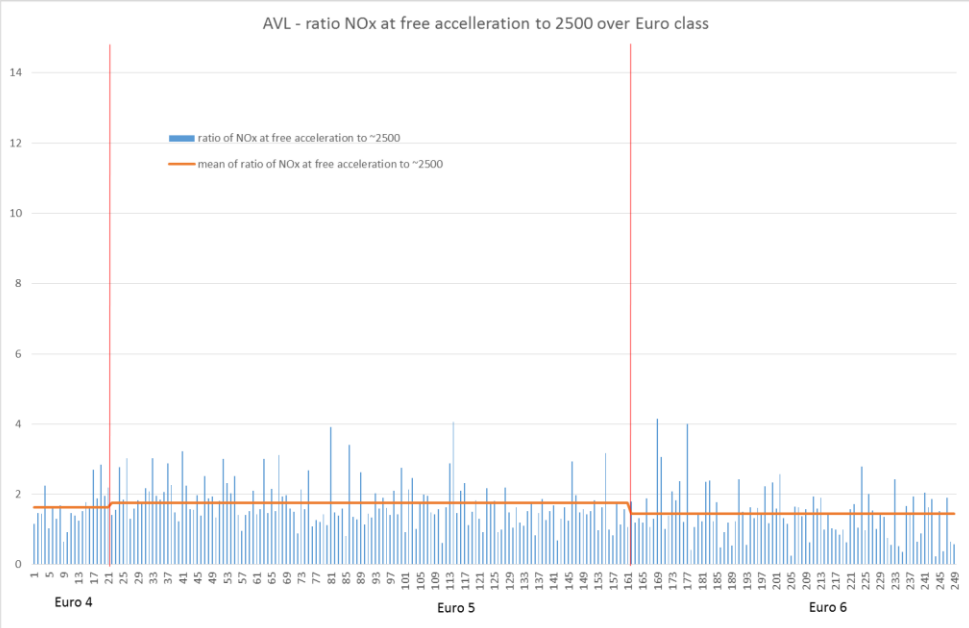


Figure 29 – The ratio of NOx [ppm] at free acceleration to NOx [ppm] at ~ 2500 [1 / min] and the associated mean are distributed among the Euroclasses.

AVL – method based on the difference between NO_X concentrations at different rpm conditions: the NO_X ratio (ratio of the NO_X value at free acceleration to NO_X value at idle) is compared and evaluated:

- AVL cycle focuses only on EGR-based aftertreatment systems
- Concentration NOx between 20 ppm and 370 ppm, average NOx concentration approx. 100 ppm
- NOx concentration even increasing from Euro 4 to Euro 6
- Further analysis for appropriate thresholds necessary

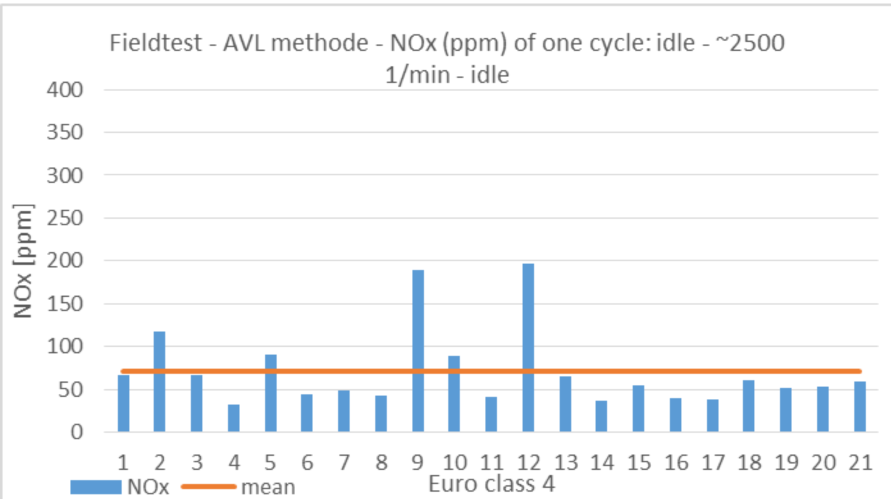


Figure 30 – The NOx [ppm] at 2500 rpm and the associated mean for the Euro 4 class vehicles.

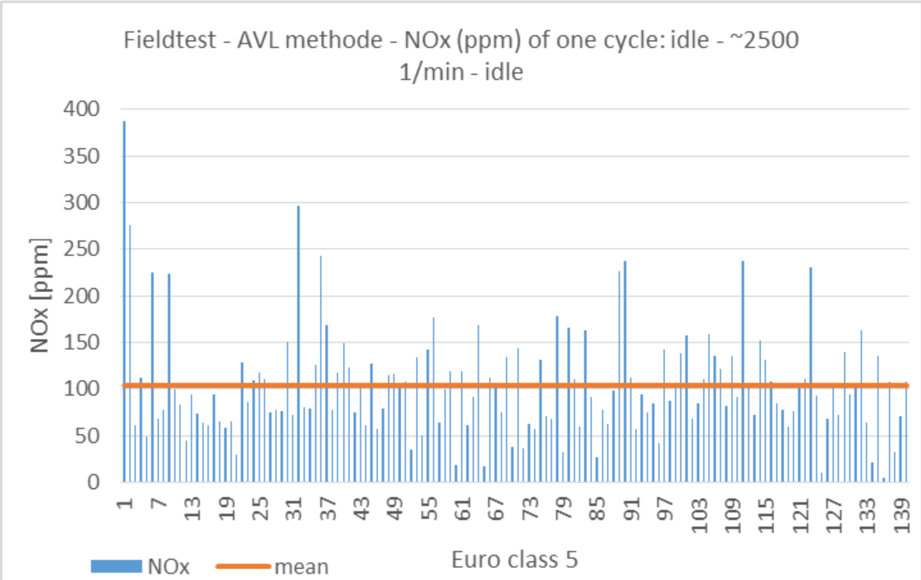


Figure 31 – The NOx [ppm] at 2500 rpm and the associated mean for the Euro 5 class vehicles

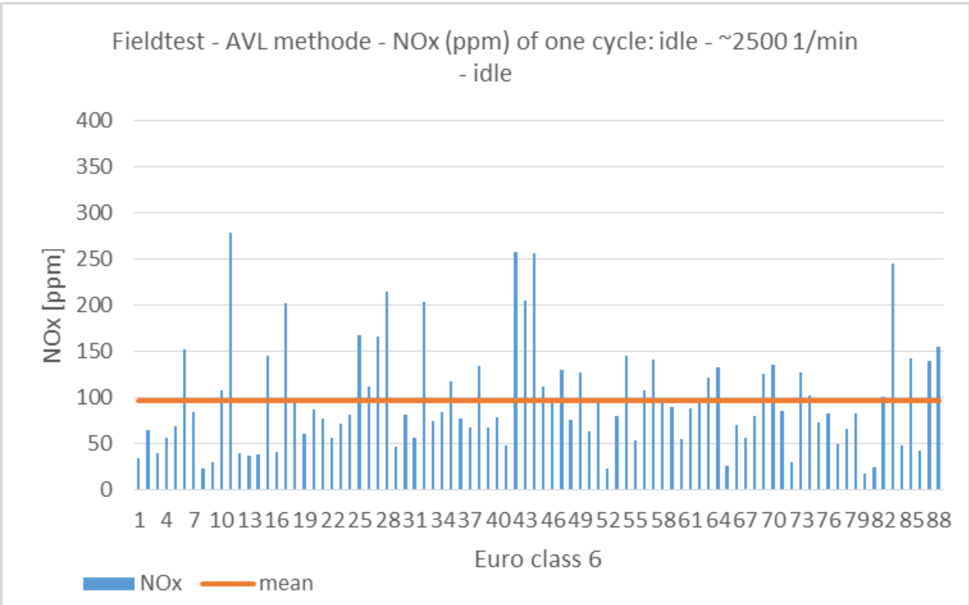


Figure 32 – The NOx [ppm] at 2500 rpm and the associated mean for the Euro 6 class vehicles

The most significant results show the ratio between acceleration phase and idle. It has been determined that there is a large spread of vehicles with low and high NOx concentration, independent of the Euro class.

Conclusion

The AVL measurement results show a huge spread, which makes it difficult to define a general threshold for a fail/pass criteria. Also, the absolute NOx concentrations are very low.

3.3.3. Capelec Test Method

The measured values of the Capelec device were used for the evaluation.

Only complete data sets were used that met all of the following conditions:

a) All speeds are > 0
b) All averaged NOx values are > 0 ppm
c) The free acceleration is> 3000 1/min

The same process as for the AVL was used in case of multiple tests for the same vehicle.

Capelec offers an evaluation method for the measurements. This method was applied to the measurements. In the following, the criteria and the evaluation method are described and the corresponding evaluation is presented.

The data sets were evaluated by means of algorithms by Capelec. It was done as follows.

Definition

Test sequence	Idle 1	High Idle	Idle 2	>3500
Filling	p1	p2	p3	p4
NOx	n1	n2	n3	n4

Criteria

	Egr close at high idle and open at idle	Egr close at idle 1 and close at idle 2	EGR open idle and high idle	EGR closed all along the cycle	EGR closed >3500
Scenario	Inverted EGR (R0)	Idle EGR (R1)	EGR ON (R2)	EGR OFF (R3)	Closing EGR (R4)
p1	< 0.75	> 0.75	< 0.75	> 0.75	X
p2	> 0.80	X	< 0.80	> 0.80	X
p3	< 0.75	< 0.75	< 0.75	> 0.75	X
p4	X	X	X	X	> 1.00

Algoritme 1

Closing EGR valve				
Filling (P1)	Conditions			Résult
	if	R3		0
	if not	R0		1
	if not	R4		1
	else			0

Algoritme 2

Opening EGR valve				
Filling (P2)	Conditions			Result
	if	R3		0
	if not	R0 ou R1		1
	if not	R2		1
	else			0

Algoritme 3

NOx on high idle and >3500 speed				
NOx High (N1)	Conditions			Result
	If	n4 > 500 ppm		0
	if not	n4/n2 > 2		1
		2 > n4/n2 > 1.5		0,5
		1.5 > n4/n2		0

Algoritme 4

	NOx on idle speed			
NOx Ral (N2)	Conditions			Result
	if	n1 et n3 < 50 ppm		1
	if not	n1/n3 > 1.5		1
		1.5 > n1/n3 > 1		0,5
		1 > n1/n3		0

Applicable criterion

Applicable Criterion	Car with RPM limited	Car with OBD not functional	Standard
P1			X
P2	X		X
N1		X	X
N2	X	X	X
Base	2	2	4

Final result

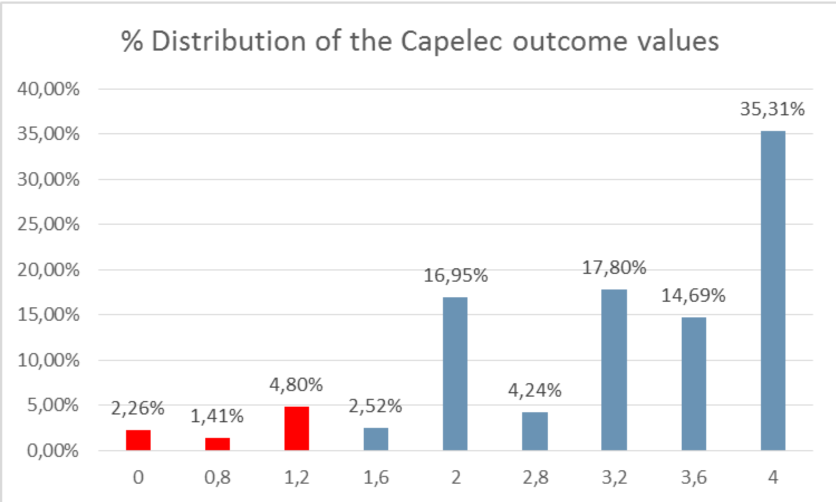


Figure 33 – Distribution of the Capelec outcome values (0 – 4)

The diagram shows the measurement results from bad (0) to good (4). This is the percentage of vehicles applied. In total, there are 254 vehicles analysed.

Conclusion

Although, this process can evaluate the EGR functionality, it cannot evaluate the other aftertreatment systems, like SCR. Also it is not always possible to conduct a free acceleration test on many vehicles due to them having a rpm limiter fitted.

