TEDDIE

A new roadworthiness emission test for diesel vehicles involving NO, NO_2 and PM measurements

Final Report

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Overview

This Report describes the work completed during the TEDDIE (TEst(D)DIEsel) project. The project was funded by the European Commission Directorate-General for Mobility and Transport (DG MOVE) and members of the International Motor Vehicle Inspection Committee (CITA). It was undertaken by a consortium of nine organisations, with CITA as the coordinator.

The overall objective was to investigate cost-effective equipment and procedures for measuring emissions of nitric oxide (NO), nitrogen dioxide (NO_2) and particulate matter (PM) during the periodic technical inspection (PTI) of diesel road vehicles in the European Union (EU).

Project background

The current EU legislation on emission testing during PTI is contained in Directives 2009/40/EC and 2010/48/EC. For diesel engine vehicles, exhaust opacity is measured during a so-called 'free acceleration' test. The limits are vehicle-specific, and stated as 'plate' values on the vehicle.

Modern vehicles feature advanced engines with electronic control, on-board diagnostics (OBD), and emission-reduction systems such as diesel particulate filters (DPFs) and selective catalytic reduction (SCR). In recent years the PTI emission test requirements have not kept pace with developments in vehicle technology and type approval procedures, as well as the increased emphasis on NO_2 and PM mass/number with respect to air quality and human health. TEDDIE was established to examine the limitations of the current PTI approach for diesel emissions, and to investigate ways in which the test could be updated and improved.

Candidate equipment and procedures were identified through a review of the literature. The characteristics of different measuring instruments were then investigated, and then potential testing approaches were evaluated in a laboratory measurement programme. The results led to recommendations for a revised test procedure (and associated equipment). Finally, a cost-benefit analysis (CBA) for the revised procedure was undertaken.

Summary of findings

Some of the main findings of TEDDIE are summarised below in relation to the following:

- Instruments for measuring NO, NO_2 and NO_x (nitrogen oxides)[1] during PTI
- Instruments for measuring PM and opacity during PTI
- PTI test procedures
- Cost-benefit analysis
- EU PTI legislation

Instruments for measuring NO, NO_2 and NO_x

Instruments which are suitable for measuring NO or NO_2 during PTI emission tests are typically based on electrochemical cells or non-dispersive ultra violet (NDUV) spectroscopy. The NDUV instrument used in TEDDIE performed well in the tests. For electrochemical cells, on the other hand, improvements are required in a number of areas, including long-term stability, especially for NO_2 measurement, reduced cross sensitivity to other exhaust components, and dynamic response. Following such developments, instruments using electrochemical cells might be able to meet PTI requirements.

[1] NO_x is, by convention, the sum of NO and NO_2, usually expressed as NO_2-equivalents.

Instruments for measuring PM and opacity

The TEDDIE tests involved three PM instruments using the laser light scattering principle (LLSP) and one 'escaping current' sensor. All the instruments were essentially prototypes, but the level of development was higher than that of the NO and NO_2 instruments.

The LLSP measurements were sufficiently accurate and stable, and had the necessary dynamic response characteristics and resolution, for testing modern vehicles in PTI programmes. Excessive PM emissions could clearly be identified, and the correlation with results from type approval tests was significantly better than for the opacimeters in current use. The cost of LLSP instruments is comparable to that of opacimeters. However, a practicable calibration procedure for LLSP instruments is still required, and a certification procedure for their use in PTI emission also needs to be established.

The escaping current sensor was an early prototype, and the measurement procedure was slightly more complicated than that for LLSP instruments. Such sensors will probably undergo further development, and should be re-evaluated for use in PTI.

PTI test procedures

Several different PTI test procedures were investigated in laboratory tests on five Euro 5/6 compliant passenger cars and one Euro V heavy-duty engine. The impacts of various simulated faults (such as damage to DPFs and faults with SCR) on emissions were measured, and the ability of different procedures and instruments to identify them was evaluated relative to the type approval tests. The ability of the OBD system to identify faults was also assessed. The TEDDIE tests were designed to answer specific questions, and the findings are summarised below.

1. *Can faults in NO_x-control systems be detected using NO_x measurement during PTI tests?*

   For the cars the simulated faults which led to increases in NO_x emissions over the type approval test were not systematically detected by the PTI tests, and a suitable PTI test could not be identified. On the other hand, some of the faults did not lead to emission levels above the vehicle-specific limits, and therefore such faults would not have been identified in the type approval test itself. This shows that exhaust emission measurement alone is not sufficient for finding faults in the NO_x-control systems of modern diesel vehicles. Additional component testing might be an option for detecting failures during PTI with a low error of omission and commission.

   For the heavy-duty engine only SCR faults were investigated. Whilst these faults led to increases in NO_x over the type approval test, none were identified by the PTI tests, primarily because the SCR system does not work efficiently under the low load conditions associated with such tests. Therefore, the overall results did not provide sufficient evidence to support the use of NO_x measurement during PTI.

2. *Can faults in PM-control systems be detected using PM measurement during PTI tests?*

   For the cars the PTI tests and opacity instruments could not differentiate between vehicles with and without faults for type approval PM values lower than around 5 mg/km. The PTI instruments for measuring PM (in mg/m^3) showed a better discrimination, and an acceptable response to low PM emissions.

   The faults in the cars which led to large increases in PM emissions, such as major defects in 'closed' DPFs, were, on the whole, detected by the PTI tests. In generally the results for measuring PM were better than those for NO_x. Of the unloaded tests, the free acceleration test tended to be the best practical indicator of faults.

The SCR faults in the heavy-duty engine had little effect on PM emissions. It would be of interest in subsequent work to investigate engine-related problems, such as faulty injectors or EGR valves, as well as after-treatment faults, which have an impact on PM emissions.

3. *Can faults in emission-control systems be detected using the NO_2/NO_x ratio?*

   The results for the NO_2/NO_x ratio were too variable and inconsistent to enable them to be used reliably for identifying faults in specific components. Whilst this metric might have been useful for identifying faults in Euro 3 and Euro 4 vehicles, in Euro 5 and Euro 6 vehicles the ratio is affected by several different elements of the emission-control system. The ratio is also very sensitive to the actual after-treatment technologies and coatings used.

   NO_2 emissions from the heavy-duty engine which were vey low, and the NO_2/NO_x ratio was therefore not suitable for identifying faults.

4. *Can faults in emission-control systems be detected using OBD?*

   For all cars tested the OBD system could not detect the simulated faults. However, OBD is not specifically designed to respond to these faults, and for cars it may - in combination with stringent limit values - still be useful for identifying failures in the NO_x-reduction system as an additional measure in combination with PM measurment. This requires further investigation in field tests.

   For the heavy-duty engine the OBD system was able to identify the faults with the urea dosing of the SCR, and DTCs were stored.

It was therefore concluded that the combination of the free acceleration test and new instruments measuring PM in mg/m^3 represents a viable option for the future PTI emission testing of cars. Further evaluation is needed for heavy-duty vehicles. The measurement of NO_x emissions (or the NO_2/NO_x ratio) and the use of OBD during PTI emission tests require further investigation in field tests.

Cost-benefit analysis

The CBA only covered diesel passenger cars. The average benefit per year of a revised roadworthiness emission test for diesel cars (based on a free acceleration test with new PM instruments) was calculated to be 864 million euro. Other criteria apart, the estimated benefits would support and immediate regulatory switch to the revised test. Implementation of a strategy to replace opacity measurement devices over a five-year period would be economically preferable to immediate replacement.

Recommendations for EU PTI legislation

Several preliminary recommendations were identified for consideration in relation to the legislation, including the following:

- The free acceleration test, as currently defined in the legislation, remains a suitable procedure for modern diesel cars. However, consideration should be given to how engine speed limiters are addressed so that the free acceleration test can be conducted for all vehicles.
- In the current legislation the diesel emission limits are stated as *k* values in m^{-1}, which are the units of opacimeters. Consideration should be given to a changeover to the measurement of the mass concentration of PM (in mg/m^3) for new vehicles meeting a specific emission standard.
- Should such a changeover be adopted, the legislation would need to make an allowance for the use of appropriate PM-measurement devices (such as LLSP instruments).

- There would also be a need to define a correlation between PM values in mg/m^3 and *k* values in m^{-1} to be used in the devices.
- General limit values for PM (or any adjustments to plate values) should be based on the findings of field trials.
- Pending the results of further studies, the extension of the use of OBD in the legislation should be considered for the evaluation of components and individual systems emissions and other parameters which are relevant to PTI tests (*e.g.* engine speed) as a supplementary part of the emission.

1 Introduction to the TEDDIE project

This report describes the work completed during the TEDDIE[2] project which ran from December 2010 to December 2011. This first chapter provides an overview of the project, including the objectives, the funding, the administrative arrangements and the work programme. The subsequent chapters present the background to the project, the work conducted, the findings, and the recommendations. A glossary of terms used in the report is provided in Appendix A.

1.1 Objectives and requirements

The overall objective of TEDDIE was to investigate cost-effective equipment and test procedures for measuring emissions of nitric oxide (NO), nitrogen dioxide (NO_2) and particulate matter (PM) during the periodic technical inspection (PTI) of diesel road vehicles in the European Union (EU). The context within which the project was conceived is described in greater detail in chapter 2.

The starting point of TEDDIE was the existing PTI legislation in the EU, and the test procedures and equipment specified therein. This legislation is contained in Directives 2009/40/EC and 2010/48/EC (amendments to 2009/40/EC), and essentially requires the following:

- For vehicles with positive ignition (petrol) engines, the measurement of the concentration of carbon monoxide (CO) in the exhaust with the engine at idle and high idle, as well as the lambda value (*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. This is often referred to as a 'free acceleration smoke' (FAS) test.

The measurement of NO, NO_2 or PM is not currently a requirement of the EU legislation.

In TEDDIE candidate equipment and procedures were identified through a review of the international literature. The characteristics of different measuring instruments were investigated, and then potential PTI testing approaches were evaluated in a laboratory measurement programme. The results led to recommendations for a revised test procedure (and associated equipment). Finally, a cost-benefit analysis was undertaken to provide the European Commission (EC) with a basis for further investigation.

The PTI emission test procedure had to meet a number of technical criteria. For example:

- The test had to provide accurate results.
- The test had to be repeatable.
- The test and limit values had to be appropriate for modern diesel and petrol engines that meet the Euro 5/V and 6/VI emission standards.
- The test had to be capable of detecting major malfunctions of overall emission-control systems.

PTI emission tests are conducted in large volumes in test and repair centres rather than in well-equipped laboratories. There were therefore a number of practical criteria which also defined the boundary conditions for the test. For example:

- Overall costs (per test) to testing centres, authorities and vehicle owners could not be excessive. Consequently:
    - The test had to be relatively short, simple and pragmatic.

[2] TEDDIE = TEst (D) DIEsel

    - The test equipment had to be relatively inexpensive (*i.e.* comparable to the cost of current equipment).
- The test equipment had to be sufficiently reliable and robust for the test centre environment.
- The test had to be applicable in all individual EU Member States.

These practical criteria effectively meant that the use of laboratory-grade equipment - such as the power-absorbing chassis dynamometer and constant volume sampling system (CVS)[3] used for type approval – was quickly excluded as an option. Consideration therefore had to be given to the difficulties associated with measuring the target pollutants using PTI-grade equipment and procedures.

1.2 Funding

TEDDIE was funded primarily by the European Commission Directorate-General for Mobility and Transport (DG-MOVE[4]) under a service contract (No. MOVE/MAR/2010/D3/59-1/S12.583229/TEDDIE). An additional budget was made available by the International Motor Vehicle Inspection Committee (CITA) and four of its members (Bilprovningen in Sweden, Capelec in France, Centar za vozila Hrvatske in Croatia and SNCT in Luxemburg) to cover supplementary work and unforeseen expenditure.

1.3 Consortium

The project was undertaken by a consortium of nine organisations, including CITA which acted as the coordinator. The partners in the TEDDIE consortium were:

- CITA (coordinator)
- TÜV NORD Mobilität from Germany
- DEKRA Automobil GmbH from Germany
- GOCA from Belgium
- SGS from Switzerland
- TRL Limited from the UK
- Peter Stricker from Austria
- IERC from Germany
- Oliver Hatton from New Zealand

1.4 Project administration

The roles of the various groups involved in the administration of the project are described below.

- The *CITA Bureau Permanent* had overall responsibility for the project deliverables.
- The *CITA Regional Advisory Group (RAG) for Europe* is responsible for managing CITA's programme of projects and development of technical best practice. It provided guidance and technical advice to the Project Steering Group (see below) during the project.
- The *Project Steering Group (PSG)* consisted of representatives of the Bureau Permanent, the RAG and the Project Management Team (see below). It was accountable to the Bureau Permanent for steering the work within the project Work Packages.

[3] In a CVS exhaust gases are sampled from a dilution tunnel. This provides clear advantages; dilution of the exhaust reduces the risk of water condensation in the sampling and transport lines, and reduces pressure and temperature fluctuations. This simplifies the sampling procedure. The flow rate can also be precisely controlled and measured.

[4] PTI is one of the responsibilities of DG-MOVE.

- A *Project Management Team (PMT)* - composed of experienced members of the consortium - oversaw the project. This team was responsible for the following:
  - Defining the detailed project structure.
  - Monitoring and managing progress and performance.
  - Controlling deliverables, and drafting the interim and final reports.
  - Evaluating the quality and efficiency of the work.
  - Communication and clarification of project goals and working arrangements to ensure that the project was carried out in an efficient and effective manner.
- *CITA members and other stakeholders* were consulted during the project to obtain technical information and any other data that were needed. A key stakeholder was the European Garage Equipment Association (EGEA).
- The *project manager* oversaw the day-to-day work, based on the input of Work Package leaders, and set the agendas for meetings. The project manager was also responsible for liaison with the EC client.

Quality control and assurance procedures were applied during the project to ensure that the data and reporting were of the highest quality. The measurements were conducted at accredited laboratories with highly experienced staff. A risk register was produced to describe foreseeable risks which, if they were to have materialised, could have had adverse consequences for the project. The register was regularly reviewed and updated by the Project Management Team, and action was taken where required. The reports produced during the project were reviewed internally by all project partners.

1.5 Work programme

The project was divided into eight Work Packages (WPs), as summarised in Table 1.

Table 1: Project Work Packages.

WP no.	WP title	WP leader
1	Project management	TÜV
2	International review of PTI emission tests	GOCA
3	Investigation of instruments for measuring emissions	DEKRA
4	Investigation of PTI procedures	TÜV
5	Data analysis and new PTI method	SGS
6	Cost-benefit analysis	IERC
7	Reporting	TRL
8	Project meetings	CITA

Work Package 1 involved the technical and financial administration of the project, the coordination of activities, and liaison with the European Commission client. An extranet site was set up by TÜV NORD to facilitate communication between partners and the archiving of project-related documents.

Work Package 2 featured a review of the international regulations and literature on PTI emission testing, including measuring instruments, existing test procedures and future plans, and relevant technical studies. It also provided recommendations for the work to be carried out during the TEDDIE measurement programme. This review is summarised in chapter 3 of the report.

Work Package 3 involved a laboratory investigation of candidate instruments for measuring emissions of NO, NO_2 and PM during PTI. This work is described in chapter 4.

In Work Package 4 emission measurements were performed on five passenger cars and a heavy-duty engine. Various emission-related faults were simulated, and the ability of different instruments and PTI procedures to detect these faults was evaluated. This work is covered in chapter 5.

Based on the analysis of the data from the measurement programme some proposals for a revised test procedure for PTI were identified in Work Package 5. This work is described in chapter 6.

Work Package 6 involved a cost-benefit analysis for the revised test method using an approved methodology, as described in chapter 7.

A summary of the key points is provided at the end of each of chapters 2-7, and the conclusions and recommendations of the project are provided in chapter 8.

1.6 Meetings

Several meetings were held during the project, and these are listed in Table 2.

Table 2: Project meetings.

Date	Location	Description
24/01/2011	Brussels	Project kick-off meeting
02/03/2011	Stuttgart	Meeting between WP3 and WP4 participants
15/06/2011	Brussels	Interim project meeting
29/08/2011.	Cologne	Meeting between WP3, WP4, WP5 and WP6 participants
05/102011.	Stuttgart	Meeting with instrument manufacturers
07/11/2011	Brussels	Preparation for stakeholder meeting
08/11/2011	Brussels	Stakeholder meeting
29/11/2011	Brussels	Final project meeting

2 Understanding the context

2.1 Air pollution from road transport

Road transport is a source of air pollutants which can have adverse effects on various spatial and temporal scales. The air pollutants which are currently causing greatest concern in terms of local air quality, primarily because of their impacts on human health, are airborne PM, NO_2 and ground-level ozone[5]. Road transport is an important contributor to all three (Krasenbrink *et al*., 2005). Emissions of nitrogen oxides (NO_x)[6] from road vehicles are also implicated in regional phenomena such as acidification, eutrophication and loss of biodiversity, as well as the formation of secondary PM in the atmosphere. Moreover, road transport is a major source of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

The significance of road transport as a source of air pollution can be illustrated by reference to sectoral emissions for the EU-27 countries, based on submissions to the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). In 2008 road transport was the largest contributor to NO_x emissions (41%), and was also a major contributor to PM emissions (EEA, 2010). In urban areas its impact is even greater due to the density of the road network, the volume of traffic, and the close proximity of the population to the emission source.

Legislation and strategies to reduce exhaust emissions from road vehicles have been in place for several decades. Calculations have established that emissions of regulated pollutants from road transport in the EU peaked in the early 1990s (Keuken *et al*., 2005), and have been reducing since then as controls on vehicles and fuels have tightened (see section 2.2). However, in many urban areas the concentrations of NO_2 and PM_{10} (particulate matter with an aerodynamic diameter of less than 10 μm) still frequently exceed health-based limits and are not decreasing (AQEG, 2004; EEA, 2007; Harrison *et al*., 2008).

The importance of NO_2 and particulate matter is explained in more detail below.

2.1.1 Nitrogen dioxide

NO_2 is an irritant and oxidant which can damage cell membranes and proteins. It has been linked to a range of adverse health effects, including asthma and cancer, but the most consistent association has been found with respiratory outcomes (COMEAP, 2009).

NO_2 is predominantly a secondary pollutant, its major atmospheric source being the oxidation of NO emitted from combustion sources - notably road vehicle exhaust. However, some NO_2 is emitted directly from vehicles, and this is commonly referred to as 'primary NO_2'. Emissions of NO_x from vehicle exhaust are regulated at type approval (see section 2.2), but NO_2 emissions *per se* are not.

In fact, analyses have indicated that a significant proportion of ambient NO_2 must be emitted directly from vehicle exhaust, and that the direct road traffic contribution to ambient NO_2 has increased in recent years (Jenkin, 2004; Carslaw and Beevers, 2004; Carslaw, 2005; Hueglin *et al*., 2006; Grice *et al*., 2009). Two contributing factors have been cited:

[5] Ozone is not produced directly from emission sources but is formed from precursors (*e.g.* NO_X and hydrocarbons) by photochemical reactions in the atmosphere. It is therefore regarded as a regional air pollution problem, and is not considered in detail in this report.
[6] NO_x is, by convention, the sum of NO and NO_2, usually expressed as NO_2-equivalents.

(i) Diesel vehicles emit more NO_x than petrol vehicles, and with a larger proportion of NO_2 in NO_x (termed *f*-NO_2). The market share of diesel vehicles has increased in many European countries. For example, the share of first registrations of diesel passenger cars in Finland increased from 17% in 2005 to 52% in 2008 (Lappi *et al.*, 2008).

(ii) The average value of *f*-NO_2 in diesel exhaust is increasing. This appears to be linked to the growth in the use of specific after-treatment technologies in modern diesel vehicles which involve *in situ* generation of NO_2, such as catalytically regenerative particle filters (Carslaw, 2005). This is treated in more detail in section 2.3.2.

Background concentrations of ozone are also increasing (Keuken *et al.*, 2009). As the ozone concentration increases the amount of NO converted to NO_2 increases.

Furthermore, it seems likely that real-world NO_x emissions from road vehicles are not decreasing as rapidly as models are predicting (Rexeis and Hausberger, 2009). Whilst this does not, in itself, affect actual NO_2 concentrations, it does suggest that NO_x controls have not been sufficiently stringent, or that vehicles are not performing as expected.

The overall consequence is that there is now a great deal of interest in the tighter regulation of NO_x and NO_2 emissions from diesel vehicles and the effects of different after-treatment devices. Direct-injection petrol engines with after-treatment technologies will also have an important impact on NO_x emissions in the future.