3.3.4. Spheretech Test Method

For the Spheretech measurements the following cycle was planned

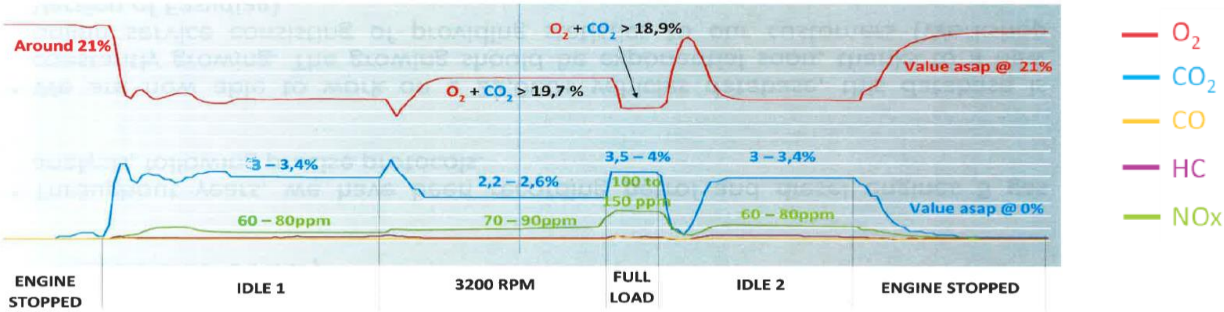


Figure 34 – The Spheretech cycle

Essentially, the measured values O_2, CO_2, NO_X should be recorded in different phases. The phases were the idling speed, the speed of 3200 rpm, full load and at the end at idle again. For this a diagram had to be created for each vehicle. For all usable measurements, the idling phases and the 3200 rpm phase were completed. Only four measurements at the full load phase were usable, since some vehicles block their rpm. Only the measurements were the high idle speed was in the range of 3200 + /- 300 rpm. were considered. Some measurements had far different speeds e.g. 2500 rpm. and thus, were not taken in account. In total, only nine measurements were considered usable and evaluated. The method proposed by Spheretech to add O_2 + CO_2 was used to create a diagram.

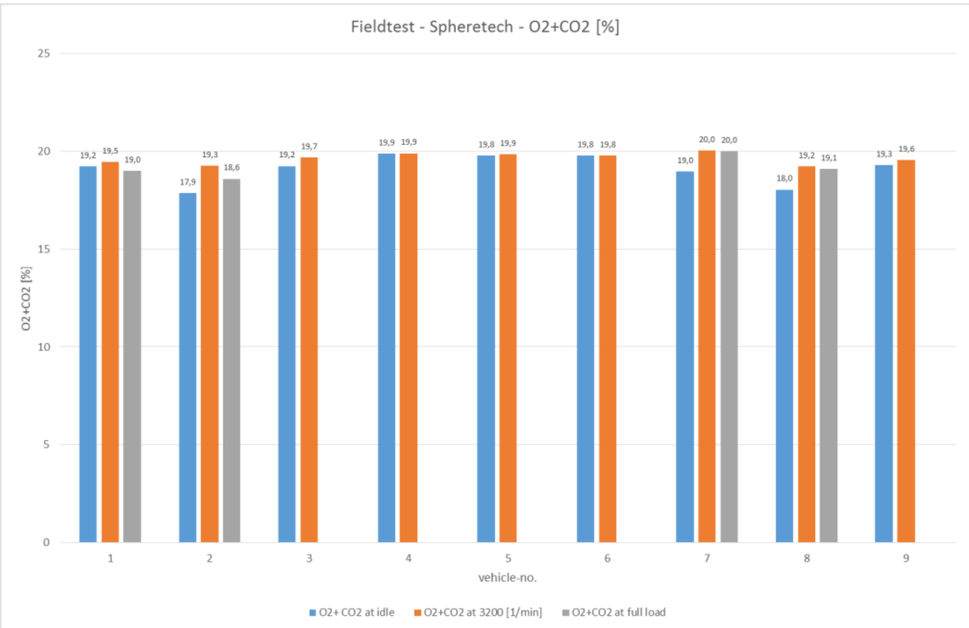


Figure 35 – Spheretech cycle : O_2+CO_2 at different rpm

According to Spheretech, an evaluation is possible for the values shown in the diagram as follows:

An engine lacking of air is over consuming fuel and becomes highly polluting. For example, we can use this simple O_2 + CO_2 to determine if:

- O2 + CO2 around 20,2% = Perfect air filling capacity (new vehicle)
- O2 + CO2 > 19,7% = Good air filling capacity for «old» vehicles
- O2 + CO2 < 19,6% = The engine is suffering from a lack of air and is highly polluting

Another diagram shows the NOx emissions at idle, at 3200 rpm and full load (where available).

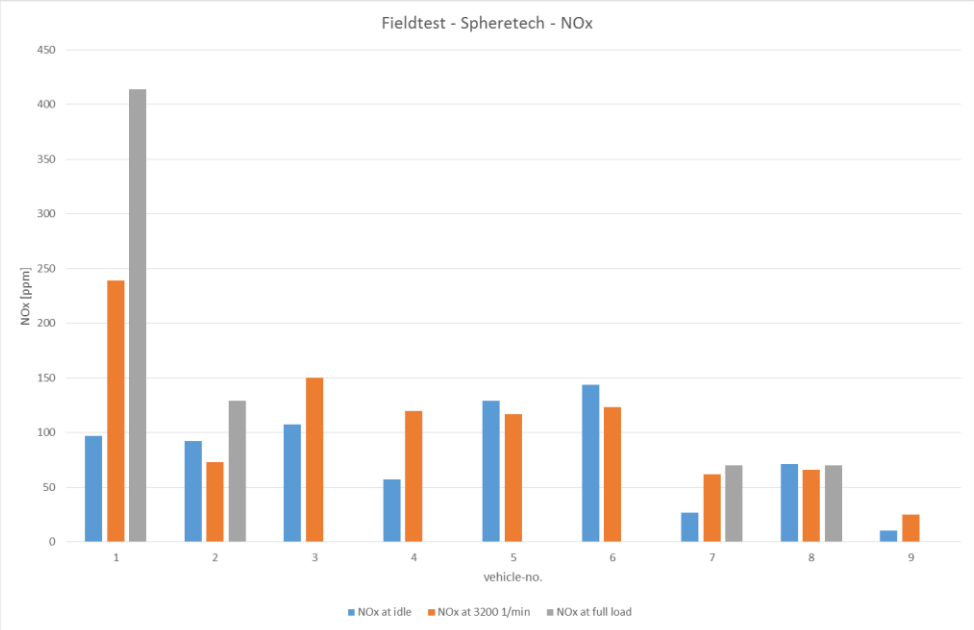


Figure 36 – Spheretech cycle : The NOx [ppm] at different rpm

3.3.5. ASM2050 Test Method

The ASM2050 measurements had two cycles. However, some field test partners have driven only one cycle per measurement and have taken several measurements on one vehicle. Since this was partner-dependent and the measurements involved a lot of effort, all measurements were included in the evaluation.

Only the records that met all of the following conditions were used:

- 45 speed values greater than 0 km/h (resulting from the cycle times) and
- > 5 NOx values greater than 0 ppm (5 or less NO_X values greater than 0 ppm is hardly technically possible).

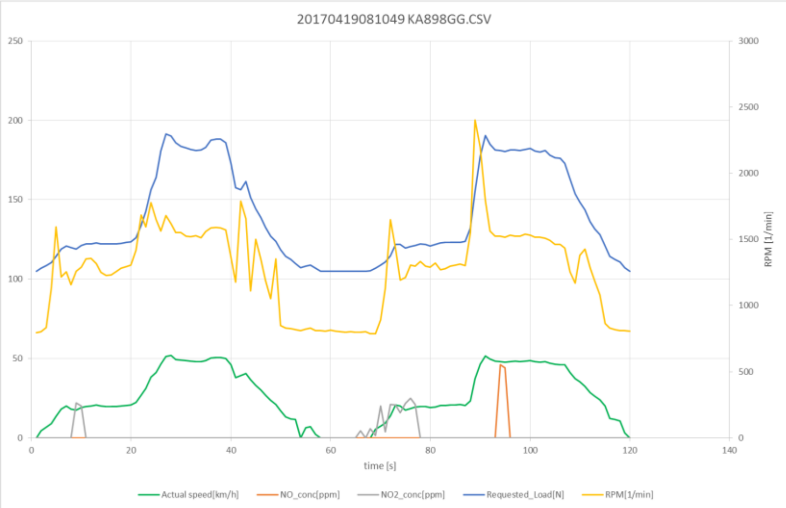


Figure 37 – ASM2050 - Example of a faulty NO_X measurement with two driven cycles

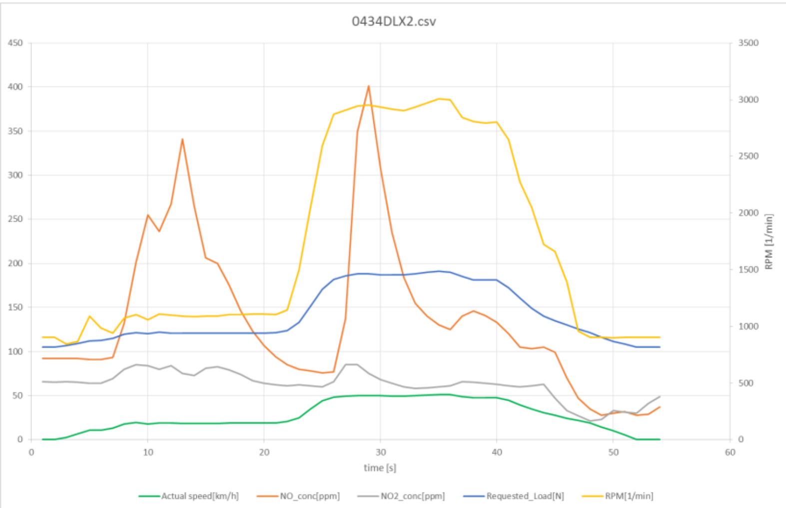


Figure 38 – Example of a good measurement with two driven cycles, all values are acceptable

The measurements are for each cycle evaluated by calculating the mean value from the NO_X values (the average from the stationary part). All cycles of a vehicle were added together and also averaged. For example, in a vehicle, if five cycle of measurements were taken, the NOx averages of the five measurements were averaged for the result.

So far, there are no special evaluation criteria for the ASM2050. Therefore, the measured NO_X values are shown in diagrams (Figure 39 and Figure 40).

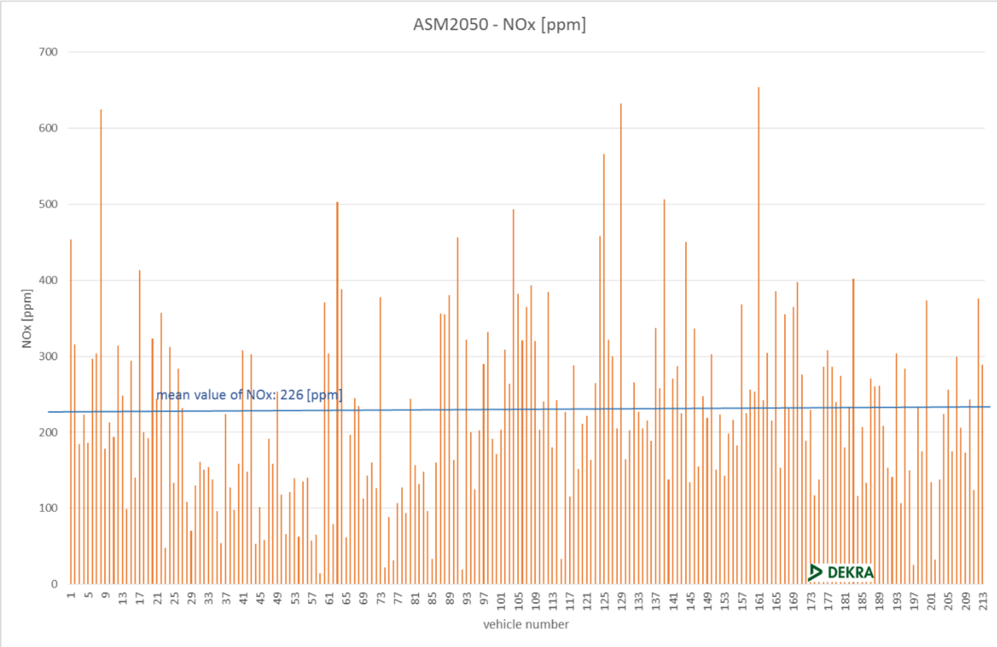


Figure 39 – NO_X-values for each tested vehicle

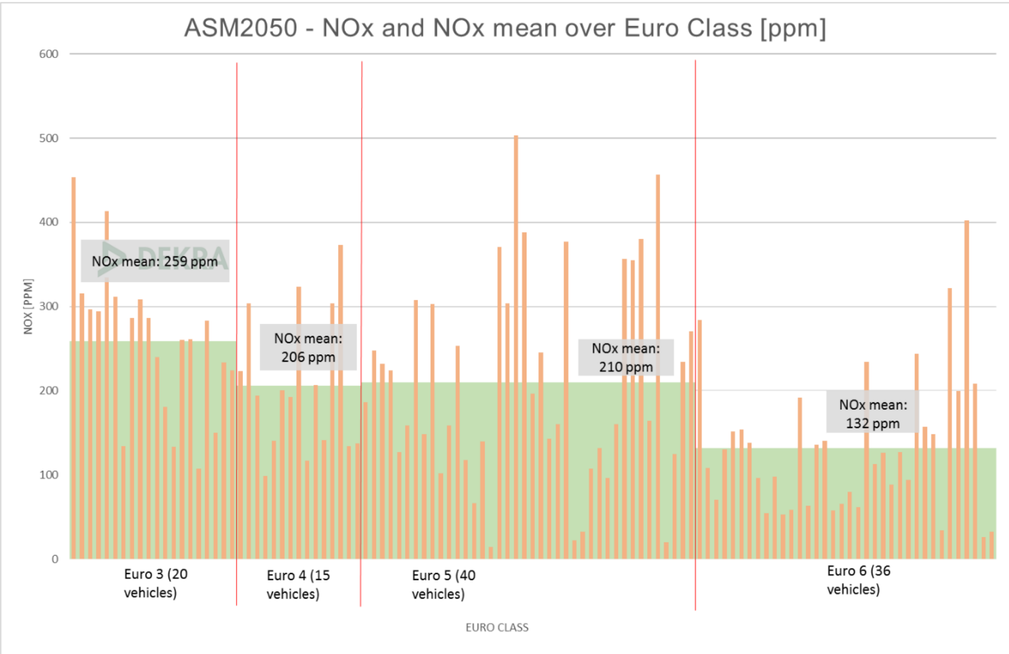


Figure 40 – NOX-values in function of the Euro classes

The ASM2050 cycles show a high spread in general and within the specific Euro classes. It is significant that there are not a few vehicles with very low concentrations as well as very high concentrations. The average concentration is decreasing with increasing Euro classes as expected.

Conclusion

The loaded ASM2050 tests showed the highest absolute NO_X concentrations. The allocation of the different concentrations was not expected. Normally you find around 90% of vehicles close to average emission concentration. Regarding NOx, it seems that there are many vehicles with very low and also many vehicles with very high concentrations which is not usual compared to the current periodic emission test, where you have more or less a Gaussian distribution.

The reasons for the wide spread of concentrations could be:

- Failure condition of components or engine (deterioration or manipulation)
- Legal reduction or switch off of the operation («thermo window»)
- Vehicle not sufficiently conditioned (e. g. temperature of the SCR catalyst)
- Regeneration phase (one vehicle was in a regeneration phase during the lab tests, note that the results during this time were excluded.)

Under the current legislation the OEM is allowed to reduce or even switch off the aftertreatment systems temporarily to protect the engine. Unfortunately, each OEM has its own strategy to design the individual motor characteristics of the vehicles. Theses strategies are confidential and not known. It is assumed that during the ASM2050 tests some vehicles reduced or legally switched off (temporarily) the aftertreatment functionality or a smaller number of the tested vehicles could have had a defective aftertreatment system.

Therefore, it is very difficult to define an applicable threshold for the fail/pass criteria if you want to be sure not to reject a vehicle without legal cause.

4. Cost-Benefit Analysis

This chapter enables an economic comparison between the different test procedures. The test procedures differ in terms of costs and accuracy of emission measurement. Therefore, the cost-benefit analysis is the most appropriate method to enable the monetary assessment of the different testing procedures. This chapter consists of four parts:

- First: Methodology and basic evaluation principles
- Second: Calculating the benefits.
- Third: Calculating the costs.
- Fourth: Benefit-cost results

4.1. Methodology and basic evaluation principles

4.1.1. Definition of CBA

A preferable approach for the socio-economic assessment of measures, new technologies or tests is the cost-benefit analysis (CBA). CBA has already been successfully applied, for instance, for the assessment of new emissions tests for diesel vehicles (CITA, 2011). The CBA uses an objective methodology that does not include any subjective weighting schemes.
In consequence, this approach is suitable for assessing the implementation of new thresholds for emission testing of petrol and diesel vehicles. It assesses costs on the one hand (e.g., cost of implementation, technology costs). On the other hand, benefits are cost savings, which means that the reductions in costs, such as accident costs, time costs, vehicle operating-costs and emission costs (for this study, a reduction in emission costs, i.e., the impact of emission savings) are benefits. By forming the benefit-cost ratio (BCR) ensures that the judgment, which test procedure is preferable, considers an objective criterion based on the theory of economic welfare. The ratio follows a certain logic:

$$BCR = \frac{\sum_{t=0}^{n} Bt(1+i)^{-t}}{\sum_{t=0}^{n} Ct(1+i)^{-t}}$$

with:

BCR:	Benefit-cost-ration
t:	length of evaluation period
Bt:	annual benefits
Ct:	annual costs
i:	social discount rate

The interpretation of the BCR-ranges is following:

- 0 < BCR < 1 poor ratio, socio-economic inefficiency;
- 1 ≤ BCR < 3 acceptable ratio, positive net benefit;
- BCR ≥ 3 excellent ratios.

4.1.2. Time horizon

Within the framework of the CBA, it is necessary to clarify at what point in time the assessment of the benefit and cost flows that occur over some time should be carried out. Base year in this study for the assessment of benefits and costs is the year 2016. The reason that the year 2016 is chosen as the base year is that the newest cost unit rates for NOx emissions are only available for the year 2016 (Umweltbundesamt, 2018). With the choice of a past base year, it is no longer necessary to forecast future price changes during the investigation period. The choice of the year 2016 as basis years avoids a forecasting risk in the calculations of the benefit-cost ratios. The evaluation period is ten years from 2021 to 2030.

4.1.3. Social discount rate

We are multiplying the annual benefits and costs by the social discount rate, which results in the present values of the benefits and costs of the respective years. Their sum is the capital value of benefits or costs. The social discount rate is used in this study to determine the annual investment cost of the test procedures. At present, there is no reasonable value for a social discount rate in EU-28 available. For this study, we use a social discount rate of 1.7%. Federal investment planning in Germany uses this amount for the social discount rate (PTV Planung Transport Verkehr AG, 2016).

4.1.4. Vehicle stock

The next figure shows the vehicle-stock development in EU-28 from 2015 to 2030. The diesel car development is divided into diesel cars with EURO 4, diesels cars with EURO 5 and diesel cars with EURO 6.

Year	Total Passenger cars	Total Petrol	Petrol Higher than Euro 3	Diesel Total	Diesel Euro 4	Diesel Euro 5	Diesel Euro 6
2015	249,477,960	143,830,976	107,209,872	105,646,984	18,597,783	38,519,607	17,176,446
2016	252,568,227	143,752,614	111,171,895	108,815,612	17,294,118	37,487,710	25,855,538
2017	255,658,494	143,674,253	115,133,918	111,984,240	15,990,453	36,455,813	34,534,630
2018	258,748,760	143,595,891	119,095,941	115,152,868	14,686,788	35,423,916	43,213,722
2019	261,839,027	143,517,530	123,057,964	118,321,497	13,383,123	34,392,019	51,892,814
2020	264,929,293	143,439,168	127,019,986	121,490,125	12,079,458	33,360,121	60,571,906
2021	267,785,702	144,067,660	129,550,872	123,718,041	10,726,581	30,641,776	68,307,994
2022	270,642,111	144,696,153	132,081,759	125,945,957	9,373,704	27,923,431	76,044,082
2023	273,498,519	145,324,645	134,612,645	128,173,873	8,020,827	25,205,085	83,780,170
2024	276,354,928	145,953,138	137,143,532	130,401,790	6,667,951	22,486,740	91,516,258
2025	279,211,336	146,581,630	139,674,418	132,629,706	5,315,074	19,768,394	99,252,345
2026	282,074,896	147,550,369	141,376,542	134,524,527	4,784,572	17,513,547	104,465,918
2027	284,938,456	148,519,108	143,078,666	136,419,348	4,254,070	15,258,700	109,679,491
2028	287,802,016	149,487,847	144,780,790	138,314,169	3,723,567	13,003,853	114,893,064
2029	290,665,576	150,456,586	146,482,914	140,208,991	3,193,065	10,749,006	120,106,637
2030	293,529,136	151,425,324	148,185,038	142,103,812	2,662,562	8,494,158	125,320,210

Table 18 – Development of the vehicle stock (passenger cars) in EU-28 from 2015 to 2030 (Based on TREMOVE Model version 3.3.2, Brussels 2010 (www.tremove.org); own calculations)

The average annual vehicle-kilometers of diesel cars are 20,000 kilometers, which is based on the TREMOVE model.

4.1.5. Monetary evaluation of NOx

The German Federal Environment Agency has developed a methodology for estimating the external environmental costs that are currently available in the updated version 3.0 since December 2018. The current cost rate for the average environmental cost of air pollution from NOx emissions from transport is € 18,500 (in € 2016 / tons of emission) (Umweltbundesamt, 2018). The cost rate considers both health damage and non-health damage from NOx. The cost rate only for health damage of NOx is 15,000 euros (in € 2016 / tons of emission). Accordingly, the cost rate for the non-health effects of NOx is € 3,500 (in € 2016 / tons of emission).

4.2. Calculating the benefits

The proceeding to determine the benefits of the sustainable emission test for diesel vehicles is as follows:

- First, the number of diesel cars, which must be inspected every year within the investigation period, is calculated. This calculation uses the stock forecasts for diesel passenger cars.
- Empirical findings determine the values for the probability of damage to the catalyst.
- It is necessary to find out how many kilometers are diesel cars drive with a malfunction of the catalysts.
- It is also necessary to determine the level of additional emissions released because of catalytic converter faults. For this purpose, the emission measurements carried out in the context of this project are used.

It is known from the TEDDIE-project (CITA, 2011) that on average 50% of the European vehicle stock is inspected every year. Using the share from the TEDDIE project and the vehicle forecast for diesel cars it is possible to derive the number of diesel cars inspected in the years from 2021 to 2030. The development of the number of inspected diesel cars shows Figure 41.

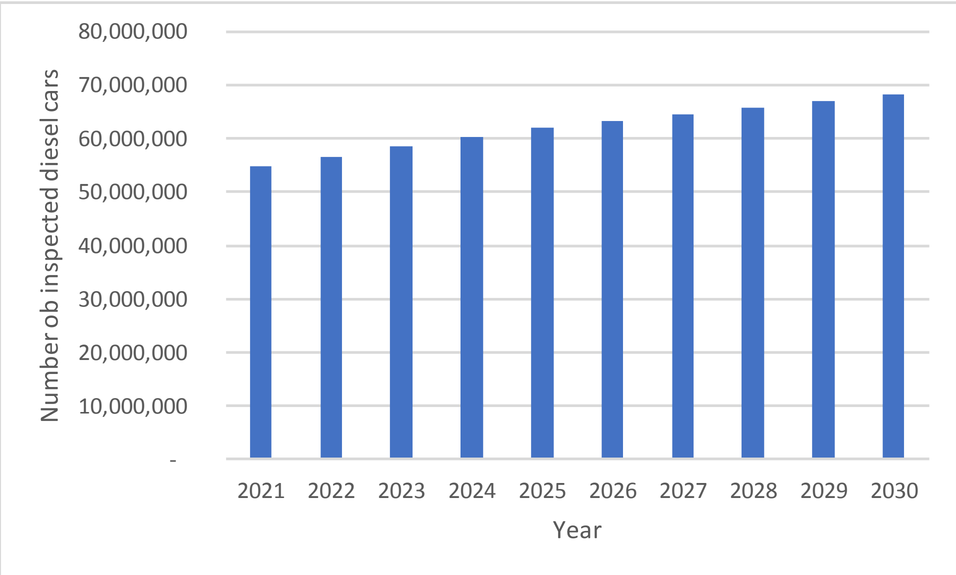


Figure 41 – Number of inspected diesel cars (EURO 4, 5, 6) in EU-28 in the years from 2021 to 2030 (derived based on Table 18)

Table 19 gives an overview of the different test procedures over the vehicles failing by exhaust emission test in percent. For all tests without CAPELEC, 5% of the tested vehicles had failures, whereas 8.47% of vehicles failed at the CAPELEC-procedure. Table 19 provides further for each test procedure the information on the ratio between with and without exhaust defects. The ratio is calculated as the NOX mean measurement with a simulated failure divided by the NOX mean measurement without the failure.