2.1.2 Particulate matter

Epidemiological studies have shown that concentrations of airborne PM are correlated with hospital admissions and death rates (Dockery *et al.*, 1993; Pope *et al.*, 1995; 2002; Dominicci *et al.*, 2006). Initially, the mass concentration of airborne particles with a diameter of less than 10 µm (PM_{10}) was identified as a key metric in relation to health outcomes. However, more recent research has suggested that smaller particles are more important. Attention has focused on particles having a diameter of less than 2.5 µm ($PM_{2.5}$), although there is still a debate as to whether it is actually the mass of even smaller particles, or indeed a non-mass metric such as particle number (PN)[7], that is primarily responsible for health effects (Laxen *et al.*, 2010). In addition to health, airborne particles are responsible for a range of other adverse effects, including nuisance and visibility reduction.

Particles in diesel exhaust have a range of sizes, and the shape of the size distribution depends on whether the weighting is by number or by mass (Figure 1). There are three distinct size modes: the nucleation mode (also referred to as nuclei or nanoparticles), the accumulation mode, and the coarse mode. The nucleation mode has traditionally been defined as particles with a diameter of less than 50 nm. Accumulation mode particles range in size from around 50 nm to around 1 µm, with particles smaller than 0.1 µm being referred to as 'ultrafine'. The nucleation mode contains many more particles than the accumulation mode, although because each particle is so small the total mass is lower. The coarse mode consists of particles larger than around 1 µm.

In the context of this project, the main implication of the particle size distribution in vehicle exhaust is that the instruments used in PTI testing need to be sensitive enough to measure particles in the relevant size range (see section 3.2.2). Moreover, the sampling of vehicle exhaust should not introduce artefacts (such as losses in the sampling system).

[7] Usually expressed as the number of particles per unit volume or per kilometre.

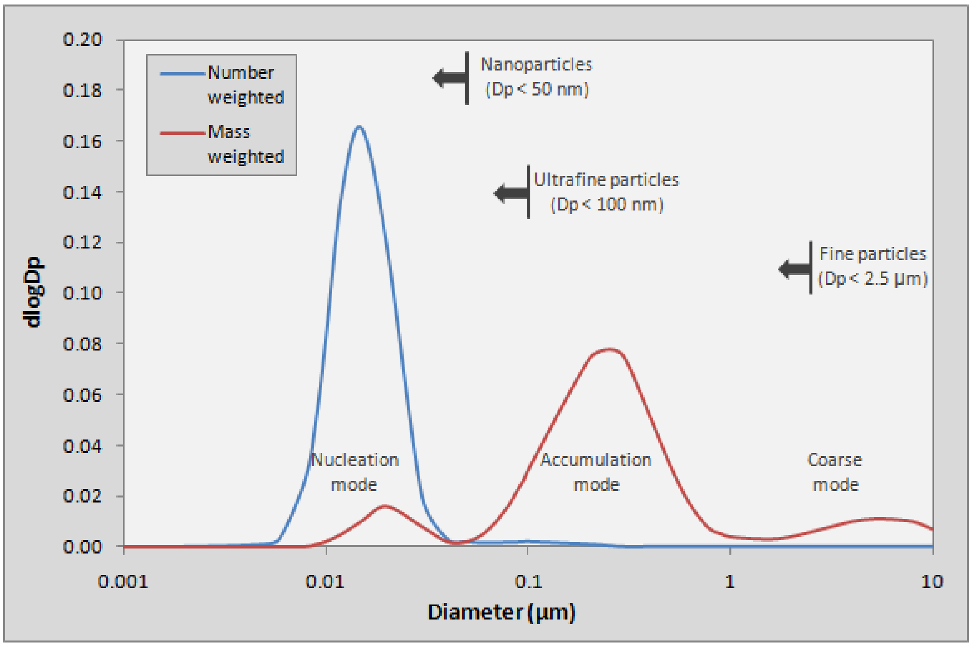

Figure 1: Typical particle size distributions in vehicle exhaust. The *y*-axis is a normalised log scale (adapted from Kittelson, 1998).

2.2 Regulation of exhaust emissions at type approval

The primary tool for combating air pollution from road transport is vehicle emission legislation. There are currently two main levels of emission legislation: type approval, which is discussed here, and periodic in-service/roadworthiness technical inspection, which is discussed in section 2.5.

In the EU emission tests are required for the type approval of all new passenger car (M_1, M_2) and light-duty vehicles (N_1, N_2), and for the engines used in heavy-duty vehicles. Emission limits have been applied to vehicles and engines at the type approval stage since the early 1970s. The exhaust pollutants which are regulated are CO, unburnt hydrocarbons (HC), NO_x and PM. The limits have been reduced in stages since they were first introduced (through progressive 'Euro' standards), and changes have been made to the test methods to make them more realistic and effective. Emission-control technologies have developed accordingly (see section 2.3).

For cars and light-duty vehicles the test procedures and limit values have been consolidated in the Euro 5 and Euro 6 legislation (Regulation (EC) No. 692/2008). In the exhaust emission test a production vehicle is placed on a power-absorbing chassis dynamometer. The driver must follow a driving cycle and the vehicle's emissions are collected and analysed. Emissions are measured over the New European Driving Cycle (NEDC), which is composed of low-speed 'urban' segments and one high-speed 'extra-urban' segment. The vehicle exhaust gases are diluted with filtered air to prevent condensation or reaction between the exhaust gas components. Dedicated analysers are used for CO, NO_x, HC and carbon dioxide[8]. CO and CO_2 are measured by non-dispersive infrared (NDIR) spectroscopy. The HC analyser is a flame ionisation detector (FID), and for NO_x a chemiluminescence detector (CLD) is used. For diesel vehicles up to and including Euro 4, PM was collected separately from the other pollutants on a filter. For Euro 5 and Euro 6 vehicles PM mass

[8] The measurement of carbon dioxide permits fuel consumption to be calculated using the carbon balance method.

and PN are measured using the new PMP[9] procedure. The PN limit is designed to prevent the possibility of the PM mass limit being met using technologies that would enable a high number of ultrafine particles (<0.1 μm diameter) to pass (see section 2.3.2). The emission limits are stated in grammes of pollutant (or number of particles) per kilometre (Table 3).

Table 3: Type approval limits for NO_x and PM from diesel cars.

Stage	Date	Limit value			
		HC+NO_x (g/km)	NO_x (g/km)	PM (g/km)	PN (#/km)
Euro 1	1992.07	0.97	-	0.14	-
Euro 2 IDI	1996.01	0.7	-	0.08	-
Euro 2 DI	1996.01	0.9	-	0.10	-
Euro 3	2000.01	0.56	0.50	0.050	-
Euro 4	2005.01	0.30	0.25	0.025	-
Euro 5a	2009.09	0.23	0.28	0.005[(a)]	-
Euro 5b	2011.09	0.23	0.18	0.005[(a)]	6×10^{11}
Euro 6	2014.09	0.17	0.08	0.005[(a)]	6×10^{11}

(a) 0.0045 g/km using PMP measurement procedure.

The emission standards for heavy-duty vehicles apply to all vehicles with a maximum laden mass of more than 3,500 kg. The responsibility for compliance is borne by the engine manufacturer, and it is therefore the engine that is subject to type approval. The engine is operated on a test bed, with the exhaust emission limits being expressed in g/kWh (Table 4).

Table 4: Type approval limits for NO_x, PM and smoke from heavy-duty engines.

Stage	Date	Limit value[(a)]		
		NO_x (g/kWh)	PM (g/kWh)	Smoke (m^{-1})
Euro I	1992	8.0	0.612[(b)]	-
Euro II	1996 (Oct)	7.0	0.25/0.15[(c)]	-
Euro III	1999 (Oct)[(d)]	2.0	0.02	0.15
	2000 (Oct)	5.0	0.10[(e)]	0.8
Euro IV	2005 (Oct)	3.5	0.02	0.5
Euro V	2008 (Oct)	2.0	0.02	0.5
Euro VI	2013(Jan)	0.4	0.01	-

(a) For the European Stationary Cycle. Smoke is measured over European Load Response test.
(b) 0.36 g/km for engines > 85 kW.
(c) New limit introduced in October 1998.
(d) For 'enhanced environmentally friendly vehicles' (EEVs) only.
(e) 0.13 g/km for smaller low-speed engines.

[9] The Particulate Measurement Programme (PMP) investigated the possibility of including a PN standard in the legislation. One of the conclusions was that the nucleation mode should be prevented to ensure consistent and repeatable measurement of PN concentrations (Andersson, 2007). A sampling procedure developed in PMP has been incorporated in the legislation.

The legislation for heavy-duty engines is consolidated in the Euro V/VI standards (Regulation (EC) No. 595/2009). In addition to introducing more stringent emission limits, the Euro V/VI regulation includes a concentration limit of 10 ppm for ammonia (NH_3), which can be emitted due to the use of additive-based control systems (see section 2.3.2). A particle number limit is also planned in addition to the mass-based limit. A maximum limit for the NO_2 component of NO_x emissions may also be defined

2.3 Emission-reduction technologies for diesel vehicles

2.3.1 Overview

Reductions in emissions from diesel engines can be realised in the short-term through improved engine design. The main challenge concerning diesel engine combustion is the simultaneous reduction of NO_x and PM, as there is a well-established trade-off between the two pollutants; engine modifications which reduce NO_x - such as exhaust gas recirculation (EGR)- tend to increase PM, and *vice versa*. The introduction of increasingly stringent emission standards for both pollutants has therefore made it necessary to use exhaust after-treatment. The most common after-treatment devices are diesel oxidation catalysts (DOCs) to address CO and HC emissions, diesel particulate filters (DPFs), and systems such as selective catalytic reduction (SCR) to address NO_x emissions. Whilst such technologies are generally fitted during manufacture, retrofitting is also a common pollution-reduction strategy.

Table 5 shows the different emission-reduction devices which are typically required for light-duty diesel vehicles in each Euro category. In modern vehicles various elements are used in combination, and these have different effects on the properties and composition of the exhaust gas.

Table 5: Typical exhaust after-treatment for diesel light-duty vehicles.

Emission standard		Emission-reduction technology				After-treatment control
Stage	Date	EGR	DOC	DPF	SCR[a]	
Pre-Euro 1		-	-	-	-	-
Euro 1	1993	✓	✓	-	-	-
Euro 2	1996	✓	✓	-	-	Passive
Euro 3	2000	✓	✓	✓(CRT[b])	-	Passive
Euro 4	2005	✓	✓	✓(CRT)	-	Active
Euro 5a/b	2009/11	✓(LP[c])	✓	✓	✓	Active
Euro 6	2014	✓(LP)	✓	✓	✓	Active

(a) SCR or NO_x trap. (b) CRT = continuously regenerating trap®. (c) LP = low-pressure EGR.

The progression of the limit values for heavy-duty engines at type approval, and the combination of devices for simultaneously reducing NO_x and PM to comply with the limits, are shown in Figure 2. The curve shows the engine-out emissions and illustrates the typical NO_x-PM trade-off. Engine-out emissions are influenced mainly by the level of engine development, such as the type of diesel injection system, and by the configuration of the EGR. The potential to reduce exhaust emissions of NO_x and PM below the Euro IV limits without after-treatment is limited.

The different chemical reactions taking place in the exhaust stream, and the physical and chemical properties of the exhaust, need to be considered when investigating methods for testing diesel vehicles at PTI. For example, there is a need to understand why the proportion of NO_x that is emitted as NO_2 may change. These processes are described below.

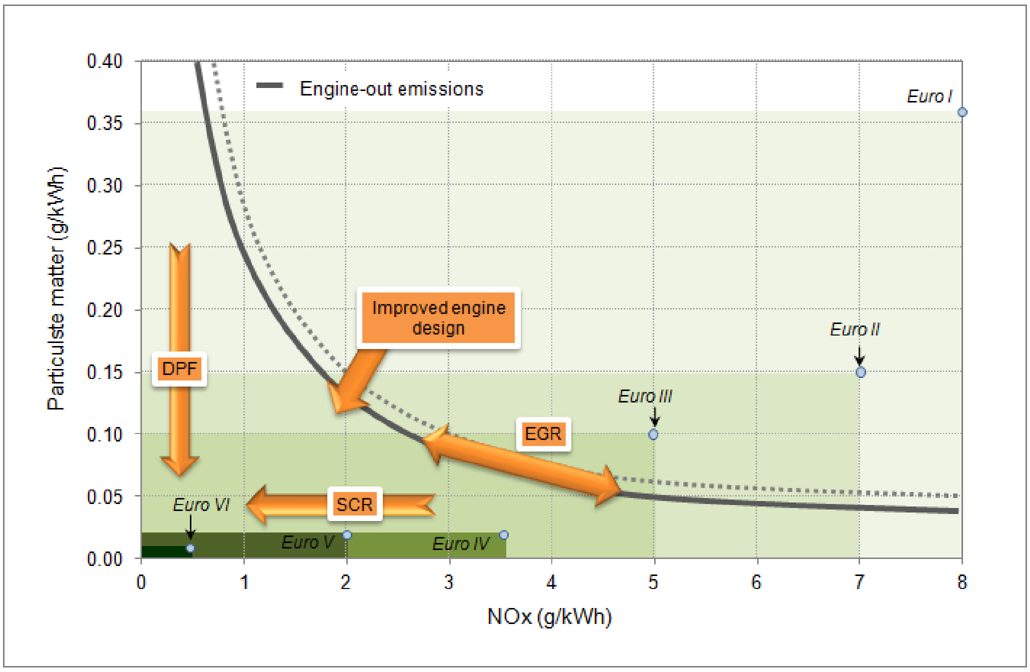

Figure 2: Options for simultaneous reduction of NO_x and PM emissions from heavy-duty engines.

2.3.2 Types of technology

Exhaust gas recirculation (EGR)

EGR has been fitted to road vehicles in Europe for some years. It works by redirecting a portion of the engine exhaust gas back into the combustion chamber. In a diesel engine this leads to a reduction in NO_x emissions via two mechanisms. Firstly, it reduces the peak combustion temperature[10]. Secondly, the recirculated exhaust gas replaces some of the excess oxygen in the pre-combustion mixture, thus reducing the amount of oxygen available for NO_x formation. However, EGR also increases the production of PM.

Diesel oxidation catalyst

A DOC is a flow-through device consisting of a substrate which is coated with an active catalytic layer of precious metal such as platinum or palladium. As the exhaust gases pass through the catalyst CO, unburnt HC and liquid HC particles are converted into less harmful compounds. The reactivity is a function of cell size, reactive surface and catalyst load, although emissions of CO and HC are typically reduced with an efficiency of more that 95%.

[10] NO_x emissions are higher for higher peak combustion temperatures.

For diesel vehicles the proportion of NO_2 in engine-out NO_x emissions is usually small. However, there is some formation of NO_2 in the DOC, with the amount being dependent upon the type of coating used.

Diesel particulate filter

The usual means of complying with the stringent PM mass emission limits for modern diesel vehicles, or complying with the entry criteria for areas with access restrictions (*e.g.* low-emission zones), is through the use of a DPF which physically captures particles in the exhaust stream.

Types of DPF

DPFs can be broadly divided into two types: (i) 'open', 'partial-flow' or 'flow-through' filters which are relatively permeable and (ii) 'closed', 'full-flow' or 'wall-flow' filters, in which all the exhaust gas is treated. Partial-flow filters have filtration rates of between 30% and 90%. They are less effective than the full-flow variety, but need no maintenance and result in lower backpressure with a lower risk of blockage. They have therefore generally been used as retrofits to older vehicles. Modern vehicles are usually equipped with full-flow filters which lead to almost complete elimination (>95%) of the solid fraction (around 50-1000 nm) of PM in diesel exhaust. However, DPFs can have limited effectiveness in controlling the non-solid components, and some increases in PN have also been reported due to hydrocarbon and sulphate nucleation occurring downstream of after-treatment devices (Sakurai *et al*., 2003; Vaaraslahti *et al.*, 2004). This is one reason why the latest emission standards include limits for PN emissions.

Passive regeneration

In order to prevent the filter from blocking the captured particles must be periodically removed using heat in the exhaust stream (a process referred to as 'regeneration'). The regeneration may be 'passive' or 'active'.

In passive regeneration a catalyst is used to lower the activation energy of the combustion reaction to enable it to occur in the exhaust stream under normal operating conditions and without additional energy inputs. Passive systems are often favoured for retrofit applications because they require no complicated control system.

One of the leading passive DPF systems is the CRT. This uses a platinum oxidation catalyst upstream of an uncoated filter[11] to generate NO_2. The oxidising catalyst is usually located very close to the engine where exhaust gases will still be relatively hot and passive regeneration is possible. The NO_2 is then used to oxidise the PM that has collected on the filter:

$$[C] + 2NO_2 \rightarrow 2NO + CO_2 \qquad (1)$$

The reaction with NO_2 is more effective than the reaction with oxygen for burning off the soot, and occurs at a lower temperature than would otherwise be required. However, some 'NO_2 slip' is inevitable.

For efficient passive regeneration NO_2/soot mass ratios of more then 10, and therefore a minimum amount of NO_x, is necessary. For earlier technologies using CRTs there was sufficient NO_x, and the NO_2 proportion of NO_x coud be as much as 50% (Nissler and Stricker, 2006). However, a typical Euro 6 vehicle has low NO_x emissions and, as a result, only marginal quantities of NO_2 are available. The small amount of NO_2 that is available is converted to NO during soot regeneration or SCR reactions (see below).

[11] The filter itself may also be coated with a catalyst (know as CCRT®).

For PTI of Euro 3 and Euro 4 vehicles it could be useful to measure the NO_2/NO_x ratio in the exhaust to evaluate the condition of a particulate filter.

Active regeneration

There are essentially two types of active regeneration system: those which regenerate periodically using additional energy to raise temperature, and those which use active controls to change the conditions in the exhaust system. Active systems include the following (Kojetin *et al.*, 1993; Houben *et al.*, 1994; Gautam *et al.*, 1999; Sadler Consultants, 2006; Mayer, 2007):

- Throttling of the intake air to the cylinders to increase the exhaust temperature.
- Post-top-dead-centre fuel injection into the cylinders or into the exhaust system. Oxidation of the fuel within or upstream of the filter can then be used to burn off the accumulated PM.
- Fuel burners, electrical heaters or microwave systems within or upstream of the filter.
- Valves for thermal management of the after-treatment system

The engine control unit (ECU) instigates the regeneration process when the filter load reaches a pre-determined level (typically around 45%). Active control systems are therefore much more suitable for OEM[12] applications than for retrofit systems.

Fuel-borne catalysts

Fuel-borne catalysts may be used in conjunction with passive and active DPFs. An additive (containing iron, cerium or platinum) is injected into the fuel line or added to the fuel tank. The PM from the engine becomes impregnated with the catalyst, thus lowering the combustion temperature. This enables the DPF to be located further from the engine.

Selective catalytic reduction

SCR will be the main technology for enabling compliance with the latest NO_x emission standards. The method involves the injection of a reagent into the exhaust stream to chemically reduce NO_x to nitrogen. Typically, an aqueous urea solution is used as the reducing agent, and is fed into the system in defined doses. The admixture is monitored by checking 'ammonia slip' in the exhaust. The following equations describe the different reactions in these systems:

$$\underset{\text{urea}}{CO(NH_2)_2} \rightarrow \underset{\text{ammonia}}{NH_3} + \underset{\text{isocyanic acid}}{HNCO} \tag{2}$$

$$\underset{\text{isocyanic acid}}{HNCO} + \underset{\text{water}}{H_2O} \rightarrow \underset{\text{ammonia}}{NH_3} + \underset{\text{carbon dioxide}}{CO_2} \tag{3}$$

$$\underset{\text{nitric oxide}}{NO} + \underset{\text{nitrogen dioxide}}{NO_2} + \underset{\text{ammonia}}{2NH_3} \rightarrow \underset{\text{nitrogen}}{2N_2} + \underset{\text{water}}{3H_2O} \tag{4}$$

NO_x trap

A NO_x trap (or 'absorber') is typically a catalytic converter support that has been treated with a special wash coat containing zeolites[13], and which traps NO and NO_2 molecules. Unlike catalysts,

[12] OEM = original equipment manufacturer.

[13] Zeolites are porous aluminosilicate minerals which are commonly used as commercial adsorbents.

which involve continuous conversion, a trap stores NO_x under lean conditions and releases and catalytically reduces it under rich conditions. Various systems are available for regenerating traps. NO_x traps are usually used in conjunction with smaller engines, and are less efficient than SCR.

2.4 On-road emissions

The main factors which govern on-road exhaust emissions are the vehicle type (*e.g.* passenger car, heavy goods vehicle), the fuel type (*e.g*. petrol, diesel) and the vehicle technology. The latter usually refers to either a specific type of engine or exhaust after-treatment or, more generally, compliance with a particular emission standard.

Important considerations, especially given the context of the TEDDIE project, are the condition of a vehicle's engine and exhaust after-treatment system, and the overall level of maintenance. A vehicle may fail an exhaust emission inspection for any one of a number of reasons, although high emission rates are often a result of component ageing, component failure, or generally poor maintenance. A list of potential faults in emission-control systems, and methods by which they can be simulated in tests, is provided in Appendix B.