Test Procedure	Total number of tested diesel cars	State of Threshold	Threshold	Vehicles failing by exhaust emission test	Ratio's between with and without exhaust defects (from lab tests)
1. Loaded Test					
1.1 DT80	/	/	/	5%	1,5
1.2 ASM2050	213			5%	4
1.3 Short test drive	no field tests			5%	1,8
2. Unloaded Test					
2.1 AVL	259			5%	1,2
2.2 CAPELEC	354	bad (0) to good (4)	<= 1,2	8,47%	1,2
2.3 SPHERETECH	9			5%	1,2

Table 19 – Vehicles failing by exhaust emission test and ratio´s between with and without exhaust defects

If damage to the catalytic converters is detected, the question arises of how many kilometers this car will travel with the defective catalytic converter. It is necessary to distinguish between the pollutant emissions that have arisen due to a defect before the emission test and the avoidable pollutant emissions because of the emission test.
Since it is not possible to determine when the damage event has occurred, it is assumed that the damage to the catalysts occurs typically distributed over the driving period. Passenger cars in EU-28 only must go to the vehicle inspection every two years (empirical average), in the event of a faulty catalytic converter, the assumption is that 40,000 km will be traveled in the defective state.
If a defect is detected in the emission testing, only future pollutant emissions can be avoided. If the emission testing did not exist, then the defect would only be discovered stochastically. If the defect is not detected, it can be detected at the latest after two years - at the next emission test. It is therefore assumed that a detected defect will result in the avoidance of increased NOx emissions over two years. This corresponds to a total mileage per passenger car of 40,000 km.
The actual economic damage due to a catalyst defect is then made up of the kilometers traveled before the emission test with one defect and the remaining kilometers to the next emission test.
By contrast, the benefit of the emission test is that future damage kilometers will be avoided after the emission test. The damage kilometers that can be avoided by the emission test amount to 40,000 km per vehicle, if another emission test takes place every two years after the first emission test.

This approach tends to underestimate the number of kilometers driven because it is assumed that future pollutant emissions will only occur over a two-year period. If there is no emission test, then it is unclear when the defect will be repaired, so that it may well happen that increased NOx emissions are emitted over a longer period.

The calculation of additional avoidable NOx-emissions follows these steps:

- Multiplying the annual number of inspected vehicles with the percentage share of vehicles failing by the exhaust emission test leads to the number of diesel cars with defects.
- The number of diesel cars consists of EURO 4-, EURO 5- and EURO 6-vehicles. This distinction is necessary because for EURO 4 diesel vehicles the NOx-limit is 0.25 g per kilometer, the NOx-limit for EURO 5 vehicles is 0.18 g per kilometer, and the NOx-limit for EURO 6 vehicles is 0.08 g per kilometer. That means the additional NOx-emission depends on the EURO-norm and the ratio between with and without defects.

Table 20 gives an overview of the annual NOx-emission savings in Million Euro related to testing procedures. The differences between the test procedures depend on the ratios between with and without exhaust defects given by Table 19.

Year	Annual NOx-emission savings in Million Euro							
	Loaded test					Unloaded test		
	ASM2050					AVL	CAPELEC	SPHERETECH
	ACTIA 4WD	ACTIA 2WD	Maha 4WD	Maha 2WD	Short Test Drive			
2021	1,010.97	1,010.97	1,010.97	1,010.97	454.94	303.29	303.29	303.29
2022	995.53	995.53	995.53	995.53	447.99	298.66	298.66	298.66
2023	980.10	980.10	980.10	980.10	441.04	294.03	294.03	294.03
2024	964.66	964.66	964.66	964.66	434.10	289.40	289.40	289.40
2025	949.22	949.22	949.22	949.22	427.15	284.77	284.77	284.77
2026	940.23	940.23	940.23	940.23	423.10	282.07	282.07	282.07
2027	931.25	931.25	931.25	931.25	419.06	279.37	279.37	279.37
2028	922.26	922.26	922.26	922.26	415.02	276.68	276.68	276.68
2029	913.28	913.28	913.28	913.28	410.98	273.98	273.98	273.98
2030	904.30	904.30	904.30	904.30	406.93	271.29	271.29	271.29
Average Value	951.18	951.18	951.18	951.18	428.03	285.35	285.35	285.35

Table 20 – Annual NOx-emission savings for each test procedure in Million Euro

4.3. Calculating the costs

For the determination of cost, it is necessary to determine the total number of test equipment, which is needed to guarantee minimum viable testing of diesel cars. Therefore, the assumption is that the average utilization, which is practically possible, is 1,000 tests per test unit. That means that in total 68,238 test units must be installed finally in 2030. Starting the inspection in 2021 will lead to a need for 54,838 test units. Following the increasing number of inspected diesel cars on average each year 1,523 units must be put into operation until 2030.

The starting point is for the estimation of costs the information provided in Table 21. Table 21 provides for the different test procedures an overview over the investment costs, the lifetime, the annual maintenance and calibration costs, the costs for the additional equipment and the additional labor time amount, which is a need for the testing procedure.

Test Procedure	penetration market price 4WD	penetration market price 2WD	how long can be used?	Yearly maintenance and calibration costs	Additional equipment	time amount labor
1. Loaded Test						
1.1 DT80						
1.2 ASM2050						
ACTIA	€ 45.000,00	€ 30.000,00	15	€ 2.000,00	€ 0,00	120 s
MAHA	€ 50.000,00	€ 18.000,00	15	€ 500,00	4WD : € 4000 2WD : € 2000	120 s
1.3 Short test drive		€ 20.000,00	10	€ 500,00		360 s
2. Unloaded Test						
2.1 AVL		€ 7.500,00	8	€ 250,00	€ 0,00	120 s
2.2 CAPELEC		€ 7.500,00	8	€ 250,00	€ 0,00	120 s
2.3 SPHERETECH		€ 7.500,00	8	€ 250,00	€ 0,00	120 s

Table 21 – Investment costs, annual maintenance and calibration costs, costs for additional equipment and time amount for the test procedure

Table 21 requires the following calculation steps.

- The calculation of the total annual costs makes it necessary to annualize the investment costs of each test procedure. The annualization of investment costs is possible because we know the social discount rate and the period of use.
- The time amount of labor for each test procedure is measured in seconds. This time value must be transformed into a monetary value.

We have three different depreciation periods: 8, 10 and 15 years. Using the social discount rate of 1.7% lead to an annuity factor of 0.13475 for a depreciation period of 8 years, to an annuity factor of 0.10959 for 10 years and finally to an annuity factor of 0.07609 for a depreciation period of 15 years.

Table 22 compares the total costs (investment cost plus maintenance cost plus cost for additional equipment) for each test procedures.

Year	Annual investment cost, maintenance cost and additional cost in Million Euro							
	Loaded test					Unloaded test		
	ASM2050					AVL	CAPELEC	SPHERETECH
	ACTIA 4WD	ACTIA 2WD	Maha 4WD	Maha 2WD	Short Test Drive			
2021	314.13	243.20	236.05	102.53	147.61	69.13	69.13	69.13
2022	324.63	251.33	243.94	105.95	152.54	71.44	71.44	71.44
2023	335.13	259.45	251.83	109.38	157.47	73.75	73.75	73.75
2024	345.63	267.58	259.71	112.80	162.41	76.06	76.06	76.06
2025	356.12	275.71	267.60	116.23	167.34	78.37	78.37	78.37
2026	363.08	281.09	272.83	118.50	170.61	79.90	79.90	79.90
2027	370.03	286.48	278.05	120.77	173.88	81.43	81.43	81.43
2028	376.99	291.86	283.28	123.04	177.14	82.96	82.96	82.96
2029	383.94	297.24	288.50	125.31	180.41	84.49	84.49	84.49
2030	390.90	302.63	293.73	127.58	183.68	86.02	86.02	86.02
Average Value	356.06	275.66	267.55	116.21	167.31	78.36	78.36	78.36

Table 22 -Annual investment cost, maintenance cost and cost for additional equipment for each test procedure from 2021 to 2030 in Million Euro (own calculation)

The average hourly labor costs in the business economy are 26.4 Euro per hour in EU-28 in 2017 (eurostat, 2018) without taxes and subsidies. Using the time amounts of Table 21 and the labor cost unit rate leads to the annual labor costs for each test procedure presented in table 23.

Year	Annual labor cost in Million Euro							
	Loaded test					Unloaded test		
	ASM2050					AVL	CAPELEC	SPHERETECH
	ACTIA 4WD	ACTIA 2WD	Maha 4WD	Maha 2WD	Short Test Drive			
2021	47.96	47.96	47.96	47.96	143.89	47.96	47.96	47.96
2022	49.57	49.57	49.57	49.57	148.70	49.57	49.57	49.57
2023	51.17	51.17	51.17	51.17	153.51	51.17	51.17	51.17
2024	52.77	52.77	52.77	52.77	158.31	52.77	52.77	52.77
2025	54.37	54.37	54.37	54.37	163.12	54.37	54.37	54.37
2026	55.44	55.44	55.44	55.44	166.31	55.44	55.44	55.44
2027	56.50	56.50	56.50	56.50	169.49	56.50	56.50	56.50
2028	57.56	57.56	57.56	57.56	172.68	57.56	57.56	57.56
2029	58.62	58.62	58.62	58.62	175.87	58.62	58.62	58.62
2030	59.68	59.68	59.68	59.68	179.05	59.68	59.68	59.68
Average Value	47.96	47.96	47.96	47.96	143.89	47.96	47.96	47.96

Table 23 – Annual labor cost for each test procedure in Million Euro (own calculation)

4.4. Benefit-Cost Results

Table 24 presents the benefit-cost ratios for the different test methods under the assumptions that the vehicle failure rate is 5% and ratios between with and without exhaust defects of Table 19 can be applied.

Year	Benefit-cost-ratios							
	Loaded test					Unloaded test		
	ASM2050					AVL	CAPELEC	SPHERETECH
	ACTIA 4WD	ACTIA 2WD	Maha 4WD	Maha 2WD	Short Test Drive			
2021	2.79	3.47	3.56	6.72	1.56	2.59	2.59	2.59
2022	2.66	3.31	3.39	6.40	1.49	2.47	2.47	2.47
2023	2.54	3.16	3.23	6.10	1.42	2.35	2.35	2.35
2024	2.42	3.01	3.09	5.83	1.35	2.25	2.25	2.25
2025	2.31	2.88	2.95	5.56	1.29	2.15	2.15	2.15
2026	2.25	2.79	2.86	5.41	1.26	2.08	2.08	2.08
2027	2.18	2.72	2.78	5.25	1.22	2.03	2.03	2.03
2028	2.12	2.64	2.71	5.11	1.19	1.97	1.97	1.97
2029	2.06	2.57	2.63	4.97	1.15	1.91	1.91	1.91
2030	2.01	2.50	2.56	4.83	1.12	1.86	1.86	1.86
Average Value	2.33	2.90	2.98	5.62	1.31	2.17	2.17	2.17

Table 24 – Benefit-cost ratios for the different test procedures for the years 2021 to 2030

In the first year, the benefit-cost ratios of each test procedure reach their maximum value. The benefit-cost ratios of each test procedure reach their minimum value in the year 2030. The reason is that the number of inspected diesel cars has in 2021 the highest amount. The vehicle stock includes only Euro 4, 5 and 6 diesel cars. The calculation does not consider successor models with Euro 6d temp and Euro 6d. Therefore the total amount of diesel vehicle decreases over the investigation period.