NO_x-reduction is dependent upon the correct functioning of the EGR, SCR and/or NO_x trap. The failure of any these systems, or damage to system components, is likely to have a significant impact on tailpipe emissions. EGR faults include, for example, malfunction or blockage of the EGR valve. SCR or NO_x trap faults include malfunction of urea dosing system, a damaged catalytic coating, or mechanical damage to the system. The ability of an after-treatment system to reduce PM emissions is affected primarily by the condition of the DPF. Faults in full-flow filters, such as mechanical damage, are relatively easy to detect. Because the efficiency of partial flow filters is variable, faults are more difficult to detect.

It has also regularly been reported that a small proportion of the vehicles on the road account for a high proportion of the total emissions, and it is likely that the identification and repair of these polluting vehicles would lead to a worthwhile reduction in total vehicle emissions. The identification and rectification of the underlying faults is therefore integral to any inspection and maintenance (I/M) programme (McCrae *et al*., 2002).

Other factors affecting on-road emissions include vehicle weight, road gradient, vehicle load, the use of auxiliary equipment (*e.g.* air conditioning), the temperature of the engine and emission-control system, the quality of the fuel (*e.g.* sulphur content), and the way in which the vehicle is operated (*i.e*. speed, acceleration, *etc*.). These should also be borne in mind when designing a PTI emission test which is representative of real-world conditions.

2.5 Periodic technical inspection in the EU

The purpose of the PTI emission test is to allow authorities to check that in-service vehicles are well maintained and conform as far as possible to their design emission levels. However, whilst type approval tests target the manufacturer, are relatively detailed, and require specialist and expensive laboratory equipment, by necessity a lower level of sophistication applies to in-service emission tests. In-service tests target the vehicle owner, are based on shorter, simplified operations of the vehicle, involve the measurement of fewer pollutants (typically CO, HC and diesel smoke[14]), and make use of equipment that is less precise and less expensive than that used in the laboratory.

[14] The term 'smoke' refers to particles, either solid or liquid, suspended in the exhaust stream which obscure, reflect or refract visible light. Diesel exhaust smoke can be either blue/white in appearance (consisting of a mixture of fuel and lubricating oil particles in an unburnt, partly burnt, or cracked state) or grey/black in appearance (consisting of solid particles of carbon formed during fuel combustion).

Moreover, PTI tests are conducted only every one or two years. In-service inspection is therefore designed to identify large faults rather than a gradual deterioration[15] in the control of emissions (McCrae *et al*., 2002). All types of road vehicle (passenger cars, light-duty vehicles and heavy-duty vehicles) are usually handled using similar procedures.

Emission testing of road vehicles as part of PTI was first introduced in some Member States of the EU in the early 1980s, and in 1996 the first consolidated roadworthiness Directive (96/96/EC) included basic requirements. The current legislation is contained in Directives 2009/40/EC and 2010/48/EC. In addition, Directive 2000/30/EC addresses emission measurement during roadside roadworthiness tests. Each Member State will have an emission testing scheme which takes the EU legislation as the minimum requirement, but with adaptations to suit the local situation.

The following sections describe the practical and quantitative aspects of the EU test procedures for petrol and diesel vehicles, and the equipment which is required. The test procedures and equipment required by the EU legislation effectively defined the starting point of TEDDIE.

2.5.1 Petrol (positive ignition) vehicles

Test procedure

For petrol vehicles the first step is a visual inspection of the emission-control equipment fitted by the manufacturer to determine if it is absent, modified or obviously defective, and to identify any leaks which would affect the emission measurements.

For vehicles without an advanced emission-control system, such as a three-way catalytic converter that is lambda-controlled, after a reasonable period of engine conditioning the CO content of the exhaust gases is measured when the engine is idling. For controlled vehicles the lambda value and the CO content of the exhaust are measured at the natural engine idle speed and at high idle speed (at least 2,000 rpm). Again, the engine is conditioned in accordance with the vehicle manufacturer's recommendations. No external load is applied to the engine in any of the tests.

For motor vehicles equipped with OBD, Member States may, as an alternative to the idle test for CO, establish the correct functioning of the emission-control system through the appropriate reading of the OBD device and the simultaneous checking of the proper functioning of the OBD system.

Pass/fail criteria

For vehicles with no advanced emission-control system the maximum permissible CO content is that stated by the manufacturer. Where this information is not available the CO content must not exceed 4.5 % or 3.5 %, depending the date of first registration, with the engine at idle.

For controlled vehicles the CO content must again not exceed that stated by the manufacturer. Otherwise, the CO content must not exceed 0.5 % or 0.3 %, depending the date of first registration, with the engine at idle, and 0.3 % or 0.2 % with the engine at high idle. Lambda must be within the range 1 ± 0.03, or in accordance with the manufacturer's specifications.

Test equipment

The concentration of CO in the exhaust is measured using a gas analyser which determines the absorption of an infrared light source by the sample. Oxygen is measured by an oxygen cell, and

[15] Of course, the cumulative effects of gradual deterioration may be large, and therefore PTI tests must also be able to detect these.

lambda is calculated via the Brettschneider equation[16]. This is the *de facto* standard method used to calculate lambda for international I/M programmes.

2.5.2 Diesel vehicles

Test procedure

In the diesel smoke opacity test the vehicle is operated through a sequence of so-called 'free accelerations' with the engine under no external load, the gear lever in neutral and the clutch engaged[17]. Directives 2009/40/EC and 2010/48/EC specify the following steps:

- *Visual inspection*. This is conducted in the same way as the petrol vehicle inspection.
- *Vehicle preconditioning*. Vehicles may be tested without preconditioning, although for safety reasons checks should be made that the engine is warm and in a satisfactory mechanical condition.
- *Test procedure*.
  - The engine must be at idle before the start of each free acceleration cycle.
  - The throttle pedal is fully depressed quickly and continuously (in less than one second), but not violently, so as to obtain maximum delivery from the injection pump.
  - During each free acceleration cycle the engine shall reach the cut-off speed or the speed specified by the manufacturer before the throttle is released.

Pass/fail criteria

The primary criterion for passing a test is that the opacity must not exceed the level recorded on the manufacturer's plate on the vehicle. In the exceptional cases where this information is not available or where the Member State decides not to use it, the opacity must not exceed the level stated by the manufacturer or the limit values given in Directive 2009/40/EC[18]. A vehicle is only failed if the mean of the last three free acceleration cycles is in excess of the limit value, although there are provisions to reduce unnecessary testing.

Test equipment

Directive 2010/48/EC does not describe test equipment. Directive 2009/40/EC, on the other hand, states that 'vehicle emissions are tested using equipment designed to establish accurately whether the limit values prescribed or indicated by the manufacturer have been complied with'.

However, no quantitative requirements for measurement equipment are given. The technical requirements of apparatus for measuring the opacity of exhaust gas are defined in the international standard ISO 11614:1999. This standard, and other international standards relating to emission measurement equipment, are summarised in Appendix C. UNECE Regulation 24 also includes requirements for opacimeters, and information on opacimeters is given in EU Regulation 72/306/ECE.

[16] This is taken from a paper written by Dr. Johannes Brettschneider at Robert Bosch, in 1979 and published in "Bosch technische Berichte", Volume 6 (1979) Number 4, pages 177-186.

[17] The inertia of the rotating and reciprocating engine components provides the only 'load' on the engine.

[18] These limit values are 2.5 m^{-1} for naturally aspirated diesel engines and 3.0 m^{-1} for turbocharged diesel engines. A lower limit of 1.5 m^{-1} applies to Euro 4 light-duty vehicles and to Euro IV, Euro V and EEV heavy-duty vehicles. Vehicles which were registered or put into service for the first time before 1 January 1980 are exempt from the requirements.

2.5.3 Limitations of current PTI tests and the need for TEDDIE

General

Modern vehicles feature advanced engines with electronic control, on-board diagnostics (OBD), and emission-reduction systems such as EGR, DPFs and SCR. In recent years the PTI emission test requirements have been updated, but they have not kept pace with developments in vehicle technology and type approval procedures, as well as the increased emphasis on NO_2 and PM mass/number with respect to air quality and human health. There is therefore a danger that current PTI emission testing in Europe will lose its effectiveness. Furthermore, the PTI emission test will not be viewed by citizens and test personnel as being important and necessary if the benefits are not seen. PTI emission tests must clearly be relevant and must cater for modern diesel and petrol vehicles with different types of exhaust after-treatment. Updates to the existing legislation, instruments and procedures would therefore seem appropriate.

In fact, several EU Member States are already considering updating their PTI emission testing schemes. For example, the German project 'Emission 2010' for diesel vehicles has investigated new test equipment for opacity measurement, the thresholds for PTI, and the response of OBD to fault simulation (VdTÜV and DEKRA, 2010). It is therefore timely to consider the development of a harmonised procedure which is applicable to the needs of all European Member States.

TEDDIE was established to address these issues and to investigate ways in which the diesel emission test could be improved. This included the possibility of measuring NO, NO_2 and/or NO_x, as well as improving the method for PM and revising the thresholds.

NO and NO_2

The absence of a measurement of NO and/or NO_2 is an apparent shortcoming of the current PTI legislation, given the environmental importance of these compounds. Moreover, the measurement of these exhaust components could potentially assist in the identification of emission-related faults. TEDDIE was designed to address these issues, and therefore no further comment is required here.

Opacity/particulate matter

The presence of smoke in diesel exhaust is suggestive of poor combustion resulting from a malfunction, maladjustment or use of improper fuel. According to the EU legislation the measurement of exhaust opacity is therefore an adequate indicator of a diesel vehicle's state of maintenance with regard to emissions.

The FAS test used in PTI also has a number of advantages. For example, it is simple, short and can be conducted rapidly. It requires relatively unskilled staff. It is inexpensive in terms of equipment and labour, and it includes transient engine operation (albeit under no load). However, the current approach to opacity measurement in European PTI does have a number of important limitations, and these are discussed below.

- *Lack of relevance to human health.* Any metric which is used in PTI tests must be an adequate indicator of the condition of a vehicle's state of maintenance with regard to particle emissions. However, the metric should also be relevant to the health and environmental effects of exhaust particles. One of the main criticisms of the current PTI test is that smoke opacity is not consistent with, or a surrogate for, the fine particle mass or number metrics which are considered to be relevant to health outcomes.

- *Poor correlation with PM mass*. Following on from the above, the correlation between opacity measurements and gravimetric PM measurements has been found to be relatively poor (Anyon *et al.*, 2000; Gautam *et al.*, 2000; Stewart, 2010).
- *Low instrument sensitivity.* Norris (2005) concluded that the 'standard' opacimeters that are widely used for in-service testing are adequate for establishing compliance with the limits up to Euro 4. They are, however, not well suited to the measurement of low concentrations of fine particles from more modern vehicles, especially those fitted with DPFs.
- *'Unrealistic' vehicle operation.* In the real world vehicles are driven under load, with variable acceleration and with gear changes. These conditions are not included in the FAS test, and the correlation between the PM over FAS tests and 'real world' tests is typically poor.
- *Poor repeatability.* Several factors can have a significant effect on the result of a FAS test, including the rate at which the accelerator pedal is depressed, the extent to which the pedal is depressed, the engine temperature, and the vehicle pre-conditioning. The test is therefore most useful as an indicator of serious emission malfunctions (Faiz *et al*., 1996). However, the sensitivity of the test to some of these parameters actually appears to be less of a problem for engines with electronic control than for older engines (Norris, 2005).
- *Undemanding limit values.* The lack of correlation between the results of FAS tests and the results of loaded transient dynamometer tests makes it necessary to set looser standards to avoid failing properly functioning engines (Faiz *et al*., 1996). However, the limit values for the FAS test in Directive 2010/48/EC are evidently set too high for most modern diesel vehicles. In the UK, Norris (2005) observed that virtually no Euro III heavy-duty vehicles were failing the test, and that the limits for light-duty vehicles were also undemanding.
- *Engine speed limiters*. FAS tests cannot successfully be performed on modern engines having electronic controls that restrict engine speed.
- *Limited exploitation of test data.* Only the peak value of each free acceleration test is recorded, and therefore the detailed information from the test record is lost. Moreover, huge numbers of vehicles are tested in I/M programmes, and if more useful metrics and tests are used then there is the potential to use the data more widely (*e.g.* verification of emission inventories).

On-board diagnostics (OBD)

The introduction of OBD - and its incorporation into standards, technical specifications and type approval regulations (from Euro 3 to Euro 6, as well as the WWHOBD[19]) – has been an important step forward in the drive to reduce emissions from road vehicles. OBD is able to detect many different malfunctions in electronically controlled systems. It has therefore been promoted as an alternative to direct emission measurement at PTI, thus reducing costs. This is currently the case in North America, where the US EPA sees inspection of OBD II (the current standard for OBD in North America) as the current and future technology for PTI emission tests.

However, OBD in both Europe and North America has not been designed for the purpose of PTI, and in Europe in particular there are a number of drawbacks of current OBD that limit its use for PTI. These are noted later in the report (see section 3.3.4). As a consequence, the emphasis in TEDDIE was on the direct measurement of emissions, although consideration was also given to the possibilities afforded by OBD.

[19] World Wide Harmonised On-Board-Diagnostics.

Key points from this chapter

1. The pollutants of greatest concern in terms of local air quality are NO_2 and PM. NO_x emissions also have regional impacts such as acidification and eutrophication.
2. Road transport is the largest contributor to NO_x emissions in the EU, and is also a major contributor to PM. In urban areas its impact is high due to the density of roads, traffic volumes, and the proximity of the population to the emission source.
3. Concentrations of NO_2 and PM_{10} frequently exceed air quality limits, and are not decreasing at many locations. For NO_2 this is due in part to increases in the market share of diesel vehicles and *f*-NO_2 in diesel exhaust. The latter has been linked to specific after-treatment devices.
4. High vehicle emission rates are often a result of component ageing, component failure, or generally poor maintenance. PTI emission tests allow authorities to check that in-service vehicles are well maintained and conform as far as possible to their design emission levels.
5. PTI emission test requirements have not kept pace with developments in vehicle technology and type approval procedures. Updates to the legislation, instruments and procedures would therefore seem appropriate.
6. The current approach to opacity measurement has several limitations, such as:
   a. Opacity is not consistent with the particle metrics which are relevant to health.
   b. Standard opacimeters are not well suited to the measurement of low concentrations of PM from modern vehicles.
   c. The results of the FAS test are influenced by the way in which it is conducted.
   d. The limit values for the FAS test are set too high for modern vehicles.
   e. FAS tests cannot be performed successfully on modern engines having electronic controls that limit engine speed.
7. Diesel exhaust PM is complex in nature. The instruments used in PTI tests should measure particles in the relevant size range, and the sampling procedures should not introduce artefacts.
8. The absence of a measurement of NO and NO_2 is an apparent shortcoming of the current PTI legislation, given the environmental importance of these compounds. The measurement of NO and NO_2 could also potentially assist in the identification of emission-related faults.
9. In modern vehicles various emission-control devices are used (*e.g.* EGR, DPF, SCR), and these have different effects on the properties and composition of the exhaust gas. These effects need to be considered when designing a new PTI emission test.
10. The way in which OBD operates and is applied currently limits its effectiveness at detecting emission-related faults during PTI. The emphasis in TEDDIE was therefore on the direct measurement of emissions.

3 Review of PTI instruments and test procedures

3.1 Overview

This chapter contains the results of a comprehensive international review of the measuring instruments (section 3.2) and procedures (section 3.3) relating to PTI emission testing. A questionnaire survey was conducted to determine the actual test procedures and future plans of individual countries (section 3.4). Particular attention was paid to the inclusion of NO, NO_2 or particulate matter in technical inspections.

3.2 Instruments for measuring emissions during PTI

This section of the report summarises the methods and instruments which are available for the measurement of NO, NO_2 and PM during PTI, including the results of any studies in which the instruments have been tested and compared. Some specific instruments are described in more detail in Appendix D.

3.2.1 NO and NO_2 instruments

Non-dispersive ultraviolet absorption spectroscopy (NDUV)

Analysers which rely upon NDUV have been used in portable emission measurement systems (PEMS) to measure on-road emissions of vehicles (*e.g.* for evaluating emission factors and models). These systems show a good correlation with the equipment used in the type approval procedure (Weiss *et al*., 2011). The advantage of measuring NO and NO_2 in the ultraviolet region of the spectrum is that there is no cross-sensitivity with water vapour and CO_2. However, NDUV instruments are currently rather expensive for PTI.

Electrochemical cells

A number of instruments based on electrochemical cells have been developed for use in PTI emission tests. In these instruments the oxidation of NO generates a small electric current, the magnitude of which is proportional to the amount of NO present. The fundamental principle involves the use of electrodes and a liquid or solid electrolyte. Variations include Na^+-conductor-based NO_x sensors (operated at about 150°C) developed in the 1980s, and a ZrO_2-based thick-film sensor (operated at 450°C) – known as a 'smart-NO_x' sensor – developed in the 1990s by NGK/VDO (Vlad, 2008).

Electrochemical cells are relatively cheap, simple and robust, and can have a high selectivity, although some cross sensitivity with CO has been reported (Szabo and Dutta, 2003). They also have a high sensitivity, and can be adjusted for the measurement of different gases by, for example, specifying chemical reactions in advance of the electrochemical reaction, modifying the diffusion barrier (porosity, pore distribution, *etc.*), or modifying the electrolyte, material and structure of the gas sensor (Vlad, 2008).

Other methods

A number of other methods are available for measuring emissions of NO and NO_2, but these are generally unsuitable for PTI testing because of, for example, cost, complexity, size, *etc.* Nevertheless, they are worth including here and are summarised below.

- *Chemiluminescence.*

  The chemiluminescence detector is the standard instrument for measuring NO and NO_2 in type approval tests (and also for ambient air quality measurements). It is also widely used as a reference method. The CLD detects the light emitted by electronically exited NO_2 molecules which are generated by the reaction between NO in the exhaust gas and ozone (O_3) which is added in a reaction chamber. The emitted light is measured with a photomultiplier sensor and is proportional to the NO concentration. To enable NO_2 to be measured, the NO_2 resulting from the reaction is reduced to NO inside the analyser using a converter. NO is then measured again to give NOx, and NO_2 is calculated as difference between NO_x and NO.

- *Non-dispersive infrared absorption spectroscopy (NDIR)*

  NDIR is based on the principle that when infrared light from a broadband source is passed through a measurement chamber, each gas present absorbs the light at a certain wavelength and in proportion to its concentration. NDIR is often used to measure CO, CO_2 and HC, although it can also be used to measure NO. However, the measurement of NO_2 is not possible as water vapour (from fuel combustion) absorbs at the same wavelengths, thus causing interference. It is therefore unlikely that NDIR will be suitable for use in PTI.

- *Fourier-transform infra-red spectroscopy (FTIR)*

  In FTIR the light from a broadband source transmitted through a scanning interferometer is measured as a function of the optical path length. The high signal-to-noise ratio of FTIR has led to its increasing use in laboratories. However, the interference of NO_2 measurement by water vapour remains. FTIR spectrometers are also significantly more complex than NDIR instruments.

3.2.2 Opacity/PM instruments

The measurement of PM in diesel exhaust is, in general, more technically demanding than the measurement of gaseous pollutants. Particles in the tailpipe are variable in chemical and physical nature, which makes sampling and characterisation difficult. Various metrics can be quantified, including mass concentration, opacity, filter smoke number (FSN), number concentration, surface area concentration and size distributions. In addition, PM sensors need to be very sensitive to measure the very low levels of PM emissions required by the more recent Euro emission standards (Ntziachristos *et al*., 2011).

Many different instruments are available for characterising PM. As with analysers for NO and NO_2, some of the instruments are relatively large, sophisticated, delicate, and costly, and tend to be designed for use in the laboratory environment (*e.g.* TEOM, SMPS, ELPI). Such instruments are considered to be unsuitable or inappropriate for PTI tests, and are therefore outside the scope of the TEDDIE project.

TEDDIE is more concerned with relatively simple, portable and inexpensive instruments which do have the potential to be used for PTI and could lead to improvements in sensitivity over and above current instruments. Norris (2005) observed that the performance of the instruments currently used in PTI is determined to a large extent by the specifications they are required to meet within a competitive marketplace rather than by the limits of the technology, given that high-performance instruments are available for laboratory use. There therefore appears to be some scope for improvement in the capabilities of the PTI instruments currently being used in the field.

'Standard' opacimeters

For many years the diesel emission test during PTI has been conducted using an opacimeter. Light propagation can be attenuated by absorption, reflection and scattering. An opacimeter is a type of smoke meter[20] which is designed to measure the opacity of plume or sample of smoke using the principle of absorption.