5. Summary, conclusions and recommendations

5.1. Summary

The study began after a comprehensive review of the methods, instruments and research related to emission testing of NO_X during PTI. This literature research made it possible to identify applicable test methods for loaded and unloaded tests which were then evaluated during laboratory tests. The aim was to derive meaningful test methods for the field tests.
From the literature research the loaded tests DT80, ASM2050 and a short test drive were selected. The unloaded tests evaluated, were the AVL-cycle (a slow acceleration) the Capelec cycle (accelerations to different idling rpm) and the Spheretech cycle (different measuremets using exhaust emissions as a kind of diagnostic scheme).

The main findings of the laboratory tests were:

- Ability to detect failure related emissions for all loaded tests; on the other hand this ability is less obvious for the unloaded tests

Test cycle	Ratio
ASM Method	**4**
DT80	**1,5**
unloaded	**1,2**
Short test ride	**1,8**

Table 25- Ratio per test cycle.

The ratio is calculated as the NO_X measurement with a simulated failure divided by the NO_X measurement without the failure.

- The DT80 cycle needs more time than the ASM2050 cycle due to the higher speed and longer cycle of the DT80.
- ASM2050 gives a good repeatability and accuracy.
- The short test ride needs a distance of 50 m or more, which is not pratical in all PTI test centers. Furthermore the repeatability has to be improved.
- Capelec cycle only focuses on the EGR system

Comparison of the different evaluated tests are summarised in the table below:

Criteria	Spheretech	Capelec	AVL	DT 80	ASM2050	Short Test Ride
Ability to detect failures of different emission systems	X	X	X	XXX	XXX	XX
Over all accuracy of method	X	X	X	XX	XX	X
Applicable for all vehicles	XX	XX	XX	XXX	XXX	XX
Time and Investment needed	XXX	XXX	XXX	X	XX	XX
XXX = very positive **XX** = possitive **X** = partly possitive						

Table 26- Compairison of the different evaluated test cycles.

A large number of field tests were performed in six different countries by 14 European PTI companies.

The NO_X emissions were measured under the conditions of either the loaded ASM2050 cycle or the unloaded combined AVL/Capelec cycle. Seven hundred thirthy five (735) Diesel tests had passed all validitations in order to be considerd for evaluation.

The loaded tests gave the following results:

- A wide spread of concentrations of NO_x between 50 ppm and 600 ppm;
- Average NO_x is decreasing from Euro 3 to Euro 6, but not in correlation with type approval;
- Further analysis for appropriate thresholds is necessary
- Inherent to field tests is that the real condition of the vehicle is not known (e. g. software concept, SCR-temperature)

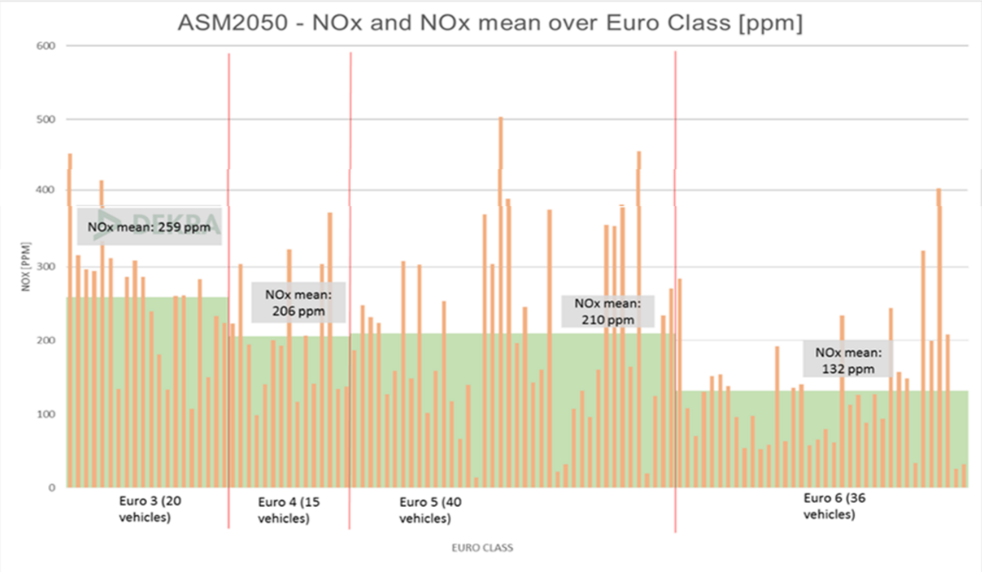


Figure 42 – ASM2050 NO_X-values in function of the Euro classes

The reasons for the wide spread of concentrations could be:

- Failure condition of components or engine (deterioration or manipulation)
- Legal reduction or switch off of the operation («thermo window»)
- Vehicle not sufficiently conditioned (e.g. temperature)
- Regeneration phase

To define possible thresholds for the loaded test ASM2050, as well as the dispersion of the vehicle values, it is necessary to take into account the uncertainties associated with the measure:

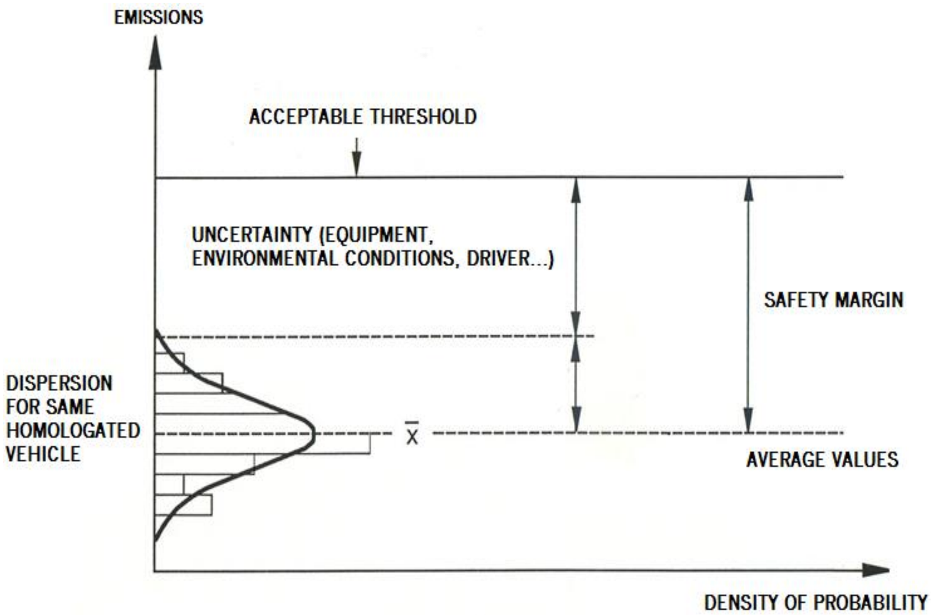


Figure 43 – Threshold value depending on uncertainties (Source: Departament of Thermal engines and machines, University of Seville)

An acceptable threshold should take in consideration the dispersion for the same homologated vehicle. This means that the vehicle should be tested serveral times in the ideal test conditions for the NO_X emissions test with the ASM2050 cycle. The average value will depend on the aftertreatment systems installed on the vehicle, the euro class, the emission strategy etc.
A safety margin should be added to the average value taking into consideration the dispersion and uncertainities such as equipment, environmental conditions or the driver

Another possible point of view to determine a threshold value takes into consideration a 'politically acceptable' rejection rate.

For the ASM2050 field tests the potential rejection rates are shown in the graph below:

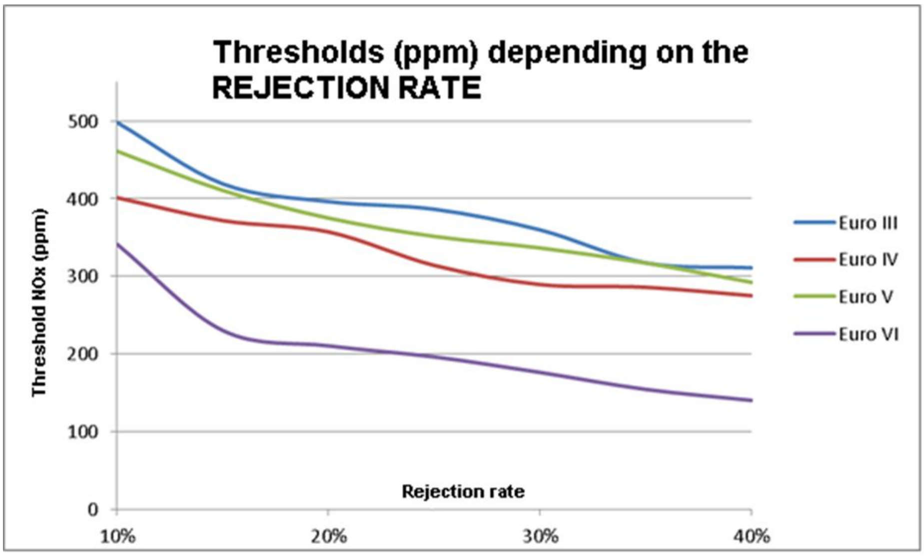


Figure 44 – Threshold depending on the rejection rate (source : VEIASA)

The Capelec cycle focuses only on EGR-based aftertreatment systems. Results indicate 8,5% of the tested vehicles have problems with the EGR systems (Values less than 1,5 are considered to indicate problems with the EGR system). Furthermore, since the Capelec test is based on the evaluation of ratios, the influence of temperature is less important.

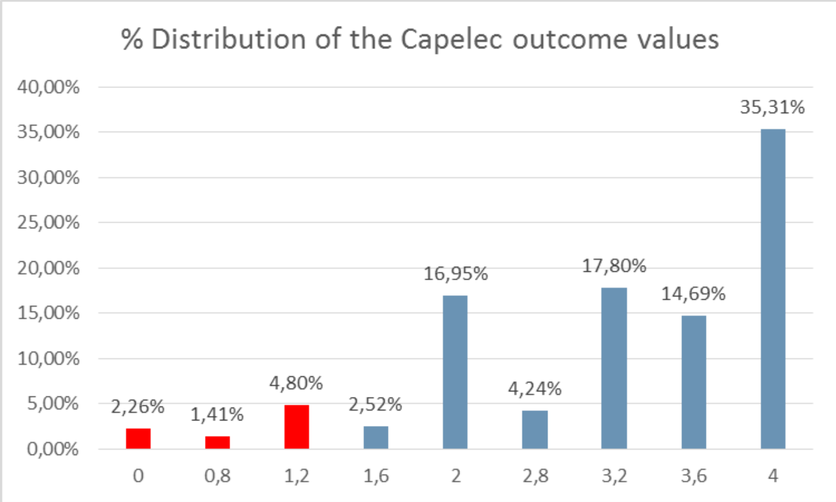


Figure 45 – Distribution of the Capelec outcome values

For the AVL cycle there is no evaluation criteria available so far. For this reason, a ratio of the NO_X measured values were compared at different rpm conditions.

The mean ratio value was situated around two, with some measurements above a ratio of four. The NO_X-concentration were between 20 ppm and 370 ppm with an average NO_X concentration of approximative 100 ppm. The NO_X concentration was even shown to increase from Euro 4 to Euro 6. It is clear that further analysis for an appropriate thresholds is necessary.