The opacity measurement and the optical path length of the instrument are used to calculate a light extinction coefficient *k* expressed on a per metre basis (m^{-1}). The smoke density is a function of the number of smoke particles per unit gas volume, the size distribution of the smoke particles, and the light absorption and scattering properties of the particles. In the absence of blue or white smoke, the size distribution and the light absorption/scattering properties are similar for all diesel exhaust samples, and the smoke density is primarily a function of the particle concentration (SAE, 1996).

Two types of opacimeter have been identified by SAE (1996):

- *The full-flow, end-of-line meter* which measures the opacity of the full exhaust plume as it exits the tailpipe. The light source and detector for this type of meter are located on opposite sides of the plume and in close proximity to the tailpipe. With this type of meter the effective optical path length is a function of the tailpipe design.
- *The sampling-type meter (also called partial-flow meter)* which continually samples a representative portion of the total exhaust flow and directs it to a measurement cell. With this type of meter the effective optical path length is a function of the meter design.

The technology developed for this measurement equipment dates back to the early 1970s.

For the purposes of TEDDIE the term 'standard opacimeter' is taken to refer to the types of instrument currently being used widely in the field. Norris (2005) noted that, at the time, the Bosch RT430[21] was the reference instrument in the UK, and as such it gave the 'accepted' absolute smoke values from free acceleration tests. Norris (2005) observed baseline drift which proved to be a problem when assessing the instrument's generic characteristics, though in practice this made very little difference when assessing smoke peaks of at least 0.2 m^{-1} from free acceleration tests. Various other models are in widespread use (see Appendix D).

Advanced opacimeters

According to Norris (2005), the advanced opacimeter can be viewed as a substantial development beyond standard opacimeters. Whilst the measurement method is similar to that of conventional opacimeters, additional signal processing is employed.

In the UK Low-Emission Diesel Research project the instrument used was produced by ATT Hartridge. The sophistication of this instrument was to take a number of measurements and to employ compensations (both physical and within the signal processing). The signal processing and controlling electronics produced a reading with a resolution of 10^{-3} m^{-1} (Norris, 2005).

The AVL 439 opacimeter is used by authorities in Germany as a reference for the certification of opacimeters used for PTI and for the development and certification of engines. It is more accurate and stable than standard opacimeters as a result of the inclusion of, for example, a diaphragm sampling pump for constant filling of the measuring chamber, sample re-circulation, a constant flow rate even at varying exhaust pressure, and heated windows to protect the optical components.

[20] The term smoke meter is a broad term which applies to all smoke-measuring devices regardless of the measurement technique employed.

[21] The current model is the RTM430.

Filter paper reflectometers

This measurement method, again investigated by Norris (2005), involves capturing exhaust PM on a filter paper. Reflectometry is then used to quantify the amount captured. Whilst reflectometers are available commercially, the approach used by Norris was more of an examination of a concept than a test of a commercial system.

Norris noted that there are two possibilities for sampling: (i) active sampling, where a pump is used to sample a controlled volume of exhaust gas, and (ii) passive sampling, where the pressure in the exhaust system pushes the exhaust gas through the filter. It was observed by Norris that reflectometry is a less accurate approach than weighing the filter, but it removes the need for an expensive balance and for the conditioning of filters prior to weighing. The issue of interference by water is also essentially removed because the addition of water to the filter causes a large change in mass but very little change in the amount of light reflected.

The basic measurement equipment is cheap and portable. In addition, the sample is retained and can be re-examined later if required. One difference between this approach and a smoke meter is that the result is obtained at the end of a test, whereas with a smoke meter separate values are measured for each free acceleration cycle (Norris, 2005).

It was found that the reflectometry method had a higher sensitivity than the standard opacimeter, and that there was a good correlation between the two. The detection limit was given as 2.5×10^{-3} m^{-1}. However, the measurement range of the system was quite limited. For opacity values larger than 0.4 m^{-1} the filter paper was heavily stained and no further discrimination was possible.

Norris also noted that, in the context of decentralised testing, to change instrument type requires training and other set-up costs significantly beyond those incurred when upgrading an instrument (*i.e.* opacimeter), and this weighs against the filter paper reflectometry approach.

Light-scattering meters

The light absorption principle used in opacimeters can work well for the black carbon particles which are typical of the visible smoke from older diesel engines. However, it cannot detect the finer particles from more modern vehicles. A more sensitive method is light scattering.

Scattering is the deflection of light in random directions by irregularities in a propagation medium, or in a surface or interface between two media. The intensity of the scattered light is dependent on the wavelength of the incident light and is sensitive to the particle size.

According to Stewart (2010), light scattering is suitable for measuring very low particle concentrations. The manufacturers of light scattering instruments typically quote a measurement range 0.1-200 mg/m^3, which is equivalent to a smoke density of 0.0013 m^{-1} (Norris, 2005).

However, Norris (2005) noted that scattering efficiencies reduce markedly when the particle size is less than 30% of the incident light wavelength. For example, for an instrument in which the wavelength of the incident light is around 670 nm the detection would be poor for particles having a diameter of less than around 200 nm. This is a problem for detecting particle emissions from diesel vehicles. However, modern LLSP instruments are capable of measuring PM concentrations down to 50 nm, and therefore cover most of the mass in diesel exhaust (Hahn, 2011).

Quartz crystal microbalances

A quartz crystal can be made to oscillate when excited by an electrical signal at the correct frequency. In a quartz crystal microbalance (QCM) the change in the crystal's resonant frequency is used to determine the particle mass deposited on it. Very high sensitivities are claimed. Moreover, the parameter it measures is mass, which is directly related to PM deposited on a filter during type approval tests. However, Abdul-Khalek (2006) observed several disadvantages of the instrument, including excessive sensitivity to temperature, pressure and humidity, and a tendency towards rapid overloading which necessitates greater dilution of the exhaust gas than other devices. Regniers (2006) noted that some improvements have been made, but it appears that the devices are not sufficiently robust and reliable for application to PTI in the test centre environment.

'Escaping current' sensors

Some instruments designed for measuring particles during PTI are based on the escaping current principle. This involves electrostatically charging particles and then measuring the current produced by the charged particles as they leave the sensor. The current carried by the particles is proportional to their concentration. The particles themselves do not need to be collected, and therefore no cleaning or regeneration of the instrument is required.

These sensors are currently under development (see Appendix D). For example, the Pegasor PPS-M is currently commercially available as a research tool, but the operational costs are relatively high compared with other PTI equipment (e.g. for accurate operation it requires a source of clean air). However, the manufacturer has stated that a system suitable for garage use could also be developed, with a cost similar to that of a smoke meter[22].

3.2.3 Evaluation studies

NO and NO_2 instruments

There are few studies in which instruments for measuring NO and NO_2 during PTI have been evaluated. Electrochemical cells have been tested with calibration gases, but few studies have involved comparisons with other instruments, such as chemiluminescence analysers, on dynamometers or engine test beds. Moreover, little information is available from manufacturers. These instruments were therefore investigated in some detail in TEDDIE.

Opacity/PM instruments

Several studies have shown that the correlation between exhaust opacity measurements and gravimetric PM measurements is generally poor. For example, for various different instruments Anyon *et al*. (2000) found a poor correlation between opacity and PM mss per unit distance (mg/km) over the CUEDC[23]. Opacity measured during an unloaded test (such as the free acceleration test) had essentially no correlation with PM mass. Until recently this has not presented much of a problem. For example, Norris (2005) concluded that the opacimeters used in the UK were adequate for establishing compliance with the limits up to Euro 4. However, modern diesel engines with high-pressure injection and DPFs emit low concentrations of fine particles which are not adequately detected by opacity measurements. Moreover, as PM emission limits become more stringent, opacity measurements cannot detect faults which result in type approval limits being slightly exceeded.

However, new PTI instruments are being developed to detect PM emissions at very low levels. In addition, whereas the standard opacimeter only measures a proxy for PM emissions (*i.e.* smoke

[22] NGK plans to develop a cheaper version under license.

[23] CUEDC = Composite Urban Emission Drive Cycle, developed by the New South Wales Environmental Protection Agency in Australia. It consists of four segments, each of which represents driving in a different urban traffic condition (congested, minor roads, arterial roads and highway/freeway).

opacity) the modern instruments can provide more quantitative data on various PM metrics, including mass concentration (mg/m³) and number concentration. Investigations have generally supported the claims of manufacturers that these instruments are more suitable than standard opacimeters for quantifying diesel PM during PTI emission tests. For example, studies have indicated that light-scattering instruments are sufficiently accurate, robust and reliable for use in PTI testing. The California Air Resources Board (CARB) has evaluated various PM analysers as alternatives to the filter method for type approval. Figure 3 shows raw exhaust measurements over the Federal Test Procedure (FTP) with the MAHA MPM-4 ('TP1') and the Dekati EtaPS system ('TP2'), and dilute exhaust measurements with a TSI Engine Exhaust Particle Sizer (EEPS) ('CVS1') and a TSI DustTrak monitor ('CVS2'). The tests showed that there was a reasonably good correlation (R^2=0.76) between the MAHA MPM-4 results and the filter method.

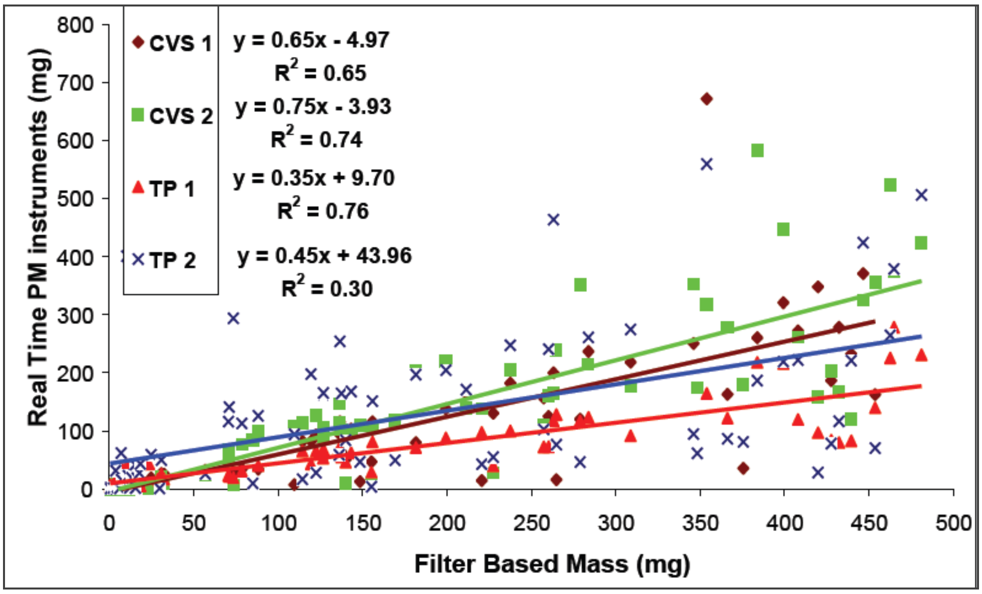

Figure 3: Correlation between real-time PM mass measurements and filter-based PM mass (Cicero-Fernandez *et al.*, 2009).

In Canada, the AirCare Research Centre has also evaluated the PM measurements obtained using a MAHA MPM-4 (Stewart, 2010). Comparisons with the SAE J1667 smoke opacity test indicated that both methods responded similarly to black diesel smoke. According to Stewart the MAHA analyser is suitable for routine PM data collection, and could be used to reliably categorise vehicles as low, medium or high emitters of PM.

Anyon *et al.* (2000) evaluated a TSI 8520 DustTrak instrument for use in I/M programmes. The instrument was specially calibrated for the measurement of diesel exhaust PM. Over the CUEDC the DustTrak (LLSP) had an excellent correlation (R^2 0.93) with PM filter mass, although it reported lower values than the filter. The CARB tests (Figure 3) also showed that there was a reasonably good correlation (R^2=0.74) between DustTrak results and a filter-based method. However, the situation changed dramatically when smoke opacity was used instead of filter mass. In this case, a much lower correlation coefficient (R^2=0.39) was obtained.

The PM mass measured using the DustTrak was also compared with filter mass and the output from a high quality AVL opacimeter over the D550, DT80 and AC5080 tests used for I/M. The AC5080 and DT80 are transient tests while the D550 is a steady-state test (see Appendix E). The DustTrak performed well over both types of test. According to Anyon *et al.* the slightly better correlations achieved for the transient tests was encouraging as they gave added confidence in the DustTrak's ability to perform during relative harsh 'real-world' transient conditions, as well as under the more stable steady-state conditions of the D550.

Anyon *et al*. (2000) concluded that instruments measuring PM mass correlated well with one another, whereas correlations with opacity were low. The APS and the TEOM[24] - both laboratory grade instruments – showed good agreement with the filter mass, but so did the less expensive DustTrak.

In the UK Low-Emission Diesel Research project it was concluded from the data obtained that neither the quartz crystal microbalance[25] method nor (contrary to the above) the light-scattering method could be recommended for consideration for the in-service testing of diesel exhaust during a FAS test (Norris, 2005). Notably, light scattering instruments have a low sensitivity to particles with a diameter of less than 200 nm. The filter paper reflectometry and advance opacimeter were both found to have higher sensitivities than the standard opacimeter (by factors of 4 and 6.4, respectively), although the practical application of the reflectometry method was more difficult.

3.3 PTI test procedures

In this section consideration is given to the various short test procedures – for both petrol and diesel vehicles (although the emphasis is on the latter) – which are currently used, or have been used in the past, in PTI tests. This work draws upon earlier reviews (*e.g.* Samaras and Zachariadis, 1995; Brown *et al.*, 1999; Norris, 2002). The use of OBD is addressed, and comparisons between different procedures are also summarised.

The procedures identified in the review are described in Appendix E, and have been categorised as follows[26]:

- Unloaded tests
- Loaded steady-state tests
- Loaded transient tests

3.3.1 Unloaded tests

The simplest, cheapest and commonest procedures are unloaded tests, which typically involve idling at both low and high engine speeds, or revving the engine several times. Other unloaded tests in INCOLL, AUTONAT and a 'gentle acceleration' test proposed by Norris (2005). Such procedures can serve as screening routines for high-emitting vehicles.

Idle tests are commonly used for petrol vehicles in I/M programmes. They are not considered to be appropriate for modern diesel vehicles, as NO_x and PM emissions under no-load conditions are low. In many countries the PTI emission test for all types of diesel vehicle involves the measurement of exhaust smoke opacity. Because smoke levels at engine idling speed (or under low load) are nearly always low regardless of the condition of the vehicle, free acceleration tests are often used. The particular test procedures used are in all cases similar, though not identical. The test is typically performed as described in the EU legislation.

[24] TEOM = Tapered Element Oscillating Microbalance.
[25] Although Norris (2005) suggested that this was not due to a fundamental problem with the technique, but rather a lack of robustness in the instrument tested.
[26] Here, 'loaded' refers to a situation in which an external load that is placed on the engine.

Some of the advantages disadvantages of the FAS test were discussed in section 2.5.3. It can also be stated that unloaded tests in general are sometimes inconsistent and are prone to manipulation.

3.3.2 Loaded steady-state tests

Some countries and certain US states use more sophisticated test methods which more closely replicate real-world driving conditions. These involve engine loading and require the vehicle to be placed on a dynamometer. They are more suitable than idle measurements for the characterisation of NO_x, which is largely produced at higher engine loads and temperatures (McCrae *et al*., 2005).

In loaded steady-state tests the engine speed/load is held constant. Examples include the US Federal 3-mode test, the Clayton Key Mode test, the CalVIP test and the D550 test (see Appendix E). Relatively inexperienced test facility employees are capable of conducting loaded steady-state tests, achieving acceptable accuracy with moderate labour costs. However, the capital costs of a dynamometer are high.

3.3.3 Loaded transient tests

In loaded transient tests, such as the Australian DT60/DT80 tests and the IM240 test used in the US, the vehicle is operated through simulated driving cycles and loads. These tests are long, costly and require relatively skilled staff. They result in a complicated I/M system which lends itself to centralisation (USAID, 2004). It has been noted that for diesel vehicles transient testing eliminates the risk of engine damage associated with unloaded tests (McCrae *et al*., 2005).

On-road smoke tests have also been considered, although their practicality is questionable and the results do not correlate well with those from transient dynamometer tests. Nevertheless, on-road tests could conceivably complement a loaded dynamometer test (Anyon *et al.*, 2000).

It is worth noting that unskilled staff - as well as inappropriate procedures - can lead to significant pass and/or fail errors in any PTI test procedure. Quality assurance systems are necessary to avoid this.

3.3.4 On-board diagnostics and its practical use in PTI

The United States has required OBD systems since 1996. The US EPA guidance document entitled *Performing On-Board Diagnostic System Checks as Part of a Vehicle Inspection and Maintenance Program* contains EPA's recommendations regarding the effective implementation of OBD checks in I/M programmes (Sosnowski and Gardetto, 2001).

OBD has been a requirement in Europe since the introduction of vehicles meeting the Euro 3 emission standard (Directive 98/69/EC). To differentiate it from the more comprehensive US version, the European version is known as EOBD. The use of EOBD to check the functioning of emission-control systems is permitted in Directive 2009/40/EC, and as alternative to emission measurements at engine idle. However, this alternative does not exist for diesel engines.

The EOBD system consists of engine management software integrated into the ECU, and is designed to detect fault codes stored in the ECU memory. In the event of an emission-related component fault, a diagnostic trouble code (DTC) is stored in the memory of the control module responsible for that component, and the malfunction indicator lamp (MIL) on the dashboard will illuminate to alert the driver. The DTC can then be retrieved using diagnostic equipment - the EOBD fault code reader (or generic scan tool) - to determine the type and status of the fault.

In November 2006 Belgium implemented an enhanced ‘second-hand car inspection’, which is applicable prior to a vehicle being sold and registered to a new owner. One of the newly introduced inspection items was an OBD scan on DTCs. Around 10% of the tested vehicles had DTCs related to motor management, and indirectly related to emissions. Most of the motor management DTCs are not related to the EOBD emission P-codes [27]. Only about 35% of motor management DTCs are standardised EOBD P-codes (Buekenhoudt, 2010).

In Germany EOBD has been used for emission testing since 2009. All vehicles after 2006 (petrol and diesel) are covered. Following the connection of the scan tool there is a visual check of the MIL and an examination of the readiness codes (RCs) and error codes. If all RCs are not set, then an exhaust gas evaluation is conducted. If the RCs are set, then the emission evaluation is based on the EOBD scan. For diesel engines where an OBD test is conducted, no opacity test is required. Other countries in Europe, such as Sweden and Finland, also perform OBD emission tests which are quite similar in specification to the German test.

OBD offers a potential alternative to direct emission measurement, thus avoiding loaded testing and significant capital expenditure. OBD can also cut the time and labour needed to conduct the inspection (USAID, 2004), and might ultimately replace 'manual' in-service inspections (McCrae *et al*., 2005). However, various issues with EOBD and its use in PTI tests have been identified, including the following:

- The application of the EOBD system can differ widely between OEMs due to different interpretations of the type approval regulations, allowing manufacturers to use a wide range of different control options.
- Current EOBD systems do not use direct measurement of emissions at the tailpipe. Where sensors are available and sufficiently inexpensive to fit to production vehicles, the reliability and accuracy are too low for PTI[28]. Findings based on EOBD interrogation may therefore differ from those based on direct tailpipe measurement.
- The EOBD thresholds for the detection of faults are very high. The reason for this is that in some cases the uncertainties in detection are large, and there is a need to avoid presenting the driver with a large number of unnecessary malfunction warnings. However, this only ensures that the Euro 1 emission values are not exceeded, provided that the MIL functions correctly (CEMT, 2006). Consequently, a vehicle with, for example, a defective DPF will not always be detected by the OBD. Even with a defective filter some modern vehicles will remain beneath the MIL threshold, and thus no DTCs will result. For the purposes of PTI this leads to a high number of reporting omissions where defects in the system are not detected.
- EOBD does not measure the functionality of the overall emission-control system. Its ability to detect faults is limited to the functionality of discrete emission control systems required to meet these standards (*e.g.* that the EGR system is functional). However, it has been shown that even where NO_x is higher than the EOBD threshold value for a defective EGR system, the EOBD cannot always detect the problem (VdTÜV and DEKRA, 2010).
- Where after-treatment components are actively controlled, faults can be detected by the ECU. Passive systems such as DOCs and CRTs are typically not controlled, and failure detection by the ECU is not possible.

[27] The DTC is displayed as a 5-character alphanumeric code. The first character is a letter that defines which vehicle system set the code (P=powertrain, B= body system, C= chassis system). P-codes are requested by the microprocessor controlling the powertrain or transmission, and refer to the emission-control systems and their components. The first number indicates if it's a mandated description (0) or a manufacturer-specific description (1). The three numbers that follow give more detailed information.

[28] It has been recognised for some time that developments in sensor technology may mean that the direct measurement of exhaust pollutants - often referred to as 'on-board measurement' could ultimately supplement or replace OBD. However, at the time of writing such technologies are still rather expensive, and it appears that they may not be commercially viable for several years.

- Some of the first generation of vehicles with EOBD did not meet the EOBD regulations; in particular, the RCs were not set up as required (CITA, 2002).
- There will still be pre-OBD vehicles in the fleet for some years to come.

These issues lead to the conclusion that mechanical faults to emission-control systems may not be captured by anything but tailpipe testing.

Despite these limitations, current EOBD does offer a number of important and beneficial functions for PTI. For example, measurements such as rpm, engine temperature and other real time values can be efficiently used as inputs for the direct measurement at the tailpipe of exhaust concentration under specified engine conditions. In addition, scanning of EOBD readiness codes can be used as a component of PTI where these codes are available and have been set correctly. This use of EOBD is permitted by Directive 2009/40/EC, which also permits EOBD to be used as an alternative to direct measurement at engine idle of CO and Lambda for petrol engine vehicles. However, this alternative does not exist for diesel vehicles.

3.4 PTI tests in different countries

In order to determine current practices concerning emission testing during PTI, a questionnaire was sent via CITA to all EU Member States and to a number of other countries outside the EU. Where necessary, the questionnaire was followed by direct approach to the relevant authorities. The questionnaire itself and the numbers of responses received are provided in Appendix F. Responses were received from 22 of the 27 Member States, and some Member States provided more than one response.

3.4.1 EU Member States

The responses from the EU Member States are summarised below:

- All EU Member States that responded to the questionnaire perform an emission test for diesel vehicles during PTI.
- In each EU Member State opacity is measured during idle and free acceleration according to Directive 2009/40/EC, except for the following:
  - The Czech Republic (which uses standard 302/2001).
  - Germany, where measurements are not made on post-2005 diesel vehicles which have no OBD fault codes, the MIL is off, and the readiness codes are set correctly[29].
  - Slovenia: 2003/27 (2009/40 to be implemented in 2012)[30].
- None of the Member States check exhaust components other than smoke opacity.
- Most Member States use the EC limit values for opacity. In Germany, MIL status and DTCs are also failure criteria.

[29] For diesel vehicles first registered before 2006 the measurements are in accordance with directive 2009/40/EC. For vehicles registered after 1 January 2006 a tailpipe measurement is conducted only if the OBD readiness codes are not set correctly. This means that for post-2005 vehicles there are no emission measurements in around 90% of PTI inspections.

[30] Several Member States still refer to Directive 2003/27/EC; Directive 2009/40/EC has not been implemented as there was no change in the relevant requirements. Directive 2009/40/EC - amended with 2010/48/EC - is to be implemented by 2012 at the latest.

- OBD is used in emission testing in France and Germany. It is also being used in Slovakia, but the MIL status and DTCs are provided for information only prior to 2012.
- In Belgium, the Netherlands and Finland a fast pass/fail criterion is used. This is the option described in Directive 2010/48/EC to avoid unnecessary testing.

3.4.2 Non-EU countries

The PTI tests for diesel vehicles in non-EU countries are summarised in Table 6. This information was taken partly from the questionnaire responses and partly from the existing literature. Whilst an attempt has been made to obtain current information, it is possible that some of the test details taken from the literature are now out of date.

It is clear that the free acceleration smoke test is the main test used for diesel vehicles, employing either opacity or Hartridge Smoke Units. This is primarily because the test has a low cost and opacimeters are simple to use.

Loaded tests are used to measure NO_x and PM in some locations, such as Australia and the US. The main types of tests in use are:

- Loaded cruise (the vehicle is tested at a fixed speed and load on a chassis dynamometer)
- ASM tests
- Transient tests
- Lug-down tests

For some types of loaded test there are many different ways in which the test can be conducted (*e.g.* different driving cycles are used for transient tests), and some programmes measure only opacity whilst others measure more pollutants. Lug-down tests are conducted in Hong Kong, Singapore, South Korea and a few states of the US. In Hong Kong this test is performed on all diesel vehicles. In other countries this test is only performed as part of 'enhanced emission inspection' or during random inspections.

As far as our study could establish, there are only a few locations (*e.g*. Australia and the US states of Oregon and Rhode Island) where a transient emission test is performed on diesel engines. In the Australian DT80 test an opacity measurement is still conducted for the continuation of the historical time series, together with the measurement of PM. It appears that Beijing is the only location at which a free acceleration test is used to measure NO_x.

In the case of the United States the general lack of guidance on how vehicles should be tested - and the resulting flexibility allowed to testing authorities - has led to a wide range of emissions test procedures in I/M programmes (Sierra Research Inc., 2001). According to McCrae *et al.* (2005) there are at least 20 types of test for cars and light-duty diesel vehicles. Approximately half of all diesel vehicles are subject to a loaded test, with the majority being steady-state.

Table 6: Summary of PTI emission tests and limit values for non-EU countries (N/A = not available).

Country	Components measured [(a)]	Chassis dyno?	Test	Source[(b)]
Australia	NO_x, PM, Opacity	Yes	DT80, DT60	BIVV
Bangladesh	HSU	-	-	ADB
Brazil, Parana State	N/A	-	Free Acceleration	Questionnaire
Cambodia	HSU	-	-	ADB
Canada, Ontario	Opacity	-	Free Acceleration	Sierra
Canada, Vancouver	Opacity	Yes	Free Acceleration	Sierra
China, Beijing	Opacity, HC, CO, NO_x	-	Free Acceleration	Sierra
China, Hong Kong	Opacity	Yes	Lug-down	Sierra
China, Hong Kong	HSU	-	Free acceleration	BIVV
China, Hong Kong	HSU	-	Loaded lug-down	BIVV
Colombia	HSU?	-	N/A	Questionnaire
India	HSU	-	Free Acceleration	ADB
Indonesia	HSU	-	Free Acceleration	ADB
Japan	-	-	*No diesel emission test*	Questionnaire
Japan	Opacity	-	Free Acceleration	BIVV
Malaysia	HSU	-	-	ADB
Nepal	HSU	-	-	ADB
New Zealand	Opacity	-	Free Acceleration	Questionnaire
Pakistan	HSU	-	Free Acceleration	ADB
Panama	HSU?	-	Free Acceleration	Questionnaire
Paraguay	Opacity	-	N/A	Questionnaire
Philippines	Opacity	-	Free acceleration	ADB
Republic of Croatia	Opacity	-	Free acceleration	Questionnaire
Singapore	HSU	Yes	Loaded lug-down	BIVV
Singapore	HSU	Yes	Lug-down	Questionnaire
Singapore	Opacity	-	Free acceleration	Sierra
South Korea	HSU	Yes	Lug-down mode	BIVV
Sri Lanka	HSU	-	Idle	ADB
Switzerland	Opacity	-	Free acceleration	Questionnaire

Country	Components measured [(a)]	Chassis dyno?	Test	Source[(b)]
Thailand	HSU	-	Free acceleration	ADB
Thailand	HSU	-	Free acceleration	ADB
Thailand	N/A	-	Loaded	ADB
Thailand	HSU	-	Filter test, free acceleration	ADB
Thailand	N/A	-	Filter test – loaded	ADB
Turkey	Opacity	-	Free acceleration	Questionnaire
USA, Arizona	Opacity	Yes	Loaded cruise mode	Sierra
USA, California	Opacity	-	Free acceleration	Sierra
USA, Colorado	Opacity	Yes	Lug-down, free acceleration	Sierra
USA, Connecticut	Opacity	Yes	Lug-down	Sierra
USA, Idaho	Opacity	-	Free acceleration	Sierra
USA, Kentucky	Opacity	Yes	Lug-down, kerb idle	Sierra
USA, New Mexico	Opacity	-	Two-speed idle	Sierra
USA, Ohio	Opacity	Yes	ASM2525	Sierra
USA, Oregon, Medford	CO, Opacity	-	Two-speed idle, OBDII	Sierra
USA, Oregon, Portland	HC, CO, NO_x, Opacity	Yes	BAR31, kerb idle, OBDII	Sierra
USA, Rhode Island	Opacity	Yes	BAR31	Sierra
USA, Utah	Opacity	Yes	Loaded cruise mode, free acceleration	Sierra
USA, Vermont	Opacity	-	Free acceleration	Sierra
USA, Washington	Opacity	-	Free acceleration	Sierra
Vietnam	HSU	-	Idle	ADB

(a) HSU = Hartridge Smoke Unit; m^{-1} = light absorption coefficient; RB = Filter or Bosch smoke meter unit

(b) ADB = (Asian Development Bank (ADB), 2001); BIVV = (Lemaire and Page, 2007) [BIVV= Belgisch Instituut voor Verkeersveiligheid (Belgian Institute for Road Safety)]; Sierra = Sierra Research Inc. (2001).

Key points from this chapter

1. Instruments which are suitable for measuring NO or NO_2 during PTI emission tests are based on electrochemical cells or NDUV spectroscopy, although the latter are currently more expensive.
2. Many instruments are available for characterising particles in vehicle exhaust during PTI, including standard and advanced opacimeters, reflectometers, light-scattering meters, quartz crystal microbalances and escaping current sensors.
3. There are relatively few studies in which NO/NO_2 instruments designed for PTI have been evaluated.
4. Studies of opacity/PM instruments are more common. The correlation between opacity measurements and gravimetric PM measurements (in g/km) is poor, especially over unloaded tests.
5. Filter paper reflectometry and advance opacimeters have higher sensitivities than the standard opacimeter, although the practical application of the reflectometry method is more difficult.
6. New instruments can measure PM emissions at very low levels. In addition, they can provide more quantitative data on various PM metrics, including mass/number concentration.
7. Studies have indicated that light-scattering instruments are sufficiently accurate, robust and reliable for use in PTI testing, with a reasonably good correlation with the filter method.
8. Unloaded tests are often used to screen for gross polluters and also at PTI, and are the least expensive option. Relatively inexperienced staff can conduct loaded steady-state tests, with acceptable accuracy at moderate labour cost, although investment in a dynamometer is required. Loaded transient tests are longer, costlier, and require skilled staff, resulting in a complicated system which lends itself to centralisation. Unskilled staff and inappropriate procedures can lead to significant pass and/or fail errors in any test procedure, and quality assurance systems are necessary to avoid this.
9. OBD offers a potential alternative to emission measurement. However, a number of issues with OBD, and its use in PTI tests, have been identified. These include thresholds which are set too high for modern vehicles, and an inability to consistently detect problems with all after-treatment devices.
10. All EU countries perform a diesel emission test during PTI. Opacity is measured at idle and free acceleration according to Directive 2009/40, except in the Czech Republic, Germany (no measurements on post-2005 diesel vehicles which have no DTCs and set RCs) and Slovenia. None of the Member States check other exhaust components. OBD is used in emission testing in France and Germany.
11. The FAS test is also the main test used for diesel vehicles outside the EU. Different loaded tests are used to measure NO_x and PM. A free acceleration test is only used to measure NO_x at one location (Beijing).

4 Investigation of measuring instruments

4.1 Overview

This part of the project involved an investigation of several candidate instruments which could potentially be used to measure emissions of NO, NO_2 or PM in PTI tests and, in the case of PM, with higher accuracy than the instruments currently used in garages. The test programme was designed to investigate the basic performance of the instruments prior to the evaluation of different PTI test procedures.

For reproducibility and comparability all tests were conducted under laboratory conditions. The instruments were evaluated in relation to the technical and practical criteria mentioned in chapter 1. Particular emphasis was placed upon the quality of the instruments in terms of their accuracy, response time (dynamics), stability, linearity and cross-sensitivity with other compounds in vehicle exhaust. Other considerations included calibration, weight, dimensions and cost (both capital costs and the cost of measurement). The results from the PTI instruments were also compared with those from high-quality reference instruments.

4.2 Methodology

4.2.1 Selection of instruments

The first step was to identify suitable instruments for measuring NO, NO_2 and PM during PTI.

The specifications of instruments which could potentially be included in the test programme were obtained through the following:

- The literature review.
- Two questionnaires which were issued (via EGEA) to instrument manufacturers, one for NO and NO_2 instruments, and the other for PM instruments. The questionnaire forms were designed and produced in cooperation with EGEA.
- A meeting[31] which was held with the equipment manufacturers from EGEA who were willing to provide measurement instruments for the study.

NO and NO_2 instruments

The information obtained for the NO and NO_2 instruments is summarised in Table 7. The actual instruments to be investigated in TEDDIE were selected based on the results of the questionnaire and the willingness of manufacturers to participate. The following instruments were selected for inclusion in the test programme:

- Autocal P550
- Capelec CAP3800
- SAXON-Junkalor Infralyt ELD
- MAHA MET 6.1
- Sensors Inc. SEMTECH-DS

Descriptions of these instruments are provided in Appendix D.

[31] This meeting was held on 2 March in Stuttgart, and hosted by TÜV-Nord and DEKRA.

Table 7: Specifications of NO and NO_2 instruments provided by manufacturers (N/A = not available).

	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5	Instrument 6	Instrument 7	Instrument 8
Company name	MAHA	Sensors Inc.	Sensors Inc.	SAXON-Junkalor	Capelec	Robert Bosch	Brain Bee	Autocal
Product name	MET 6.1	SEMTECH NO_x	SEMTECH-DS	Infralyt ELD	CAP3800	BEA 050 with NO	AGS-688	P550
Parameters	NO, NO_2 (O_2, CO, CO_2, HC)	NO, NO_2	NO, NO_2, O_2, CO, CO_2, HC	NO, NO_2 (O_2, CO, CO_2, HC)	NO_x[(a)]	NO	NO	NO
Measurement method(s) for NO and/or NO_2	NO: electrochemical NO_2: CCFET[(b)]	NDUV	NDUV	Electrochemical	Capelec method	NO: electrochemical	NO: electrochemical	NO: Electrochemical
Range	NO: 0-5,000 ppm NO_2: 0-500 ppm	NO: 0-3,000 ppm NO_2: 0-500 ppm	NO: 0-2500 ppm NO_2: 0-500 ppm	NO: 0-2,000 ppm NO_2: 0-500 ppm	NO_x: 0-5,000 ppm	NO: 0-5,000 ppm	NO: 0-5,000 ppm, resolution: 1 ppm	NO: 0-4,995 ppm
Accuracy	NO: 32-120 ppm NO_2: 32-120 ppm	N/A	NO: ±3% of reading or ±15 ppm NO_2: ±3% of reading or ±10 ppm	N/A	±15 ppm of reading up to 1,000 ppm, and ±1.5% above 1,000 ppm.	N/A	NO: ± 25 ppm or 4%/8%, depending on range.	N/A
Calibration interval	1 year	3-6 months	3-6 months	26 weeks	6 months	3 months	1 year	6 months
Weight	5 kg	13 kg	35.4 kg	9 kg	500 g (bench)	9 kg	5 kg	5 kg
Dimensions: length x height x width (cm)	40.6 x 22.5 x 16.0	30.8 x 13.6 x 43.6	55 x 36 x 43	29.4 x 23.8 x 35.5	13 x 7 x 7	N/A	43.4 x 19.0 x 29.1	29.0 x 14.0 x 18.0
Data interface available	USB	CAN, RS232, Ethernet, USB. Options available.	Wireless	RS232	RS232, USB	No	USB, RS232, Bluetooth.	RS232. Data logging optional extra

	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5	Instrument 6	Instrument 7	Instrument 8
Max. sampling rate of interface	10 Hz	1 Hz	N/A	9600 Baud	2 Hz	N/A	3 Hz	1 Hz
Max. sampling rate of instrument	10 Hz	1-10 Hz	> 1 Hz	2 Hz	2 Hz	2 Hz	4 Hz	Continuous
Response time (T_{90}) of instrument	0.3 sec.	< 2 sec.	≤ 2 sec.	<15 sec.	<15 sec.	N/A	3.5 sec.	<10 sec.
Warm-up-time of the instrument	Approx. 10 minutes	< 1 hour, depending on accuracy and configuration.	60 minutes at 20°C	10 minutes	< 9 minutes	2 minutes	Less than 10 minutes (typically 3 minutes)	15 minutes
Practical experience of stability and durability	NO in standard instrument (stable), NO_2 prototype	NDUV bench for NO is used in 3,000 analysers in California. NO/NO_2 bench has been part of the SEMTECH PEMS equipment since 2002. Excellent stability and durability, even in harsh operating environments.	See left.	On the market for 3 years, and in use in Germany and other countries.	Five years	N/A	Marketed since 2008. The stability and durability of the instrument have been evaluated in many countries and under many different climatic conditions.	UK MOT approved
List price (excl. VAT)	Approx. 12,000 euro (NO, NO_2, PM)	2,500 to 29,000 euro, depending on configuration	94,000 for basic unit	7,300 euro + 165 euro for sampling probe	N/A	N/A	4,543 euro	4,000 euro
Available on market?	Yes	No	Yes	Yes	No	Yes	Yes	N/A

(a) NO_x is reported, but it is not actually clear what is measured by the instrument.
(b) CCFET = Capacitive-Coupled Field-Effect Transistor

Sensors Inc had hoped to create an instrument specifically for the project, measuring only NO and NO_2. However, the instrument could not be delivered in time for the programme. Consequently, the original SEMTECH-DS was used (this employs the same measurement technique), but in a special version with deactivated channels for CO, CO_2, HC. Both non-heated and heated FID sampling probes are available for the SEMTECH-DS, and the effects of these were also investigated.

BOSCH provided feedback to the questionnaire and a representative was present at the Stuttgart meeting. However, the company cancelled its participation in this part of the work programme.

Capelec also responded to the questionnaire and attended the meeting. Unfortunately, the instrument (CAP 3800) could only be supplied after the measurement programme had begun, and therefore not all tests could be conducted using this instrument.

BrainBee responded to the questionnaire but there was no subsequent contact. The BrainBee instrument is an electrochemical sensor, and is similar to the MAHA and SAXON-Junkalor instruments which have been included. It was decided that the instruments which were included in the programme were sufficiently representative of instruments that use electrochemical cells.

PM instruments

The information obtained for the PM instruments is summarised in Table 8. The instruments included in the WP3 test programme were:

- AVL Smoke 2000
- BOSCH BEA 080
- MAHA MET 6.2

} Based on laser light-scattering photometry (LLSP)

- Pegasor PPS-M - Based upon 'escaping current' principle

Again, descriptions of these instruments are provided in Appendix D.

However, at the time the measurements were made (April 2011) the Pegasor instrument was not calibrated to display particulate matter values (*i.e.* in mg/ m^3), and so the results from this instruments have not been included in this report.

Capelec provided feedback to the questionnaire but did not provide an instrument in time for the measurement programme.

Hartridge also responded to the questionnaire and attended the Stuttgart meeting, but they could not supply an instrument for the tests. Following the recommendations from the review, the AVL 439 was used as a reference instrument.

4.2.2 Experimental set-up

The main part of the measurement programme for the NO and NO_2 instruments was undertaken at the DEKRA Automotive Test Centre in Klettwitz, Germany. The measurement programme for the PM instruments was conducted using a reference engine at DEKRA in Stuttgart, Germany. DEKRA also coordinated the delivery of the selected instruments to the measurement locations.

It was important to have accurate and reproducible reference measurements to evaluate the performance of the PTI instruments. For NO and NO_2 certificated span gas with high accuracy (±1%) was employed for this purpose. In the case of PM a recognised reference instrument (AVL 439 opacimeter) was used in combination with a diesel engine operated at constant load and speed. The AVL instrument is used in different laboratories for the development of diesel engines, and is the reference method for the certification of PTI opacimeters in Germany.

Table 8: Specifications of PM instruments provided by manufacturers (N/A = not available).

	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5	*Reference*
Company name	MAHA	AVL DiTEST	Robert Bosch GmbH	Capelec	Pegasor	AVL
Product name	MET 6.2 (MPM-4)	Smoke 2000	BEA 080	N/A	PPS-M	439
Parameters Available	PM mass conc. Opacity HSU	PM mass conc. Opacity[(a)]	PM mass conc. Opacity	PM mass conc. Opacity	PM mass conc. Number of particles/cm^3 mV	Opacity (%) or absorption *k* (m^{-1})
Measurement method	LLSP	LLSP	LLSP	LLSP	'Escaping current'	Light absorption
Range	PM: 0.01-700 mg/m^3	PM: 0.01-500 mg/m^3 Opacity: 0.001 to 3 m^{-1}	Min. 0.001 m^{-1} to 3 m^{-1}	0-5 m^{-1}	1 µg/m^3 to 250 mg/m^3	0 to 100% or 0 to 10 m^{-1}
Accuracy	0.01 mg/m^3	0.01 mg/m^3 +/- 3 %	N/A	N/A	1 µg/m^3	Resolution: 0.01 % opacity or 0.0025 m^{-1} Detection limit: 0.1 % opacity
Correlation between conc. and opacity	Yes	Yes	Yes	Yes	Yes	N/A
Weight	5 kg	4 kg	5 kg	10 kg	1.5 kg	47 kg
Dimensions: length x height x width (cm)	40.6 x 22.5 x 16.0	40.0 x 20.0 x 23.0	38 x 20 x 21	20.0 x 20.0 x 40.0	40 x 14 x 11	46x 44 x 68
Data interface available	LAN, WLAN	USB, RS232, Bluetooth	USB, Digital interface	USB, Bluetooth	USB, RS485	Analogue, RS232, digital interface
Maximum sampling rate of interface	10 Hz	100 Hz	N/A	50 Hz	100 Hz	N/A
Maximum sampling rate of instrument	10 Hz	100 Hz	100 Hz	50 Hz	100 Hz	10 Hz
Response time (T_{90}) of instrument	0.3 sec.	N/A	N/A	1 sec.	0.3 sec.	0.1 sec.