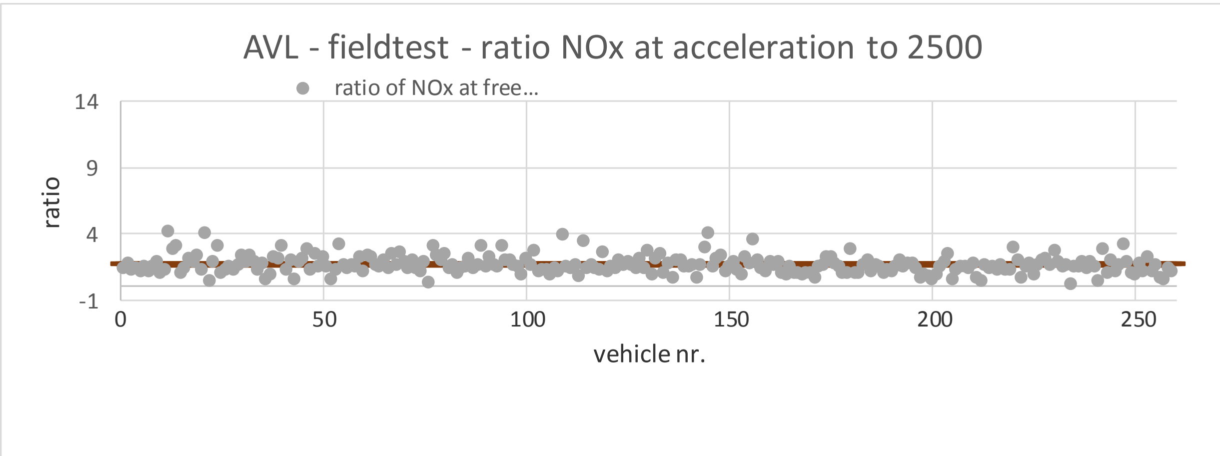


Figure 46 – AVL fieldtest NO_X ratio at 2500 rpm

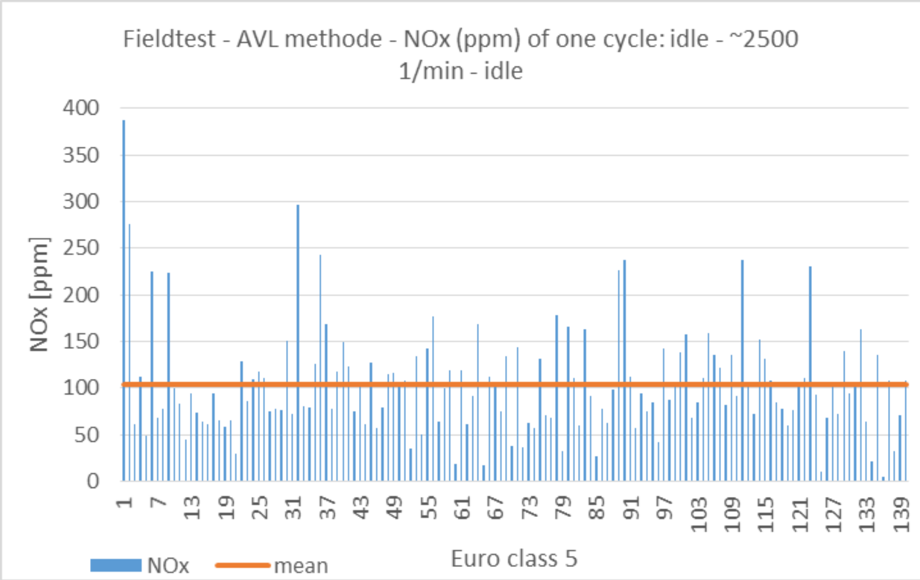


Figure 47 – AVL Fieldtest NO_X values

5.2. Conclusions and recommendations

In general terms, without an appropriate load on the engine and exact temperature conditioning, a measurement of NOx and the control of exhaust aftertreatment of modern vehicles is not sufficient. For SCR – systems (selective catalytic reduction) a minimum temperature of approximately 230°C (500 K) needed. Without this prerequisite, an emission test is under certain conditions misleading.
Test methods without load simulation are mainly focused on EGR valves. Up to Euro 5 vehicles this method can be used to find failures on EGR (exhaust gas recirculation) but only if the knowledge is available, on the types of aftertreatment system fitted. In most cases a combination of different systems are used.

Based on the lab test on 5 different vehicles it seems to be the best technical solution to detect all relevant system conditions on SCR as well as lean NOx trap – systems (LNT) and EGR – systems by putting a defined load on the engine under test. Load for an appropriate time has to be exact and the repeatability has to be also clearly defined. From the literature analysis there are a lot of different cycles and methods in use and elaborated. So for the lab test it was agreed to focus on the main and best known cycles which are also partly tested in the project in France, initiated by the Ministry of Transport. The is based on the Acceleration Simulation Mode, ASM form US (ASM2050) and the DT80, both on roller dynos. As an interesting solution a test bench can be seen, which is using small rollers on two axles (for 4WD vehicles), this alternative was tested within the study in France.
Another alternative method was a short vehicle trip, accelerating the vehicle for a short time and putting a load on the engine. Repeatability and a safe method to do such a short trip is a key question.

The exhaust measurement systems for NOx are actually quite well developed. Compared with the original SET project the systems are better calibrated and the T90 time is compared with the earlier systems much better. A difference can be seen by using NO and NO_2 measurement cells or only NO measurements and the calculation of NO_2. As a reference measurement system a PEMS was used for static and dynamic tests.

Another measurement possibility is given by the on board NOx – sensing devices. On some modern vehicles a NOx-Sensor is on board, depending on the aftertreatment system which is used. The sensing value can be read via OBD, but not in a standardised and guaranteed way. These devices are quite good as the high resolution and measurement frequency could be useful for dynamic measurements. The issue concerning calibration seems on the other side not easy to be resolved, however the technology can be used within an off board measurement device.

In general, we have found that:

- Test methods with load simulation show a good potential to detect emission related failures: the ratio between concentration values between vehicles that pass and fail is high (up to 4);
- The test methods without load simulation show lower ratios (less than two) between vehicles that pass and fail. High idle tests are sometimes not possible because of the limitation of the cut off speed;
- Conditioning is important for a robust result of an emission test. Especially for SCR systems the catalyst temperature is very significant for the level of NO_X-concentration and the efficiency of the system in general;
- It is important to have information regarding the complete aftertreatment system as well as the software strategy and its function to evaluate possible interaction of several installed systems;
- Different aftertreatment systems can interact and compensate for a defect in a different system

This brings us to the following conclusions for the SET II study:

- To be able to effectively evaluate the NOx-behavior of diesel engine aftertreatment systems, there is a need for specific technical information for the vehicle:
    - Aftertreatment system(s) installed;
    - Software strategy (mode of operation);
    - Sensor information which already exists in most of the OBD systems like SCR temperature, urea injection rate, EGR valve activity or NOx values in a standardised way
- Preconditioning of the vehicle is crucial for a valid test result;
- Loaded tests are more meaningful than unloaded tests;
- The combination of comprehensive OBD-information and real emission tests are necessary for a proper evaluation;
- The tests conducted emphasise the complexity of NOx measurement in practice;
- Further tests are required to give confidence in the initial results.

Some open questions are still appropriate as are the useful level of thresholds and the required pre-conditioning. The thresholds have to be seen in correlation to the type approval measurements. A reference value measured during type approval would be helpful for the evaluation of new vehicles in future. For older vehicles, an average of in use vehicle measurments could be used to form a representative sample to calculate an acceptable standard.
The potential of short trip tests might be a subject for further investigation as well as the use of measurement sensors which are used on vehicles, e.g. within a so called MINI PEMS test.
The overall findings and results from the test methods without load for the engine, using different rpm – levels and changes of the rpm over different periods of time, the processes which are defined from different suppliers of test equipment are not completely convincing . The same result is communicated by the members of the study in France. The method is working but a certain definition of pass/fail criteria is very complicated and a major disbenefit is its capability of being only for EGR – equipped vehicles. With some assumptions, a misuse or deviation of the EGR can be found, but only if enough data concerning the real vehicle calibration and software program is known, along with the evaluation of OBD – Data.

A combination of the measurement of different components like CO, HC, CO_2 and O_2 and the other loaded measurements on a load simulation can be useful, but only an EGR valve based evaluation is not sufficient at all for the whole fleet.

A cost benefit analysis was performed on the proposed SETII test procedures. The test procedures differ in terms of costs and accuracy of emission measurement. The CBA was based on the time taken to perform the tests and the additional faulty vehicles detected and repaired. The equipment used varies enormously depending on the test procedure. The benefit-cost ratio's (BCR's) for the loaded tests ASM2050 were the highest, starting from approximately 2,8 – 6,7 (depending on the used equipment) and decreases to 2 – 4,8 in 2030. The unloaded tests start at approximately 2,6 and decreases to 1,8. The reason why the BCR's decreases over the years is that the total amount of diesel vehicles decreases over the investigation period. Nevertheless, the analysis shows that the benefit-cost ratio's are excellent for all investigated test procedures over the time period of 10 years.

It is clear that further investigation is needed. Therefore, the authors of this study recommend taking the following points in consideration for the next NO_X emission study related to PTI.

- Further tests are required:
    - To define thresholds;
    - To get better understanding of the behavior of aftertreatment systems;
    - To elaborate practical procedures for periodic emission tests;
- Short test drive as an alternative seems promising, but needs further investigation;
- Further tests should include an extended OBD-reading (diagnostic tool) and vehicle specific information provided by the OEM:
- Specific reference values for periodic emission tests should be defined at the time of type approval (Euro 6 and further) for future vehicles;
- It seems appropriate to combine the loaded ASM2050 method with the unloaded test method for EGR assessment and OBD – read out for better evaluation;
- Coordinated EU-wide approach is necessary.

6. Annexes

1. Type approval emission Limits
2. Technologies for the control of NOx emissions
3. Instruments for measuring NOx during PTI
4. PTI test procedures for the test of diesel vehicles involving NO_X measeurements
5. Lab tests results
6. Field tests results

These annexes can be found in a separate document.

7. References

AECC The Association for Emissions Control by Catalyst. (2015). AECC Clean Diesel Euro 6 Real Driving Emissions Project [PowerPoint slides in PDF document]. AECC Technical Seminar on Real-Driving Emissions, Brussels, 29 April 2015. retrieved on 7/03/2016 from http://www.aecc.eu/content/RDE_seminar/06%20-%20AECC%20RDE%20seminar%20AECC%20Clean%20Diesel%20RDE%20Program.pdf

Andersson, J., May, J., Favre, C., Bosteels, D. et al. (2014). On-Road and Chassis Dynamometer Evaluations of Emissions from Two Euro 6 Diesel Vehicles. *SAE Int. J. Fuels Lubr.* 7(3):2014, doi:10.4271/2014-01-2826.

Anyon P., Jones D., Real J. & Jamieson R. (1996). Motor Vehicle Pollution in Australia. Report on the National in-Service Vehicle Emissions study. Federal Office of Road Safety, Canberra, Australia, May 1996. Retrieved on 8/03/2016 from https://infrastructure.gov.au/roads/environment/emission/pdf/natinservicestudy.pdf

Anyon, P., Brown S., Pattison, D., Beville-Anderson, J., Walls, G. & Mowle, M. (2000). In-Service Emissions Performance - Phase 2: Vehicle Testing. National Environment Protection Council, Adelaide, Australia. ISBN 0 642 323 348. Retrieved on 29/02/2016 from http://www.scew.gov.au/system/files/resources/45fee0f3-1266-a944-91d7-3b98439de8f8/files/dve-prepwk-project2-2.pdf

Baudirektion Kanton Zürich (n.d.). RSD-Messverfahren: Beschreibung und Angaben zu Messprinzip, Messgenauigkeit, Messgrössen sowie Auswertung der Messungen. Amt für Abfall, Wasser, Energie und Luft. Retrieved on 5/12/2016 from http://www.awel.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/rsd_messverfahren.pdf

Barlow, T., Latham, S., McCrae, I. & Boulter, P. (2009). A reference book of driving cycles for use in the measurement of road vehicle emissions. TRL Limited published project report PPR354, Department for Transport, June 2009.

Bishop, G. (2014). FEAT Equations for CO, HC and NO [PDF document]. Last updated Feb. 2014. retrieved on 5/03/2016 from http://www.feat.biochem.du.edu/assets/reports/FEAT_Math_II.pdf

Bishop, G., Stedman, D. (2008). A Decade of On-road Emissions Measurements. Environmental Science and Technology, April 2008. DOI: 10.1021/es702423b

Borken-Kleefeld, J. (2013). Guidance note about on-road vehicle emissions remote sensing. ICCT, Retrieved on 23/02/2016 from http://www.theicct.org/sites/default/files/publications/RSD_Guidance_BorKlee.pdf

Borken-Kleefeld, J. & Chen, Y. (2015). New emission deterioration rates for gasoline cars – Results from long-term measurements. Atmospheric Environment 101 (2015) p58-p64;

Brown, S., Bryett, C. & Mowle, M. (1999). Proposed Diesel Vehicle Emissions National Environment Protection Measure Preparatory Work. In-Service Emissions Performance - Drive Cycles. Volume 1. March 1999. National Environment Protection Council, Adelaide, Australia. ISBN 0 642 32323 2.

Bussink, H. (2014). Onderzoek beoordeling roetfilters. Eindrapportage. RDW, VT APK, H Bussink. 1/03/2014.