	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5	*Reference*
Sampling probe	Standard probe for 4-gas analysers.	Standard probe for 4-gas analysers.	N/A	Opacimeter probe	Heated flexible line to avoid water condensation in line and sensor. Sensor and sampling line must be heated to min. 100 °C, 160 °C preferred.	4 m
Is the gas flow fitted with an active flow (pump) or passive flow	Active (pump)	Active gas flow with pump 2l/min	Active	Partial flow / fan (passive)	Gas flow is fitted with an active flow in (ejector pump)	Active.
Warm-up-time of the instrument	Approx. 10 minutes	N/A	3 minutes	< 9 minutes	30 minutes in order to allow temperature stabilisation.	N/A
Practical experiences of the stability and durability of the instrument module	PM in standard instrument (stable)	Many tests in comparison with Micro-soot and Opacimeter 439; long term test with different loading conditions, Tests with humidity/condensation. Tests on a test bed.	Tests in workshop environment with positive results	N/A	Steady-state ±7%, dynamic repeatability ± 8%. Sensor is equipped with full self diagnostics. Service interval is typically several hundred hours.	N/A
List price (excl. VAT)	12,000 euro (NO, NO_2, PM)	N/A	N/A	N/A	11,950 euro. However, it is anticipated that the PTI version will have a significantly lower price.	N/A
Available on market?	Yes[(b)]	Yes[(b)]	Yes[(b)]	N/A	Yes	Yes

(a) Opacity is calculated from the concentration.

(b) Certification is in progress. After certification by the Physicalisch Technische Bundesanstalt Braunschweig (PTB), an instrument can be used for PTI in Germany, as well as for the measurement of modern vehicles with very low PM emissions.

It is also widely recognised that when evaluating new technologies and tests it is useful to include the equipment and procedures used for type approval as reference. For NO and NO_2 a laboratory-grade chemiluminescence analyser was included in the measurement programme, and for PM the filter mass was recorded.

The measurements using constant engine speed and load were undertaken using a Euro 1 diesel engine on a test bed (Figure 4 and Figure 5). The specification of the engine is given in Table 9. The engine was controlled using an electromagnetic brake, with speed and load being adjusted via an adapted control system. The constant loads and speeds are listed in Table 10. The mechanical fuel injection pump on the engine meant that the amount of injected fuel could be controlled, and hence k values in the exhaust of between 0.5 m^{-1} and 3.0 m^{-1} could be obtained.

As PTI tests are not normally conducted on engines under strict laboratory conditions, but on vehicles in less well controlled garages, it was also considered important to examine the performance of the instruments under typical usage conditions, and for this vehicle free acceleration tests were used. The test vehicle was a Euro 5 Volkswagen Passat (Figure 6) equipped with a particulate filter and OBD. The specification for the vehicle is provided in Table 11. It should be noted that the DPF of this vehicle had mechanical defects (29 holes with a diameter of 10 mm), and therefore the PM emissions were abnormally high. A k value of 0.56 m^{-1} was obtained during the free acceleration test (the manufacturer's limit value was 1.0 m^{-1}, the plate value was 0.6 m^{-1}, and the MIL was off). The vehicle also had an engine speed limiter (2,500 rpm), but this was temporarily disabled by switching off the electronic stability program (ESP).

Figure 4: Installation of engine.

Figure 5: Measurements (constant speed and load tests).

Table 9: Engine specification.

Parameter	Value/description
Engine type	Peugeot DJZ(XUD9Y)
Displacement	1905 cm^3
Fuel injection system	Distributor fuel injection pump
Maximum power (kW/rpm)	47 / 4600
Maximum torque (Nm/rpm)	120 / 2000
Emission standard	Euro 1

Table 10: Constant load and speed values.

Load point	Torque (Nm)	Power (kW)	Engine speed (rpm)
1	80.0	16.6	2,000
2	69.2	15.0	2,070
3	60.8	12.9	2,020
4	52.1	11.0	2,010
5	39.2	8.2	2,010
6	31.3	6.7	2,060
7	22.0	4.5	2,000

Figure 6: Vehicle used for free acceleration tests.

Table 11: Specification of vehicle used in free acceleration tests.

Manufacturer	Volkswagen
Model	Passat 3C Bluemotion
Displacement (cm^3)	1,968
Maximum power (kW)	81 @ 4200 rpm
Fuel injection system	Common rail
Emission standard	Euro 5
Odometer (km)	29,000

4.2.3 NO and NO_2 measurements

Each NO and NO_2 instrument was calibrated by the manufacturer before the measurements, and Table 12 shows the calibration information. The characteristics of the instruments were then examined in six separate steps, as shown in Table 13. Further details of these steps are provided below. Two examples of the SAXON-Junkalor Infralyt ELD (with identical specifications) were available, and therefore both instruments were included in the test programme.

Table 12: Calibration method and concentrations for NO and NO_2 instruments.

Instrument	Calibration method	NO concentration (ppm)	NO_2 concentration (ppm)
Autocal P550	1 point	1,000	-
Capelec CAP 3800	4 point	50, 100, 150, 1,500 (NO_x)	50, 100, 150, 1500 (NO_x)
Junkalor Infralyt ELD	1 point	1,770	146
MAHA MET 6.1	1 point	500	500
Sensors SEMTEC-DS	1 point	1,500	500

Table 13: Measurement programme for NO and NO_2 instruments.

Step	Test procedure	Parameters investigated
1	Using a gas divider: comparison of test equipment with type approval equipment for span gas and 9 different concentrations.	Accuracy, linearity, stability, reproducibility.
2	Using two different concentrations of span gas for NO and NO_2. Measurements were taken after 0, 2, 5, 15, 30, 60, 90 and 120 minutes.	Accuracy, linearity, stability, reproducibility.
3	Using calibration gas with higher concentrations of O_2, CO, CO_2, HC and no NO or NO_2.	Cross-sensitivity.
4.	10%-to-90%-delay time and 90%-to-10%-delay-time with calibration gas (step function response).	Practicability, sensor dynamics.
5	Free acceleration (5 times) with one vehicle (with rpm measurement).	Practicability, sensor dynamics.
6	Repeating of one of the gases used in Test No. 1 before re-calibration of equipment or after end of WP4.	Long-term properties.

The Capelec CAP3800 was not available at the start of the measurement programme, and could not therefore be included in all the tests. In addition, according to Capelec the CAP 3800 is calibrated to measure emissions under exhaust humidity levels which are similar to those encountered in the real world. Because the calibration gas was very dry, additional tests were therefore devised using a special construction to give higher humidity in the span gas (Figure 7). The calibration gas was bubbled through water in a sealed bottle, and the gas measurements were taken from the air space above the water. The construction was airtight, as indicated by the measured oxygen values which were close to zero, and resulted in high levels of humidity in the calibration gas.

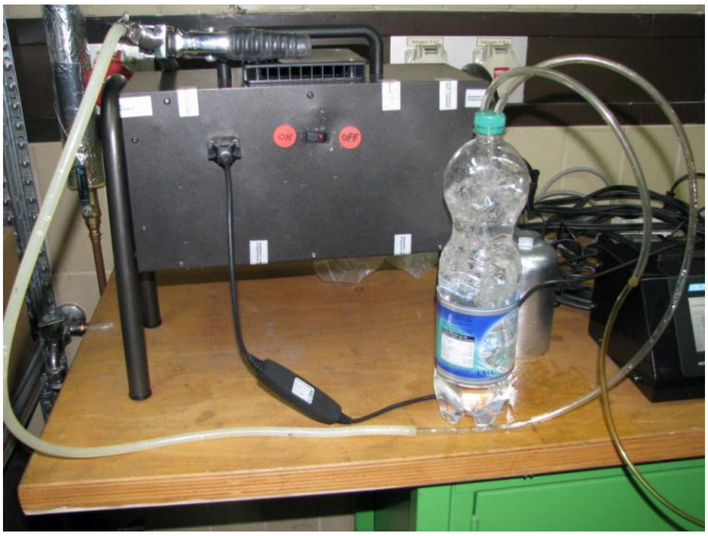

Figure 7: System used to increase the humidity of the span gas.

Steps 1 and 2: Accuracy, linearity, stability and reproducibility

The accuracy and linearity of the PTI instruments were examined using span gas in combination with tests on engines under different load conditions. The span gas concentrations are shown in Table 14. By using a divider (Pierburg PNG 2000) this gas was used to produce nine different concentrations.

Table 14: Concentrations of span gas.

Component	Concentration (ppm)	Accuracy
NO	907	+/- 1%
NO_2	16	+/- 1%

As a reference, concentrations were measured with a Pierburg (AVL) AMA 4000 laboratory-grade chemiluminescence analyser. The detection limit of the analyser was 6 ppm (diluted) and 50 ppm (undiluted). The drift was less than 0.5 per cent of the measured value.

The measurements began with the highest concentration and ended with the lowest concentration. A 'zero' concentration was also included to detect the zero point of the instruments.

To investigate the stability of the PTI instruments two reference concentrations of NO and two reference concentrations of NO_2 were used. The concentrations were measured using each instrument during a two-hour period, with measurements being taken at the start of this period and after elapsed times of 2, 5, 15, 30, 60, 90 and 120 minutes.

Step 3: Cross-sensitivity

The cross-sensitivity between NO or NO_2 and other exhaust components (O_2, CO, CO_2, HC) was investigated using calibration gas with typical components of a combustion engine. Measurements were made using high concentrations of O_2 (0.498 vol.%), CO (3.498 vol.%), CO_2 (13.995 vol.%) and

HC (998.2 ppm), but no NO or NO_2. For the Capelec CAP3800 the humidity-adjustment system described earlier was again used in these tests.

Interference from water vapour was not investigated in detail in the study. For the NDUV instrument it was not an issue, and for the other instruments the size of the effect is generally within the accuracy range. However, this still needs to be resolved by the manufacturers.

Steps 4 and 5: Dynamic behaviour

For dynamic test procedures it is important that the measurement equipment has a minimal delay in its response. The dynamic behaviour of each PTI instrument was therefore examined using two appropriate indicators: the T_{90} time (ascent) and the T_{10} time (descent) of the response to a step-function input signal. The step-function responses for NO and NO_2 were determined using calibration gas under laboratory conditions. In addition, dynamic response characteristics were investigated during free acceleration tests on the vehicle described in section 4.2.2.

Step 6: Long-term properties

The long-term measurement characteristics of the instruments were determined by repeating the accuracy and linearity tests after the completion of the vehicle and engine test programme (see chapter 5) and before instrument re-calibration, with the exception of the Sensors SEMTECH-DS (which had to be re-calibrated before the completion of the vehicle test programme).

4.2.4 PM measurements

The characteristics of the PM instruments were examined in two steps, as shown in Table 15. As with NO and NO_2, steady-state tests were conducted using an engine test bed and vehicle-based free acceleration tests (see section 4.2.2).

Table 15: Measurement programme for PM instruments.

Step	Test procedure	Parameters investigated
1	Test with reference engine: 7 steps, constant load and speed. Using AVL 439 as reference.	Accuracy, stability.
2	Free acceleration test (5 times) with one passenger car (or reference engine), using AVL 439 as reference.	Accuracy, reproducibility, practicability.

4.3 Results

4.3.1 NO and NO_2 instruments

Accuracy and linearity

Figure 8 shows the comparison between the NO results from the PTI instruments and the corresponding results from the chemiluminescence analyser. The corresponding NO_2 results are shown in Figure 9. In each graph the *x*-axis represents the nine different concentration values used in these tests.

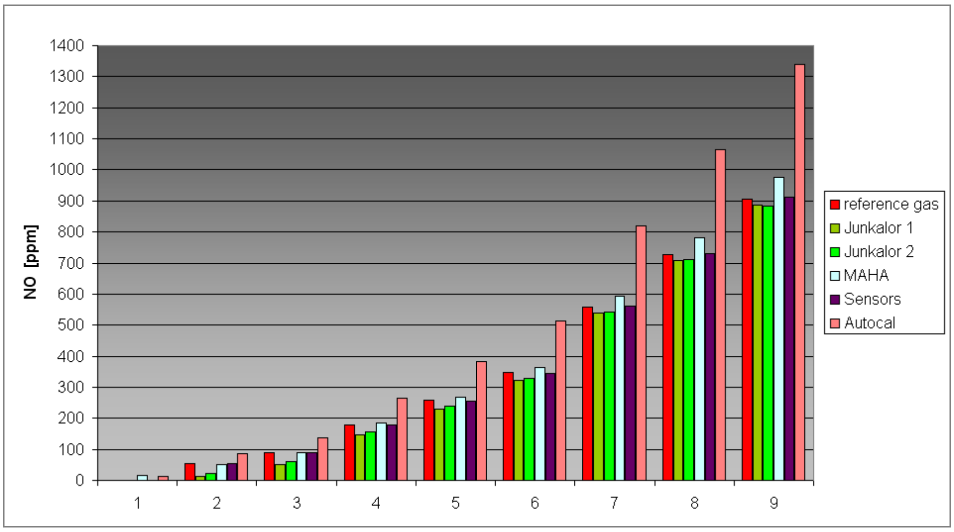

Figure 8: Accuracy and linearity – NO.

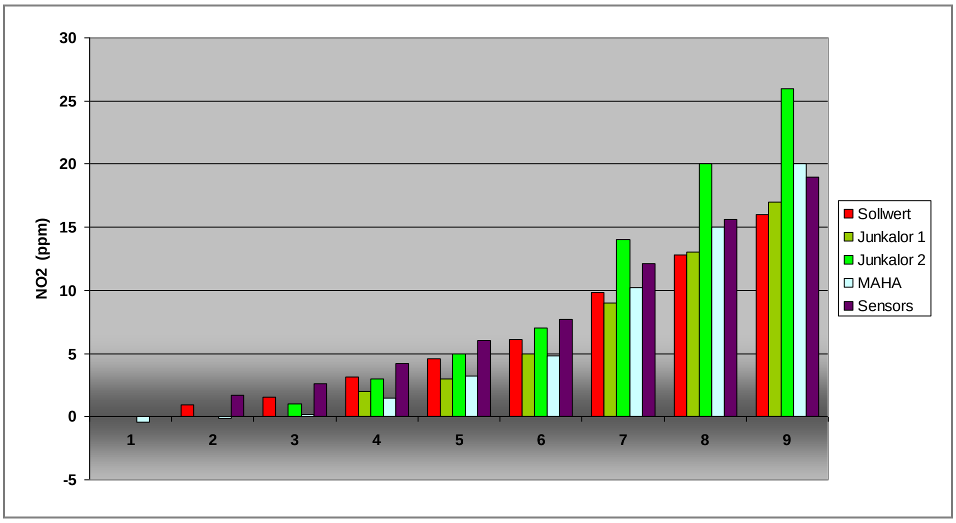

Figure 9: Accuracy and linearity – NO_2.

The data for NO are also presented in Table 16. Again, the nine rows represent the nine concentration values. The accuracy of the span gas (±1 %) is taken into account (conc. -1% / conc. +1%), and the accuracy of each PTI instrument has been evaluated in terms of how close the measurements were to those from the laboratory-grade instrument (using limits of ±5%). The limit of ±5% is the maximum permissible error on initial verification for PTI 4-gas-analysers according to the OIML R99-1 (ISO 3930).

The SAXON-Junkalor instruments were found to be inaccurate at low NO concentrations, but their performance improved at higher concentrations. In addition, the agreement between the two Junkalor instruments was good, which suggests that this is general characteristic. Conversely, the MAHA MET 6.1 had a good correlation with the laboratory-grade instrument at low concentrations (without zero point) but not at high concentrations (> 500 ppm). The SEMTEC-DS exhibited very good results. With the exception of one measurement point, this instrument measured concentrations which were very close to those of the span gas. The concentrations measured by the Autocal P550 were all outside of the imposed 5% limits.

Table 16: Comparison of PTI instruments with chemiluminescence analyser (NO).

Test no.	Chemiluminescence analyser			SAXON-Junkalor Infralyt ELD (1)	SAXON-Junkalor Infralyt ELD (2)	MAHA MET 6.1	Sensors Inc. SEMTECH-DS	Autocal P550
	NO (ppm)	conc.-1%	conc.+1%	NO (ppm)	NO (ppm)	NO (ppm)	NO (ppm)	NO (ppm)
1	0.0	0.0	0.0	0	0	15	0.0	14.0
2	53.6	53.1	54.1	14	23	52	54.8	85.0
3	89.3	88.4	90.2	52	61	90	89.6	138.0
4	179.9	178.1	181.7	146	157	185	178.8	266.0
5	258.6	256.0	261.2	229	239	269	256.0	382.0
6	347.6	344.1	351.1	321	330	363	345.4	512.0
7	558.1	552.5	563.7	539	543	593	560.9	818.0
8	727.0	719.7	734.3	708	710	780	730.9	1,066.0
9	907.0	897.9	916.1	885	883	977	911.8	1,338.0

Key:

- (green) Measurements within ±1% limits. Instrument would be very well suited to use in PTI emission tests.
- (yellow) Measurements within ±5% limits. Instrument would less accurate but still suitable.
- (red) Measurements outside limits. Instrument would be unsuitable.

It is worth noting that the Junkalor Infralyt ELD was calibrated using a NO concentration of 1,770 ppm, whereas the MAHA MET 6.1 was calibrated using a NO concentration of 500 ppm. This may partly explain the acceptable performance of the MAHA instrument at low concentrations but poor performance at high concentrations, and *vice versa* for the Junkalor instrument.

For NO_2 the concentration of the span gas was very low (max. 16 ppm), and this placed a high demand on the measurement equipment. The Autocal P550 detected only NO, so was not included here. All the other investigated instruments gave results which were outside the 5% limit.

Stability

The results of the stability tests are summarised in Table 17, and are presented graphically in Appendix G. Again, the colours indicate the pass/fail criteria.

Table 17: Summary of stability tests.

Instrument	NO	NO_2
Autocal P550	Measurements very stable but very different from calibration gas concentration.	Not measured by instrument.
Capelec CAP 3800	Measurements very stable but very different from calibration gas concentration.	Measurements very stable but very different from calibration gas concentration.
Junkalor Infralyt ELD	Measurements very stable at 2,800 ppm. Much lower stability at 500 ppm.	Both stability and accuracy unacceptable.
MAHA MET 6.1	Acceptable stability.	Stability not acceptable.
Sensors Inc. SEMTEC-DS	Very stable and accurate measurements over a long period.	Very stable and accurate measurements over a long period.

In general, the NO measurements were considerably more stable than those for NO_2. Given that several instruments had unstable NO_2 measurements the manufacturers were contacted and, where necessary, the instruments were returned for repair and recalibration. However, the very good results for the SEMTECH-DS clearly show that the measurement procedure was appropriate and that that the measurement techniques used in some of the other instruments may require further refinement. The Junkalor Infralyt ELD and the MAHA MET 6.1 gave acceptable values for NO but not for NO_2.

Cross-sensitivity

Figure 10 shows the cross-sensitivity results for the Autocal P550. Whilst the values for CO, CO_2, HC and O_2 – measured by an infrared cell - were very stable (but not very accurate), the values for NO (dark blue line) were unstable. The NO values varied between 0 and 19 ppm (even though there was no NO present). For the first 22 seconds the NO value was zero or close to zero, meaning that there was little or no interference from the other exhaust components. The increase in the NO value after 22 seconds was indicative of a long-term interference problem, or a problem with stability (see stability tests in Appendix G, which show a small instability after long measurement times). Because of this instability it was not possible to provide definitive conclusions about the cross-sensitivity of NO measurement for the P550 instrument.

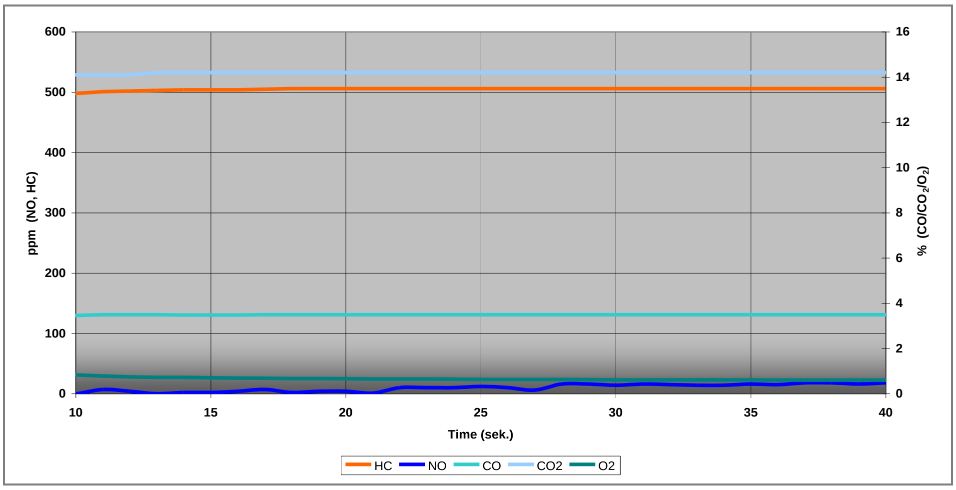

Figure 10: Cross-sensitivity – Autocal P550.

Figure 11 shows the reaction of the Capelec CAP3800 instrument to interference from CO, CO_2, HC and O_2. As the instrument only provides information on NO_x and O_2 the traces for the other pollutants were not available. These results were very different from the stability behaviour with no other exhaust components involved. It was therefore concluded that the instrument had a significant cross-sensitivity to other exhaust components.

The Infralyt ELD showed good stability for all components, and also for NO and NO_2 (Figure 12). The NO_2 values (red line) varied between 0 and 2 ppm over a long measurement period. This indicated that there was little or no cross-sensitivity for NO_2. The NO values (dark blue line) are interesting. Beginning at 0 ppm, the concentration had increased to 18 ppm by around 22 seconds, indicating that there was a significant cross-sensitivity for NO.

In the case of the MAHA MET 6.1 the values for NO and NO_2 were zero over a long period (Figure 13). It was therefore concluded that for NO and the NO_2 the instrument had no cross sensitivity to CO, CO_2, HC and O_2.

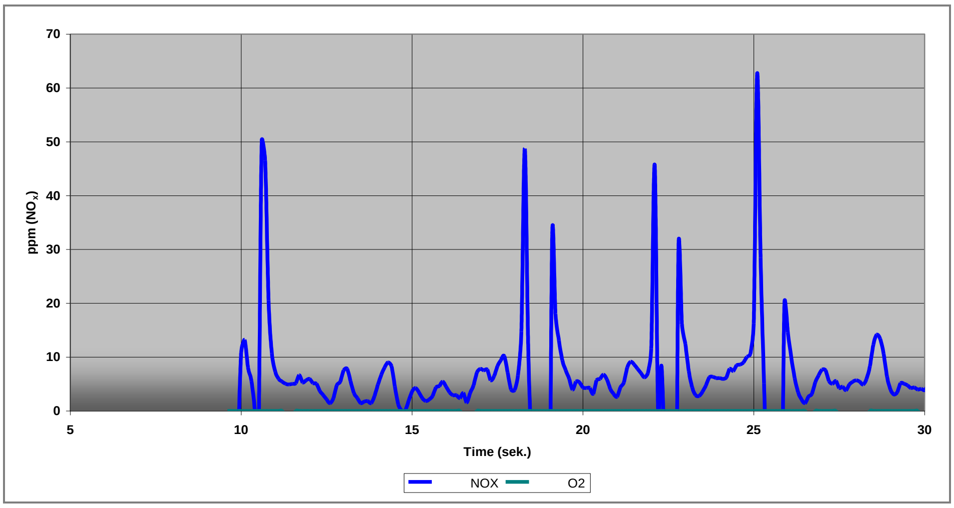

Figure 11: Cross-sensitivity – Capelec CAP3800.

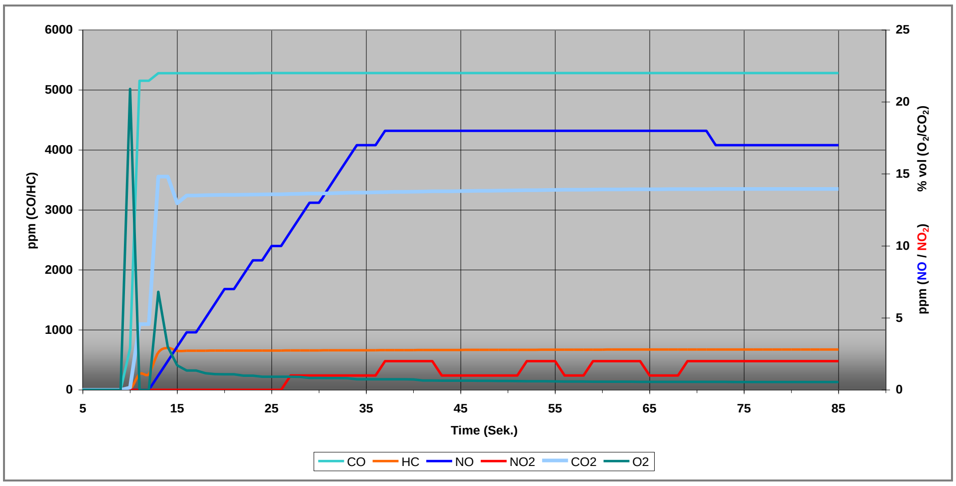

Figure 12: Cross-sensitivity – Junkalor Infralyt ELD.

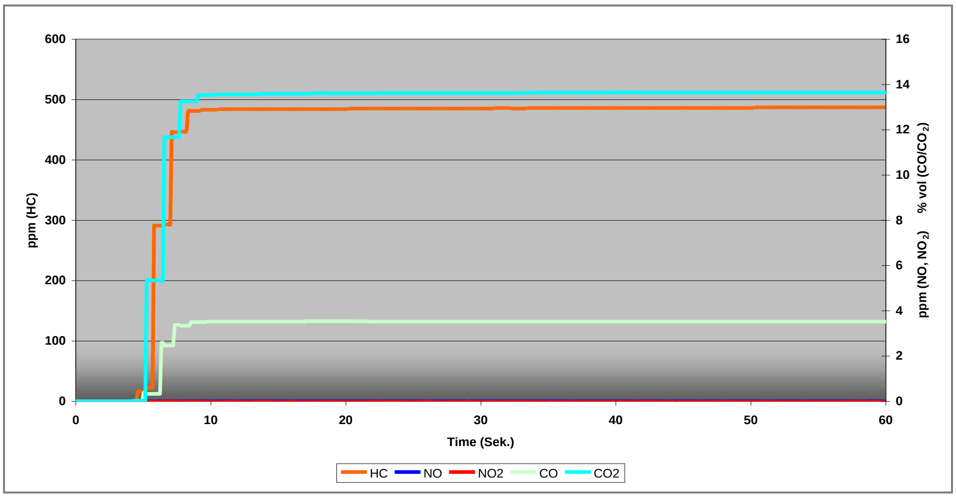

Figure 13: Cross-sensitivity – MAHA Met 6.1.

For the Sensors SEMTECH-DS the values were below 1 ppm, with the exception of an initial period of higher values for NO_2 (Figure 14) which was probably due to residual air in the gas hose at the start of the measurement. It was therefore concluded that the other exhaust components had no influence on the NO and NO_2 measurements.

The overall results from these tests are summarised in Table 18.

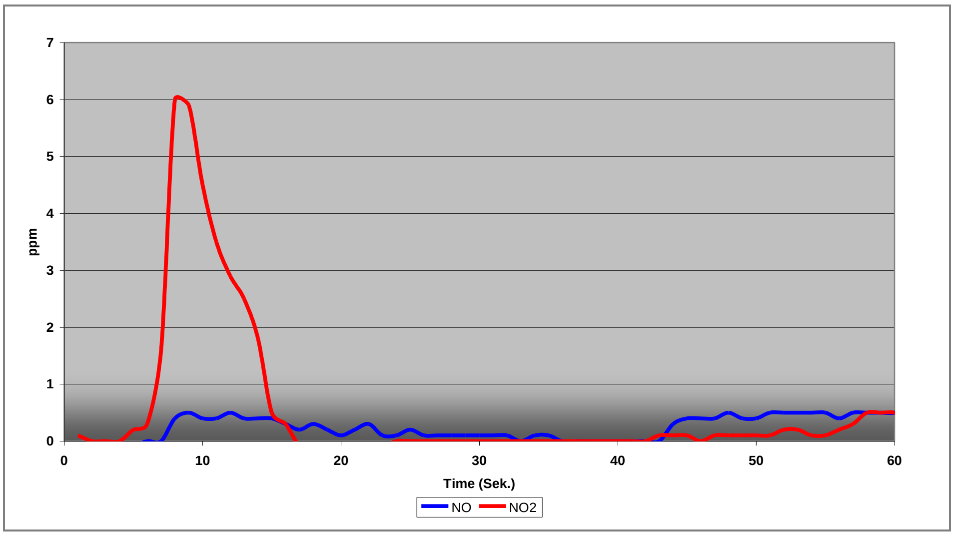

Figure 14: Cross-sensitivity – SEMTECH-DS.

Table 18: Summary of cross-sensitivity of NO and NO_2 (NO_x) instruments.

Instrument	NO (NO_x)	NO_2
Autocal P550	No, or very low cross-sensitivity, but problems with stability after long measuring times	-
Capelec CAP 3800	Important cross-sensitivity	-
Junkalor Infralyt ELD	Important cross-sensitivity	No, or very low cross-sensitivity
MAHA MET 6.1	No cross-sensitivity	No cross-sensitivity
Sensors SEMTEC-DS	No cross-sensitivity	No cross-sensitivity

Dynamic behaviour

Step function response

The results of the step function response tests are summarised in Table 19.

The Autocal P550 values were again very different from the concentration of the calibration gas (499.3 ppm NO). The Capelec CAP 3800 required 11 seconds to display 90% of the accumulated value, and 86 seconds to display 10% of the baseline value. The response times of the Autocal P550 (descent) and Capelec CAP3800 were therefore considered to be inadequate for dynamic test procedures.

The Junkalor Infralyt ELD had a slow response to the changing NO_2 concentration, with a T_{90} of 12 seconds and a T_{10} of 7 seconds. Moreover, it can be seen from Figure 15 that the instrument required a long time period to display the 100% and 0% NO_2 values. This performance was deemed to be unacceptable for dynamic PTI tests. A similar problem was observed with the MAHA MET 6.1 (both instruments have electrochemical sensors for measuring NO and NO_2).

Compared with the other instruments the SEMTEC-DS instrument had relatively short delay times for NO and NO_2. The accuracy of the instrument in this test was also very good. For NO_2 there was some drift in the signal, but this was not as pronounced as for the instruments employing electrochemical sensors.

Table 19: Summary of dynamic behaviour tests for NO and NO_2 instruments.

Instrument	NO		NO_2	
	T_{90} (ascent)	T_{10} (descent)	T_{90} (ascent)	T_{10} (descent)
Autocal P550	5 sec.	8 sec.	-	-
Capelec CAP 3800	11 sec. (NO_x)	6 sec. (NO_x)	-	-
Junkalor Infralyt ELD	6 sec.	6 sec.	12 sec.	7 sec.
MAHA MET 6.1	4.5 sec.	4 sec.	14 sec.	8 sec.
Sensors Inc. SEMTEC-DS	5 sec.	3 sec.	4 sec.	3.5 sec.

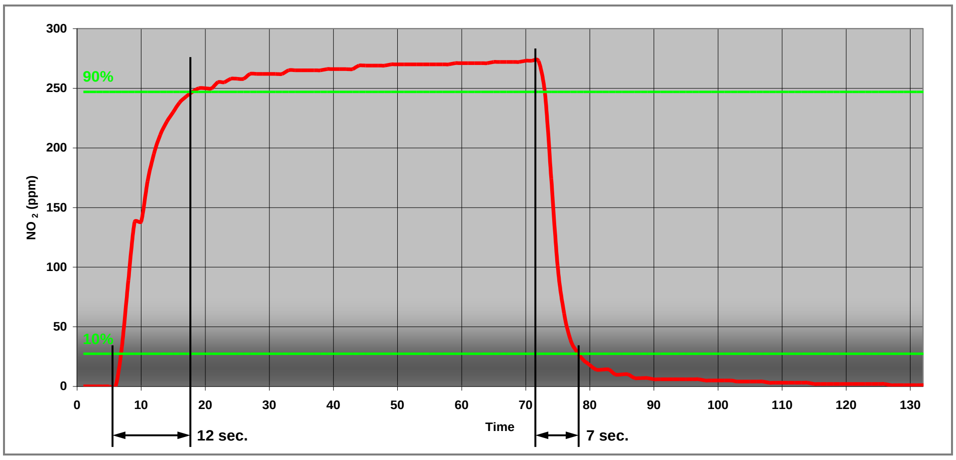

Figure 15: Dynamic response, step function – Junkalor Infralyt ELD (NO_2, 360 ppm span gas).

Free acceleration tests

The results of the free acceleration tests are summarised in Table 20, and are presented graphically in Appendix G. The results confirm those from the dynamics behaviour tests in terms of the time lag between engine speed and concentration. In this test the values for NO, NO_2 and NO_x differed widely between the instruments. There was no reference value for this test, but the results of the Autocal P550, and especially the Capelec CAP3800, appeared to be too high. For the other instruments the differences may be associated with the unacceptable dynamics observed in some of the step function response tests. For the Sensors Inc. SEMTECH-DS there were no significant differences between the results with the heated probe and the unheated probe.

Table 20: Arithmetic mean values of free acceleration results (5x).

Instrument	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
Autocal P550	377	N/A	N/A
Capelec CAP 3800	N/A	N/A	1720
Junkalor Infralyt ELD	87.5	22.5	110.0
MAHA MET 6.1	124.0	10.6	134.6
Sensors Inc. SEMTEC-DS (unheated probe)	155.0	16.9	171.9
Sensors Inc. SEMTEC-DS (heated probe)	154.4	18.4	172.8

Long-term properties

The measuring instruments gave very similar results to the original accuracy and linearity tests (Figure 8 and Figure 9). This meant that the performance of the instruments was stable over a long time period and large number of tests.

4.3.2 PM instruments

Constant load and speed tests

Figure 16 shows the particulate matter values (in mg/m³) obtained for three different instruments at the different load points. As noted before, the results from Pegasor instrument are not included as it was not calibrated to give values in mg/m³.

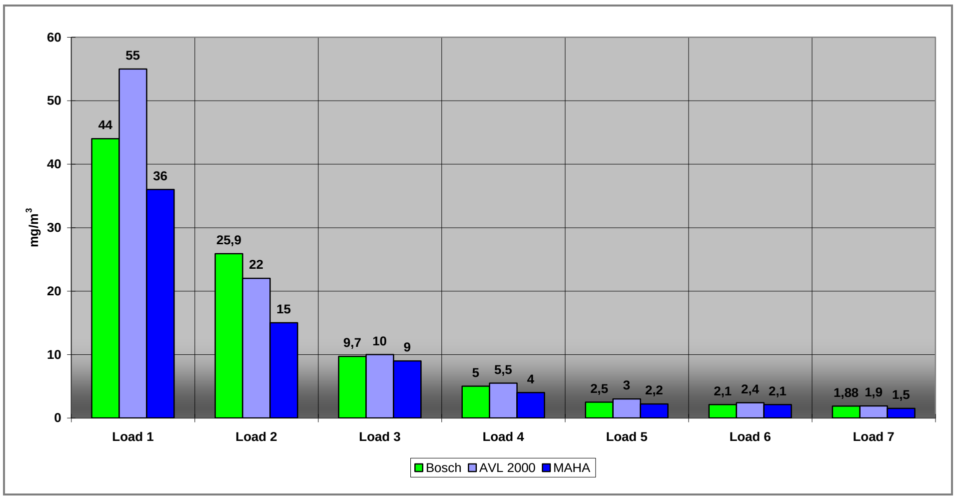

Figure 16: PM concentrations (mg/m³) for constant load and speed tests.

The three instruments exhibited a very good agreement under low-load conditions (and hence low PM concentrations – load points 3 to 7). For high PM concentrations (load points 1 and 2) the values differed somewhat, but there was a consistent pattern. This suggests that the results are dependent upon the instrument calibration, as the instruments are still being developed by the manufacturers and the German PTB.

In addition, NO and NO_2 concentrations were measured with the Junkalor and the MAHA instruments, and the results are shown in Figure 17 along with the opacity measurements of the reference instrument (AVL 439) and the calculated opacity values for the three test instruments. The opacity values of the three instruments differed in percentage terms from the reference value (maximum 60% / minimum 3%), but the absolute differences were small (*e.g.* maximum 0.08 m^{-1} for the MAHA-instrument). Again, the differences between the candidate instruments and the reference instrument were very consistent, and so it again appears that this is a calibration issue and relates to the calculation of the m^{-1} values from the mg/m^3 values.

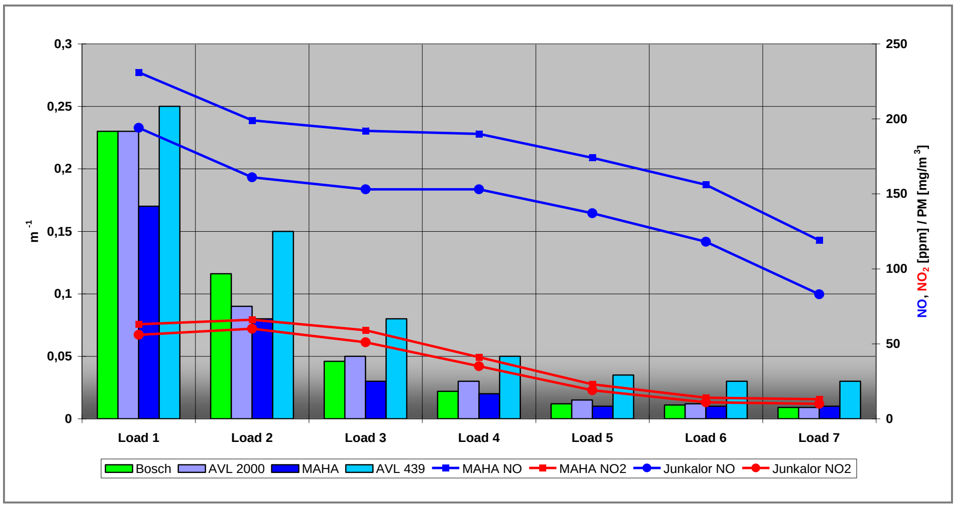

Figure 17: *K* values (m^{-1}) and NO and NO_2 concentrations (ppm) for constant load and speed tests.

Free acceleration tests

For constant values and good condition, Table 20 shows the arithmetic mean of the last three of five free accelerations. Additionally, the values of the AVL 439 are given as reference. The measurements of the PTI instruments differed somewhat, but were similar to the reference, and the differences were similar to the values with constant load and speed. As stated earlier, for the moment there is no adequate procedure for the calibration of the LLSP instruments, and this may be responsible for the differences between the instruments. The results should be more consistent if calibration can be standardised, and manufacturers are currently cooperating with the PTB in Germany to identify a solution.

Table 21: Arithmetic mean values of free acceleration results (3x).

Instrument	K (m^{-1})	PM (mg/m_3)
AVL Smoke 2000	-	152.5
BOSCH BEA 080	-	202.3
MAHA MET 6.2	-	134.2
AVL 439 (Opacimeter)	*1.382*	-

Key points from this chapter

1. For NO and NO_2, instruments operating on the NDUV principle are currently better suited to measuring emissions during PTI than the instruments using electrochemical cells. However, NDUV instruments are also more expensive.
2. Electrochemical cell instruments performed inconsistently in the tests. They do not appear to be very useful for measuring NO and NO_2 during dynamic PTI tests because of problems with accuracy, stability and dynamic response and cross-sensitivity to other exhaust components. Further development is required.
3. All the instruments used for PM measurement were essentially prototypes, but the level of development was higher than that of the NO and NO_2 instruments. Sufficiently accurate and stable measurements could be made using instruments based on the LLSP principle, and with good dynamic response characteristics and resolution for PTI tests.
4. LLSP systems are much more accurate than the advanced opacimeters which are used for type approval, and the technology has been developed to a sufficient level for testing modern vehicles in PTI programmes.
5. Excessive PM emissions can clearly be identified using LLSP instruments, and the correlation with type approval results is significantly better than for opacimeters.
6. The cost of LLSP instruments is comparable to that of conventional opacimeters, and in some cases can be lower. In addition, they are easy to handle and their practical use during PTI emission tests would not appear to be a problem.
7. For LLSP instruments there is a need to clarify calibration procedures, and a correlation must be defined between PM values in mg/m^3 and opacity values in m^{-1}. These issues are currently being investigated by the manufacturers and the German PTB.