Cambustion. (n.d. a). Measurement of engine-out NO_x for transient SCR urea dosing accuracy. Cambustion Application Note CLD02v01. Retrieved on 11/03/2016 from http://www.cambustion.com/sites/default/files/applications/CLD500/cld02v01.pdf

Cambustion. (n.d. b). Heavy Duty NO_x and EGR control. Cambustion Application Note CLD03v01. Retrieved on 11/03/2016 from http://www.cambustion.com/sites/default/files/applications/CLD500/cld03v01.pdf

Cambustion. (n.d. c). Euro IV transient NO_x on WLPT cycle. Cambustion Application Note CLD04v01. Retrieved on 11/03/2016 from http://www.cambustion.com/sites/default/files/applications/CLD500/cld04v01.pdf

Cambustion. (n.d. d). Measurement of EGR delay and its effects on NO_x emissions using the NDIR500 and CLD500. Cambustion Application Note NDIR05v02. Retrieved on 11/03/2016 from http://www.cambustion.com/sites/default/files/applications/CLD500,%20NDIR500/NDIR05v02%20EGR%20delay.pdf

Carslaw, D., Beevers, S., Tate, J., Westmoreland, E. & Williams, M. (2011a). Recent evidence concerning higher NO_x emissions from passenger cars and light duty vehicles. Atmospheric Environment 45 (2011) p.7053-p.7063. doi:10.1016/j.atmosenv.2011.09.063

Carslaw, D.C., Beevers, S.D. Westmoreland, E. Williams, M.L. Tate, J.E., Murrells, T., Stedman, J. Li, Y., Grice, S., Kent, A. and I. Tsagatakis (2011b). Trends in NO_x and NO_2 emissions and ambient measurements in the UK. Version: July 2011. Retrieved on 12/12/2016 from https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1108251149_110718_AQ0724_Final_report.pdf

Carslaw, D. & Rhys-Tyler, G. (2013). Remote sensing of NO_2 exhaust emissions from road vehicles – a report to the city of London Corporation and London Borough of Ealing. Retrieved on 12/12/2013 from https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1307161149_130715_DefraRemoteSensingReport_Final.pdf

Carslaw, Williams, Tate & Beevers. (2013). The importance of high vehicle power for passenger car emissions. Atmospheric Environment, 68, 8-16.

CITA International Motor Vehicle Inspection Committee. (2011). TEDDIE (TEst (D) DIEsel) Project : A new roadworthiness emission test for diesel vehicles involving NO, NO_2 and PM measurements. Retrieved on 28/07/2016 from http://citainsp.org/wp-content/uploads/2016/01/teddie_final_report.pdf;

CITA International Motor Vehicle Inspection Committee. (2015). CITA SET Project – Sustainable Emissions Testing. Retrieved on 28/07/2016 from http://citainsp.org/wp-content/uploads/2016/01/teddie_final_report.pdf

Chatterjee, D., Koci, P., Schmeisser, V., Marek, M., Weibel, M. & Krutzsch, B. (2010). Modelling of a combined NO_x storage and NH_3-SCR catalytic system for Diesel exhaust gas aftertreatment. Elsevier, Catalysis today 151, 395-409, doi:10.1016/j.cattod.2010.01.014.

Chen, Y. & Borken-Kleefeld, J. (2014). Real-driving emissions from cars and light commercial vehicles e Results from 13 years remote sensing at Zurich/CH. Atmospheric Environment 88 (2014) p157–p164.

Chen, Y. & Borken-Kleefeld, J. (2016). No Emissions from Diesel Passenger Cars Worsen with Age EnvSciTech 50(7):3327-3332 · April 2016

Chernich, D. (2003). Development of a chassis based inspection and Maintenance Program for Heavy-Duty Diesel Powered Vehicles. 13th CRC Workshop, April 2003. Retrieved on 3/03/2016 from www.arb.ca.gov/msprog/m17/m17crc.ppt#sthash.i9j5iS0O.dpuf

Clark, N., Kern, J., Atkinson, C. & Nine, R. (2002). Factors Affecting Heavy-Duty Diesel Vehicle Emissions, Journal of the Air & Waste Management Association, 52:1, 84-94, doi: 10.1080/10473289.2002.10470755

Denis, M., Budd, R., Hager, S. & Hager, Y. (2015). Connecticut Vehicle Inspection Program – 2014 On-Road Vehicle Survey. (Unpublished paper). Revecorp Inc. & Hager Environmental & Atmospheric Technologies (H.E.A.T.) February 9, 2015.

Driver & Vehicle Standards Agency. (2014). In service vehicle emissions standards. Department for Transport, Driver & Vehicle Standards Agency, Bristol, Eighteenth Edition, July 2014, ISBN 978-0-9549352-8-3.

Ensfield, J. , Gordon Jr., J. & Lindner, J. (2003). Evaluation of a Low- Cost Transient Mass Measurement System in Vehicle Inspection and Maintenance Testing: Results of a Gordon-Darby Study, Journal of the Air & Waste Management Association, 53:9, 1098-1108, DOI: 10.1080/10473289.2003.10466260

Erlansson, L. & Walsh, M. (2003). Motor vehicle Inspection in the National Capital Region (NCR) of India, retrieved on 4/3/2016 from http://www.walshcarlines.com/pdf/delhi_im_report.pdf

European Environment Agency. (2015). Air quality in Europe — 2015 report. EEA report No 5/2015, Luxembourg, ISBN 978-92-9213-702-1, ISSN 1977-8449, doi:10.2800/62459.

European Environment Agency. (2016). Explaining road transport emissions - A non-technical guide. EEA, Copenhagen, 27/01/2016. ISBN: 978-92-9213-723-6.

European Union. (2014). Directive 2014/45/EU of the European parliament and of the council of 3 April 2014 on periodic roadworthiness tests for motor vehicles and their trailers and repealing Directive 2009/40/EC. Official Journal of the European Union OJ L 127, 29.4.2014;

Favre, C., Bosteels, D., & May, J. (2013). Exhaust Emissions from European Market - Available Passenger Cars Evaluated on Various Drive Cycles. SAE Technical Paper 2013-24-0154, 2013, doi:10.4271/2013-24-0154.

Franco et al. (2014). Real-world Exhaust Emissions from Modern Diesel Cars – a Meta-Analysis of PEMS Emissions Data from EU (Euro 6) and US (Tier 2 Bin 5/ULEV II) Diesel Passenger Cars. The ICCT, White Paper, October 2014

Fung, F., He, H., Sharpe, B., Kamakaté, F., & Blumberg, K. (2011). Overview of China's vehicle emission control program. The International Council on Clean Transport, Published Thu, 2011.04.07. retrieved on 4/3/2016 from http://www.theicct.org/overview-chinas-vehicle-emission-control-program.

Fung, F. & Suen, B. (2013). A Review of the Hong Kong Inspection and Maintenance Programme for On-road Vehicles. Civic Exchange, August 2013.

Götsch, M. & Alt, G-M. (2015). Bericht und Auswertung RSD Messungen 2015. Kanton Zürich, Baudirektion, Amt für Abfall, Wasser, Energie und Luft, december 11, 2015. Retrieved on 5/12/2016 from http://www.awel.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2015.pdf

Heywood, J. (1988). Internal Combustion Engines Fundamentals. McGraw-Hill, New-York, 1988.

Hooftman, N., Messagie, M., Coosemans T. & Van Mierlo, J. (2014). Innovating the periodic technical inspection of passenger cars - A study on the potential for emission monitoring. Unpublished manuscript, the Vrije Universiteit Brussel, VUB, rapport 2012-2014.

Hussain, J., Palaniradja, K., Algumurthi, N. & Manimaran R.(2012). Diesel engine emissions and aftertreatment techniques – a review. Jers, Vol. III, Issue II, April-June, 2012/p34-p44

Jiménez, J. (1999a). Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing. Massachusetts Institute of Technology, Dept. of Mechanical Engineering, Massachusetts, 1999. Retrieved on 10/03/2016 from http://hdl.handle.net/1721.1/44505

Jiménez, J., McClintock, P., McRae, G.J., Nelson, D., & Zahniser M. (1999b). Vehicle Specific Power: A Useful Parameter for Remote Sensing and Emission Studies [PowerPoint slides in PDF document]. 9th CRC On-Road Vehicle Emissions Workshop, San Diego, April 21st 1999. Retrieved on 10/03/2016 from http://cires1.colorado.edu/~jjose/Papers/Jimenez_VSP_9thCRC_99_final.pdf

Johnson, T. (2013). Vehicular Emissions in Review. SAE Int. J. Engines, June 2013, 6:699-715, doi:10.4271/2013-01-0538

Johnson, T. (2014). Vehicular Emissions in Review. SAE Int. J. Engines, August 2014, 7:1207-1227, doi:10.4271/2014-01-1491

Johnson, J. (2015). On-road Heavy-duty Emissions Measurement System (OHMS): In-Use Measurement Technology for Heavy-duty vehicle exhaust emissions and potential Applications [PowerPoint slides in PDF document]. 2015 PEMS International Workshop, 26/3/2015. Retrieved on 2/3/2013 from http://www.cert.ucr.edu/events/pems2015/liveagenda/05johnson.pdf

Jordan-Gerkens, A, Auderset, K, Andres, H, Spiegel, J, Hogström, R, Riccobono, F, Nowak, A, Hildebrandt, M, Kuntze, A, Boese, A & Ebert V. (2014). Evaluation of measuring methods for particle emissions from modern diesel vehicles in periodic emissions control – Studies and Results. PTB, 2014 Retrieved on 08/09/2017 from https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_3/3.2_analytische_messtechnik_und_druck/3.23/Poster_Jordan-Gerkens_ETH2014.pdf

Kadijk, G., Ligterink, N. & Spreen, J. (2015). On-road NO_x and CO2 investigations of Euro 5 Light Commercial Vehicles. TNO, TNO 2015 R10192, March 2015.

Kadijk, G., van Mensch, P., & Spreen, J. (2015). Detailed investigations and real-world emission performance of Euro 6 diesel passenger cars. TNO 2015 R10702, May 2015

Katsis, P., Ntziachristos, L. & Mellios, G. (2012). Description of new elements in COPERT 4 v10.0. Emisia SA, Thessaloniki, 2012.

Ladommatos, N., Abdelhalim, S. & Zhao, H. (2000). The effects of exhaust gas recirculation on diesel combustion and emissions. *International Journal of Engine Research* 2000 1: 107, DOI: 10.1243/1468087001545290

Latham, S. (2007). An innovative dynamometer: free-running rollers to provide a potential cheap representative roadside emission procedure. TRL report PPR 216. TRL Limited, Wokingham, United Kingdom. retrieved on 23/02/2016 from http://www.transportresearchfoundation.co.uk/pdf/ppr216.pdf

Ligterink N. et al. (2013). Investigations and real world emission performance of Euro 6 Light-Duty vehicles. TNO report 2013 R11891, December 2013

MECA Manufacturers of Emission Controls Association. (2007). Emission Control Technologies for Diesel-Powered Vehicles. MECA, white paper, Washington, December 2007. Retrieved on 15/04/2016 from http://www.meca.org/galleries/files/MECA_Diesel_White_Paper_12-07-07_final.pdf

May, J., Favre, C. & Bosteels D. (2013). Emissions from Euro 3 to Euro 6 light-duty vehicles equipped with a range of emission control technologies. AECC, November 2013.

McCormick, R., Graboski, M., Alleman, T., & Alvarez J. (2003). Quantifying the Emission Benefits of Opacity Testing and Repair of Heavy-Duty Diesel Vehicles. Energy and Environmental Analysis, Inc., Arlington, VA 22209. Environmental science and technology, February 2003, doi: 10.1021/es0256919

Ministère de l'écologie, du développement durable et de l'énergie (2015). La loi n°2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte. Legifrance. retrieved on 08.02.2016 from http://www.legifrance.gouv.fr/eli/loi/2015/8/17/2015-992/jo/article_65.

Molden, N. (2015). Where do Euro 6 cars stand? Presentation from Emission Analytics at the AECC RDE conference, April 2015

National Heavy Vehicle Regulator (NHVR) (Australia) (2016). Heavy Vehicle (Vehicle Standards) National Regulation. Retrieved on 29/02/2016 from https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/H/HeavyVehVSNR.pdf

National Research Council. (2001). Evaluating Vehicle Emissions Inspection and Maintenance Programs. the National Academy of Sciences , National Academy Press 2101 Constitution Ave., NW Box 285 Washington, DC 20055 800–624–6242 202–334–3313.

National Transport Commission (2006). Road transport legislation – Vehicle Standards, Amendment Regulations 2006 (No.1), Rule 147A, 15 February 2006. Retrieved on 29/03/2016 from http://www.austlii.edu.au/cgi-bin/download.cgi/au/legis/cth/num_reg/ntctlvsar20061n37o20061075

Norris, J O W. (2002). An In-Service Emissions Test for Spark Ignition (SI) Petrol Engines: Phase 2b Report - Identification of options for alternative test procedures. EMStec/02/027. EMstec, Didcot.

Norris, J O W. (2005). Low Emission Diesel Research CP17/18/770: Phase 3 – Report. Report AEAT/ENV/R/1873/Issue 1. AEA Technology – Environment, Didcot, UK. retrieved on 31/03/2016 from https://www.transportoffice.gov.uk/crt/repository/Low%20Emission%20Diesel%20Research%20-%20Annex%201.pdf

Pando, L. Á. G. (2016) Desarrollo de soluciones para la medicion de nox y microparticulas en estaciones ITV, Madrid: itv AECA, 12/07/2016. retrieved on 9/2/2018 from http://www.f2i2.net/documentos/lsi/jornadas/20160712_Emisiones/Desarrollo%20de%20soluciones%20para%20la%20medici%C3%B3n%20de%20NOx%20y%20micropart%C3%ADculas%20en%20estaciones%20ITV%20(2).pdf

Park, J. (2015). The effects of the emission test using a chassis dynamo in Korea. [PowerPoint slides in PDF document]. CITA Conference Dubai U.A.E., 2015, Korea Transport Safety Authority. retrieved on 11/03/2016 from http://citainsp.org/wp-content/uploads/2016/01/4.-Workshop-D-Final-Presentation.pdf

Petelet, G. (2015). CAP3050 - NO_x measurement & Diesel engines euro 4/5/6. [PowerPoint slides in PDF document]. CITA WG2, 8th meeting 7th & 8th October 2015, London

Pillot, D., Legrand-Tiger, A., Thirapounho, E., Tassel, P., & Perret, P. (2014). Impacts of inadequate engine maintenance on diesel exhaust emissions. Transport Research Arena 2014, Paris

Posada, F., Bandivadekar, A., & German, J. (2012). Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles. Washington: ICCT. Retrieved on 21/04/2016 from http://www.theicct.org/sites/default/files/publications/ICCT_LDVcostsreport_2012.pdf

Posada, F., Yang, Z. & Muncrief, R. (2015). Review of Current Practices and New Developments in Heavy-Duty Vehicle Inspection and Maintenance Programs. ICCT 2015, International Council on Clean Transportation, 1225 , Street NW Suite 900, Washington DC 20005 USA.

Samaras, Z. & Zachariadis, T. (1995). The Inspection of In-Use Cars in Order to Attain Minimum Emissions of Pollutants and Optimum Energy Efficiency. Detailed Report 1 - Review of Short Tests. LAT Report 9502. Aristotle University of Thessaloniki.

Sands, J. (2015). Introduction to Monitoring and Enforcement of Light-Duty and Heavy-Duty Vehicle Exhaust Emissions with Remote Sensing Services. [PowerPoint slides in PDF document]. CITA Conference Dubai U.A.E., 2015, Opus Inspection. retrieved on 4/08/2016 from http://citainsp.org/wp-content/uploads/2016/01/5.-Workshop-B1-Final-Presentation.pdf

Schnitzler, J. (2009). Particulate Matter and NO_x Exhaust Aftertreatment Systems. FEV Motorentechnik GmbH, 1.09.2009. Retrieved on 15/04/2016 from http://www.fev.com/fileadmin/user_upload/Media/TechnicalPublications/Diesel_Systems/ParticulateMatterAnd NO_xExhaustAftertreatmentSystems.pdf

Scholz et al. (2015). PEMS-Messungen an drei Euro 6-Diesel-Pkw auf Streckenführungen in Stuttgart und München sowie auf Außerortsstrecken. March 2015

Sira Ltd. (2003a). Remote Measurement of Vehicle Emissions at Low Cost. Final Technical Report. REVEAL, project funded by the European Community under the ‘Competitive and Sustainable Growth’ Programme (1998-2002), Growth-1999-10657

Sira Ltd. (2003b). Remote Measurement of Vehicle Emissions at Low Cost. Recommendations for use in Europe of Remote Sensing Devices (RSDs) for measurement of motor exhaust emissions. REVEAL, project funded by the European Community under the ‘Competitive and Sustainable Growth’ Programme (1998-2002), Growth-1999-10657

Sjödin, A., & Jerksjö, M. (2008). Evaluation of European road transport emission models against on-road emission data as measured by optical remote sensing. Swedish Environmental Research Institute, Göteborg, Sweden. 17th International Conference 'Transport and Air Pollution' 2008, Graz. Retrieved on 12/12/2016 from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.519.7085&rep=rep1&type=pdf

Stedman, D. & Bishop, G. (1996). Measuring the Emissions of Passing Cars. Acc. Chem. Res., 29:489-495, 1996. Retrieved on 10/08/2016 from http://www.feat.biochem.du.edu/assets/publications/Passing%20Cars_acr_29_1996.pdf

Szabo & Dutta (2003). Strategies for total NO_x measurement with minimal CO interference utilizing a microporous zeolitic catalytic filter, Sensors and Actuators B 88 (2003), pp. 168–177.

Texas A&M Transportation Institute. (2013). Heavy-Duty Diesel Inspection and Maintenance Pilot Program. October 2013. Retrieved on 2/3/2013 from http://www.nctcog.org/trans/air/hevp/documents/NCTCOG_DieselIM_Final_Report_UpdatedOctober2013.pdf

Tietge, U., Diaz, S., Mock, P., German, J., Bandivadekar, A., Ligterink, N. (2016). From Laboratory to Road. A 2016 update of official and 'Real-world' fuel consumption and CO2 values for passenger cars in Europe. White Paper ICCT November 2016. Retrieved on 6/04/2017 from https://cleantechnica.com/2016/11/21/icct-average-gap-official-fuel-consumption-figures-actual-fuel-use-eu-hit-42/

The International Council on Clean Transportation, ICCT. (2015) European Vehicle Market Statistics Pocketbook 2015. Berlin, 2015.

The International Council on Clean Transportation, ICCT. (2017) European Vehicle Market Statistics Pocketbook 2017/2018. Berlin, 2017.

Transport and Environment. (2013). Mind the Gap! Why official car fuel economy figures don't match up to reality. Transport and Environment, March 2013.

Transport and Environment. (2015). Don't Breathe Here – beware the invisible killer. Transport and Environment, September 2015.

United States Agency for International Development. (2004). Vehicle Inspection and Maintenance Programs: International Experience and Best Practices. Bureau for Economic Growth, Agriculture and Trade. U.S. Agency for International Development, Washington DC.

United States Environmental Protection Agency. (1998). Clean Screening in Inspection and Maintenance Programs. EPA420-F-98-023, May 1998.

United States Environmental Protection Agency. (2015). California Notify Volkswagen of Clean Air Act Violations -Carmaker allegedly used software that circumvents emissions testing for certain air pollutants. EPA, 18/09/2015. retrieved on 02.02.2016 from http://yosemite.epa.gov/opa/admpress.nsf/bd4379a92ceceeac8525735900400c27/dfc8e33b5ab162b985257ec40057813b!OpenDocument.

UTAC OTC. (2013a). RAPPORT N° OTC/2013/014, Étude sur la relation entre les anomalies de témoin OBD et les mesures pollution non-conformes relevées lors des contrôles techniques des véhicules légers, December 2013. Retrieved from http://www.utac-otc.com/Upload/base_doc/3917/OTC-2013-14%20-%20Etude%20OBD%20UTAC.pdf

UTAC OTC. (2013b). Instruction technique SR/V/F9-3 : Procédure de contrôle de l'OBD VERSION F applicable au 15/07/2013, May 2013. Retrieved from http://www.utac-otc.com/Upload/base_doc/3793/SRVF9-3%20version%20F_15052013.pdf

VdTÜV and DEKRA. (2010). Emission Check 2010 Teil 2 – Diesel.

VdTÜV and DEKRA. (2013). Projectgemeinschaft Emission Check 2020 Teilprojekt 1 – Auswirkung von Fehlern und Verschleiss an modernen Otto- und Dieselfahrzeugen mit Direkteinspritzung auf das Abgasverhalten.

Vlad, D. (2008). Study Integrated Thesis Literature Research into Technical and Market Status of CO and NO_x Gas Sensors, Rheinisch Westfälische Technische Hochscule, Aachen 2008.

Vyt, S. (2008). Voorbereidende haalbaarheidsstudie voor de implementatie van een vermogenbank in de emissiekeuring voor personenwagens (Unpublished bachelor thesis). Karel de Grote Hogeschool - Katholieke Hogeschool Antwerpen-Departement Industriële Wetenschappen en Technologie - Campus Hoboken.

Weiss, M., Bonnel, P., Hummel, R., Manfredi, U., Colombo, R., Lanappe, G., Le Lijour, P. & Sculati, M. (2011). Analyzing on-road emissions of light-duty vehicles with Portable Emission Measurement Systems (PEMS). European Commission Joint Research Centre, Institute for Energy, EUR24697EN-2011, Ispra.

Yang, L., Franco, V., Campestrini, A., German, J. & Mock, P. (2015). NO_X control technologies for Euro 6 Diesel passenger cars - Market penetration and experimental performance assessment. ICCT 2015, International Council on Clean Transportation, Neue Promenade 6, 10178 Berlin

8. Glossary of terms

The following table provides definitions for terms relevant to this document.

4WD	Four-wheel drive, (4×4)
a	Acceleration in [m/s^2]
A	Frontal surface in [m^2]
ABS	Anti-lock braking system
ASM	Acceleration simulation mode
BAR	Oregon Bureau of Automotive Repair
BC	Black Carbon
CADC	Common Artemis driving Cycle
CARB	California Air Resources Board
CCFET	Capacitive-Coupled Field-Effect Transistor
CF	Conformity Factor
CO	Carbon monoxide
CO_2	Carbon dioxide
CUEDC	Composite Urban Emissions Drive Cycle
CVS	Constant volume sampling (system)
C_w	Drag coefficient
Cyl	Engine displacement in [cm^3]
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DTC	Diagnostic trouble code
EF	Emission Factor
EGR	Exhaust gas recirculation
EOBD	European on-board diagnostics
EPA	Environmental Protection Agency
EU	European Union
Euro 1, 2, 3, …	Emission standards for passenger cars
Euro I, II, III …	Emission standards for large goods vehicles
FID	Flame ionization detector
FTIR	Fourier-transform Infra-red spectroscopy
FTP	(US) Federal Test Procedure
HC	Hydrocarbons
HDV	Heavy Duty Vehicle
HGV	Heavy Good Vehicles
I/M	Inspection and maintenance
ISO	International Organization for Standardization
k	Absorption coefficient
K	Kelvin, unit of measure for temperature
LDDV	Light-Duty Diesel Vehicles

LDV	Light Duty Vehicle
LLSP	Laser-Light-Scattering Photometry
LNT	Lean NO_x trap
m	Vehicle mass;
MAF	Mass Air Flow (sensor)
$\dot{m}_{air}$	Air Mass flow in [kg/h]
MIL	Malfunction indicator lamp
N	Revolutions per minute
NDIR	Non-dispersive infrared absorption spectroscopy
NDUV	Non-dispersive ultraviolet absorption spectroscopy
NEDC	New European Drive Cycle
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides (NO + NO_2)
O_2	Oxygen
O_3	Ozone
OBD	On-board diagnostics
OHMS	On-road Heavy-duty Emissions Measurement System
OIML	L’Organisation internationale de métrologie légale or The International Organization of Legal Metrology
PEMS	Portable Emission measurement system
PM	Particulate Matter
PN	Particulate Numbers
PTI	Periodic technical inspection
RC	Readiness code
RDE	Real Driving Emissions
rpm	Revolutions per minute
RSD	Remote Sensing Device
SAE	Society of Automotive Engineers
SCR	Selective catalytic reduction
THC	Total hydrocarbon emissions
US	United States
USEPA	United States Environmental Protection Agency
v	Vehicle speed expressed in [m/s]
VSP	Vehicle Specific Power
v_w	Wind velocity
WLTC	World-Harmonized Light-duty Vehicle Test Cycle
λ	Oxygen/Combustibles balance (Lambda)
ρ_{air}	Air density in [kg/m³]
$\rho_{remplissage}$	Engine filling ratio (Capelec)

9. List of figures

10. List of tables