5 Investigation of PTI procedures

5.1 Overview

PTI emission tests need to reliably identify those vehicles with malfunctions of emission-control systems which result in excessively high 'real-world' emissions. In this part of the work the pre-selected PTI instruments were examined during different PTI emission test procedures, and under different engine loads. Emission measurements were carried out on five modern diesel passenger cars and on one modern heavy-duty engine in a laboratory environment to maximise repeatability. It was not the aim here to compare the different PTI instruments *per se*, as this was already covered in some detail in chapter 4. At this stage it was of more interest to investigate the detection of failures and the correlation with type approval results.

Malfunctions of emission-control systems were investigated through the simulation of faults under realistic operational conditions. The impacts of these faults on emissions were measured, and the ability of different procedures and instruments to identify them was evaluated. The ability of the OBD system to identify faults was also assessed.

The results from the PTI instruments were benchmarked against those from laboratory-grade equipment. In addition, comparison of the results from PTI procedures with those from type approval tests was used as a general pass/fail criterion; if a simulated fault led to a significant increase in emissions (or an exceedance of limit values) over the type approval test, then the PTI procedure also had to show a value which would indicate the presence of a fault.

5.2 Methodology

5.2.1 Vehicles and engine

The work was conducted using five diesel cars and one heavy-duty diesel engine. The basic specifications of the cars are given in Table 22. All the vehicles had OEM after-treatment systems (*i.e.* there were no retrofits). One vehicle was certified to the Euro 4 standards but was compliant with the Euro 5 limits, three vehicles were certified to the Euro 5 standards, and one vehicle was certified to the demanding Euro 6 standards[32]. At the time of the project the Euro 6 vehicle represented the state of the art in terms of emission control.

Table 22: Specifications of test vehicles.

Vehicle	Displacement (cm^3)	Fuel injection system	Emission standard	Odometer (km)	Engine speed limiter
Vehicle 1	1,968	Pump injector	Euro 4 + DPF[(a)]	166,500	No
Vehicle 2	1,968	Common rail	Euro 5	36,500	Yes, but could be temporarily disabled
Vehicle 3	2,143	Common rail	Euro 5	25,500	N/A
Vehicle 4	2,143	Common rail	Euro 5	33,000	N/A
Vehicle 5	1,968	Common rail	Euro 6	17,500	Yes, but could not be disabled

(a) Euro 5 compliant

[32] The measurements on the Euro 6 car were funded by CITA members.

The basic specification of the heavy-duty engine is provided in Table 23. The engine was compliant with the Euro V emission standards, and featured an approach to emission control which was common for commercial vehicles meeting these standards. More specifically, the manufacturer designed the engine so that engine-out PM emissions already met the Euro V limit. However, given the NO_x-PM trade-off mentioned earlier, this required that engine-out NO_x emissions were approximately at the Euro II level, and hence the use of after-treatment to reduce NO_x below the Euro V limit. The engine was therefore fitted with SCR, but had no DOC, EGR or DPF.

Table 23: Specification of test engine.

Displacement (cm^3)	11,967
Power (kW)	220 @ 2,000 rpm
Torque (Nm)	1250 @ 1,100 rpm
Fuel injection system	Pump injector
Emission standard	Euro V
Exhaust after-treatment	SCR
SCR reagent	32.5 % urea solution

5.2.2 Experimental set-up

Vehicles 1, 2 and 5 were tested on the chassis dynamometer at DEKRA, and vehicles 3 and 4 were tested on the chassis dynamometer at TÜV NORD. This dynamometers were used for transient loaded transient tests (type-I type approval test, DT80 and AC5080). The PTI instruments identified in chapter 3 were allocated to the two test laboratories as shown in Table 24.

Table 24: PTI instruments tested in each laboratory – vehicle measurements.

	TÜVNORD	DEKRA
NO and NO_2 instruments		
Reference	NOXMAT 5E CLD	Pierburg CLD
PTI	SAXON-Junkalor Infralyt ELD	SAXON-Junkalor Infralyt ELD
	MAHA MET 6.1	MAHA MET 6.1
		Sensors Inc. SEMTECH-DS
PM instruments		
Reference	AVL 439	AVL 439
PTI	AVL Smoke 2000	AVL Smoke 2000
	BOSCH BEA 080	MAHA MET 6.2
	MAHA MET 6.2	PEGASOR PPS-M (not reported)

The heavy-duty engine was investigated using a test bed at TÜV NORD. During the study the pollutant analysers were calibrated using standard gas at the beginning of each day. The PTI instruments used in these tests are given in Table 25.

Table 25: PTI instruments tested at TÜV NORD – heavy-duty engine measurements.

	NO and NO_2 instruments	PM instruments
Reference	Pierburg AMA 4000	PM mass: AVL Smart Sampler 472 Smoke: AVL 439
PTI	MAHA MET 6.1	AVL 2000
	Saxon Junkalor Infralyt ELD	MAHA MET 6.2
		BOSCH BEA 080

5.2.3 Simulation of faults

Malfunctions of emission-control systems were investigated through the simulation of faults. A list of typical faults is provided in Appendix B, and a number of these were used in the tests. The weak points of modern after-treatment systems are well known, and faults in certain components can lead to significant increases in emissions. Some components are also not fully under the control of the OBD system. OBD system capability is limited to sensor read-out or complex algorithms which introduce some uncertainty. The emphasis here was therefore on the most important systems which are responsible for the condition of the engine-out exhaust, as well as the after-treatment components. Engine manipulation and 'chip-tuning' were considered to be of interest, but given that so many different approaches are possible it was considered that these were beyond the scope of the project. Following discussions with stakeholders (*e.g.* ACEA) it was concluded that only 'realistic' failures from experience in the field should be used.

The faults simulated in the cars are described in Table 26 to Table 30.

Table 26: Simulated faults, vehicle 1.

Fault no.	Fault	Description
1	DPF defect (ageing)	This fault simulated normal ageing of the DPF. The DPF was not modified for the test, but was an in-service unit (Figure 18) which was subsequently replaced. The test on the replacement unit was taken as the 'initial' state'.
2	Crankcase breather removed ("blow-by")	This is a simple fault (Figure 19) which can result from mechanical work on the vehicle (repairs, maintenance) or ageing (becomes brittle). This causes incorrect air/oxygen detection by the ECU and, as a result, incorrect fuel injection and EGR rates, and can increase NO_x.
3	Air mass flow meter manipulated	Air mass flow meters can be affected by soiling (dirt, oil), deterioration (ageing) or defective air filters (poor maintenance). This causes incorrect air/oxygen detection and incorrect fuel injection/EGR, and can decrease NO_x. Here, the active diameter of the air intake was reduced (Figure 20), with the result that the sensor registered a higher air speed and mass. This led to greater fuel injection by engine management system. This fault was used to determine the response of different test methods to EGR failures in different directions. Due to the NO_x-PM trade-off, lower NO_x emissions and high PM emissions will have an impact on DPF regeneration and its frequency.

Table 27: Simulated faults, vehicle 2.

Fault no.	Fault	Description
1	DPF defect (mechanical damage)	The DPF was mechanically damaged by drilling 29 holes with a diameter of 10 mm (Figure 21).
2	Crankcase breather removed	See vehicle 1, fault 2.
3	DOC defect (mechanical)	The DOC was mechanically damaged.

Table 28: Simulated faults, vehicle 3.

Fault no.	Fault	Description
1	DPF fault (Unloaded[(a)])	The DPF was 'unloaded - *i.e.* it had no metallic wash coat. This was used to simulate a worst-case for a retrofitted DPF.
2	DOC fault (removed)	DOCs are subject thermal and mechanical stress. To simulate the damage caused to the catalyst monolith by these stresses the DOC was removed.
3	DPF fault + DOC fault	Combination of faults 1 and 2.

Table 29: Simulated faults, vehicle 4.

Fault no.	Fault	Description
1	DPF fault (Unloaded)	See vehicle 3, fault 1.
2	DPF fault + DOC fault	See vehicle 3, fault 3.
3	DPF fault (mechanical defect)	As with DOCs, DPFs are subject thermal and mechanical stress. To simulate these effects a mechanical defect was introduced into the DPF. The DPF was mechanically damaged by drilling 1 hole with a diameter of 10 mm.

Table 30: Simulated faults, vehicle 5.

Fault no.	Fault	Description
1	DPF defect (mechanical damage)	To simulate the effects of thermal and mechanical stresses an adjustable 'bypass' was built around the DPF.
2	SCR catalyst ageing	This represented the normal deterioration with age of a SCR catalyst. The catalyst was thermally 'aged' in a kiln for 10 hours at a temperature of 650°C (Figure 22).
3	SCR catalyst damaged	Mechanical damage is one of the most common reasons for catalyst (and DPF) failure. To simulate this problem, the SCR catalyst was disconnected, and a hole of diameter 15 mm was drilled through the NO_x-reducing area. Some parts of the ceramic SCR tray were also damaged to reduce the catalyst surface.

Figure 18: Vehicle 1, fault 1: DPF defect (ageing).

Figure 19: Vehicle 1, fault 2: Crankcase breather removed.

Figure 20: Vehicle 1 fault 3: manipulation of air mass flow meter.

Figure 21: Vehicle 2, fault 1: DPF defect (mechanical damage).

Figure 22: Vehicle 5, fault 2: ageing of SCR catalyst.

The heavy-duty engine faults were based on the type approval requirements for OBD. These were typical of faults that could arise as a result of damage or failure (Table 31).

Table 31: Simulated faults, heavy-duty engine.

Fault no.	Fault	Description
1	Intermittent open circuit of temperature sensor before SCR	Removed connector plug from temperature sensor before SCR. Simulation of a damaged sensor or a cable break.
2	Empty reagent reservoir	The urea reservoir was emptied to simulate a leak or deliberate non-refilling.
3	Reagent diluted with 50% H_2O	The urea solution was diluted with water to simulate a deliberate action of this kind.

5.2.4 Test procedures

Vehicle measurements

PTI emission test procedures must be, as a matter of necessity, relatively short, simple and pragmatic, relatively inexpensive, reliable and generally appropriate to the test centre environment. 'Unloaded' tests – that is tests that use no external load, with the only load being that associated with overcoming inertia and friction within the engine - meet these criteria. These include free acceleration tests, oscillating acceleration tests, and idle tests. The following unloaded tests were therefore examined:

- Idle
- High idle
- Free acceleration
- The Norris-A test, with a rate of increase in engine speed of 50 rpm per second
- INCOLL

Given that there have previously been some criticisms of unloaded tests (*e.g.* Anyon *et al*., 2000), the following loaded tests were also evaluated using a chassis dynamometer with a load similar to that used for the NEDC:

- Transient
  - NEDC
  - DT80
  - AC5080
- Steady-state with constant external load
  - Constant speed of 50 km/h
  - Constant speed of 80 km/h

Because of the trade-off between NO_x and PM emissions, the same test procedures were investigated for both pollutants. The candidate PTI tests were conducted both with (i) the vehicle's engine and after-treatment system in working order and (ii) a simulated fault/failure. The OBD system was also monitored (DTCs and MIL) to determine whether the faults were detected.

All tests were conducted with modal measurements of relevant exhaust pollutants (O_2, CO, CO_2, HC, NO, NO_2) using the laboratory-grade equipment. This provided a better indication for characteristic of engine management and the exhaust after treatment. For the loaded tests bag samples were taken from the CVS, and modal measurements were taken from the raw exhaust. For the unloaded PTI tests the measurements were made on the raw exhaust. The correlation between the results from the PTI tests and the results from the type approval test (NEDC) was also investigated.

Heavy-duty engine measurements

The heavy-duty engine was subjected to the tests listed in Table 32. Faults in SCR systems have little effect on the PM emission, and therefore the measurements of PM were less extensive than those NO and NO_2.

Table 32: Tests on heavy-duty engine.

Test type	Test	NO and NO_2	PM
Type approval tests	European Stationary Cycle (ESC)	Raw, modal : Pierburg AMA 4000	PM mass: AVL Smart Sampler 472
	European Load Response (ELR)	-	Opacity: AVL 439
	European Transient Cycle (ETC)	Raw, modal: Pierburg AMA 4000, MAHA MET 6.1, Saxon-Junkalor Infralyt ELD	PM mass: AVL Smart Sampler 472
Constant speed/ torque tests	1430 rpm / 415 Nm /62 kW	Raw, modal: Pierburg AMA 4000, MAHA MET 6.1, Saxon Junkalor Infralyt ELD	-
	1700 rpm / 450 Nm / 80 kW		-
Idle tests	Idle (510 rpm)	Raw, modal: Pierburg AMA 4000, MAHA MET 6.1, Saxon-Junkalor Infralyt ELD	-
	High idle (1,100 rpm)	Raw, modal: Pierburg AMA 4000, MAHA MET 6.1, Saxon-Junkalor Infralyt ELD	-
Free acceleration tests	INCOLL (x20)	Raw, modal: Pierburg AMA 4000, MAHA MET 6.1, Saxon Junkalor Infralyt ELD	-
	Standard free acceleration (x4)	-	PM/opacity: AVL 439 (Standard), AVL 2000, MAHA MET 6.2, BOSCH BEA

5.3 Results

The intention of this section of the report is to give an overview of the results and to provide indicative answers to four main questions:

1. Can faults in NO_x control systems be detected using NO_x measurement during PTI tests?
2. Can faults in PM-control systems be detected using PM measurement during PTI tests?
3. Can faults in emission-control systems be detected using the NO_2/NO_x ratio during PTI tests?
4. Can faults in emission-control systems be detected using OBD during PTI tests?

These questions will be addressed further in chapter 6.

The full test results are tabulated in Appendix H and are summarised separately below for each vehicle. Given the uncertainties involved in PTI emission measurement, these questions can only be answered with confidence where large and systematic changes in emissions are observed, and this is recognised in the following discussion.

5.3.1 Vehicle 1

Figure 23, Figure 24 and Figure 25 show the results for NO_x, PM and NO_2/NO_x respectively. The NO_x/NO_2 data are based on the chemiluminescence measurement method in all cases[33]. For PM the NEDC data are based on the regulatory filter mass and the PTI data are based on the MAHA MET 6.1/6.2 measurements. The Euro 5b type approval limits are also shown as dashed red lines in Figure 23 and Figure 24. No PM measurements were made for the idle test.

NO_x emissions over the NEDC were much lower than those over the DT80 and AC5080, primarily because the engine load over the NEDC was much lower, and therefore in Figure 23 the results for the latter two tests are divided by a factor of 10 to make comparison easier.

The data revealed some interesting effects, with some faults having a large impact on the emissions behaviour of the vehicle. The results are summarised below. It is worth noting that where a fault did not lead to a significant increase in emissions of NO_x and/or PM over the NEDC it was not possible to identify an appropriate PTI procedure.

Fault 1 – The **aged DPF** resulted in only a small change in NO_x emissions over the NEDC. There was, however, a large increase in PM emissions over the NEDC, such that the absolute PM level slightly exceeded the type approval limit value. This increase showed up clearly in the results from the loaded transient PTI tests (DT80 and AC5080), as well as in the free acceleration, Norris-A and INCOLL tests. The increase in PM was not clearly detected by the high idle and constant speed tests. The fault led to a large reduction in the NO_2/NO_x ratio over the NEDC, and this was also picked up in most of the PTI tests (except the idle tests).

Fault 2 – the removal of the crankcase breather – resulted in a large increase in NO_x emissions over the NEDC, so that the type approval limit was exceeded. This was due to additional air being aspired between the air-mass-flow sensor and the intake valve, and therefore leaner combustion went towards leaner conditions which favoured NO_x formation. However, this increase in NO_x was not detected by any of the PTI procedures. Short tests with low loads cannot usually identify EGR-related effects because the EGR is not active. At higher loads (*e.g.* DT80 and AC5080) the EGR rate also tends to be low, leading to small effects for this type of fault. There was little change in either PM emissions or the NO_2/NO_x ratio over

33 It should be noted (for all vehicles) that in some cases the NO_2/NO_x mass ratio is used (*e.g.* over the NEDC, where NO_2 and NO_x are stated in g/km), whereas in others the volume ratio is used (*e.g.* for the PTI tests where the measurements are in ppm). Because the use of mass or volume affects the ratio, this confounds the results to some extent. However, PTI tests are concerned with identifying large changes in emissions, and therefore this issue becomes less important.

the NEDC, as the DPF was probably working as normal, and similar results were observed for the PTI tests. Overall, the PTI tests were not useful for identifying this fault.

Fault 3 - the **manipulation of the air mass flow meter** - led to a noticeable decrease (as expected) in NO_x emissions over the NEDC, and only a slight increase in PM emissions. Some of the PTI procedures gave slight increases in NO_x, and the effects on PM and the NO_2/NO_x ratio were very similar to those for fault 2.

OBD: For all three simulated faults the MIL was off and no DTCs were recorded (*i.e.* no faults were detected by the OBD system).

Figure 26 and Figure 27 show the continuous measurements over the unloaded test procedures - idle, high-idle, free acceleration (5x), Norris-A (2x) (excluded from Figure 27) and INCOLL - recorded with the AVL 2000 instrument. In Figure 26 the vehicle is in the initial state, and in Figure 27 the vehicle has the DPF defect (fault 1). It should be noted that the scales for PM (left scale, marked red) are very different in the two graphs; the values with the defective DPF are nearly 100 times higher than those in the repaired state. As already stated, most of the test procedures were suitable for detecting such a defect.

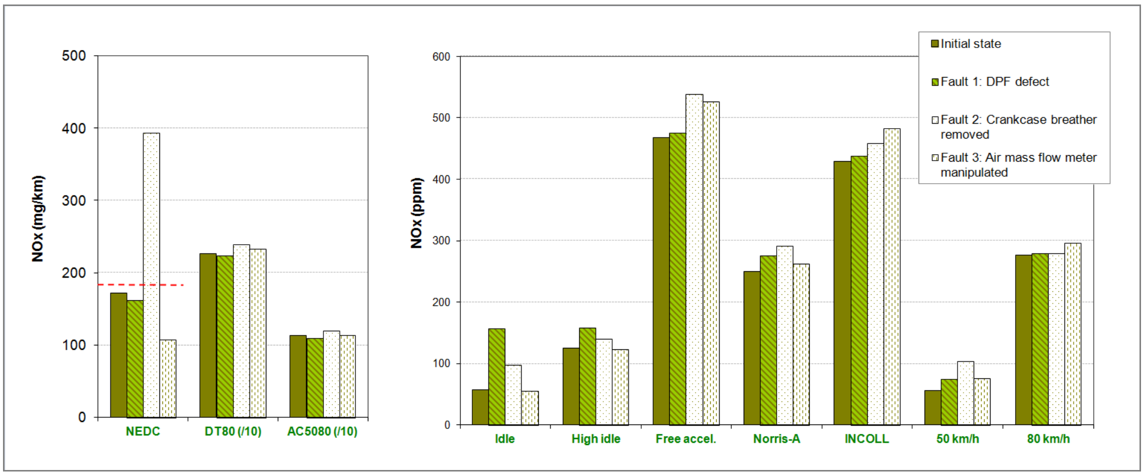

Figure 23: NO_x emissions by test procedure and simulated fault, vehicle 1. Dashed red line = Euro 5b type approval limit for NO_x.

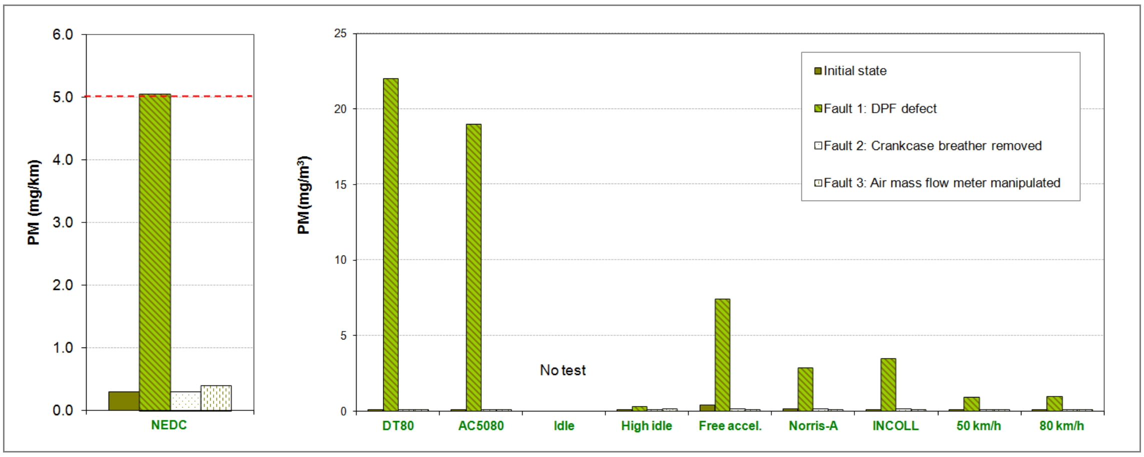

Figure 24: PM emissions by test procedure and simulated fault, vehicle 1. Dashed red line = Euro 5b type approval limit for PM.

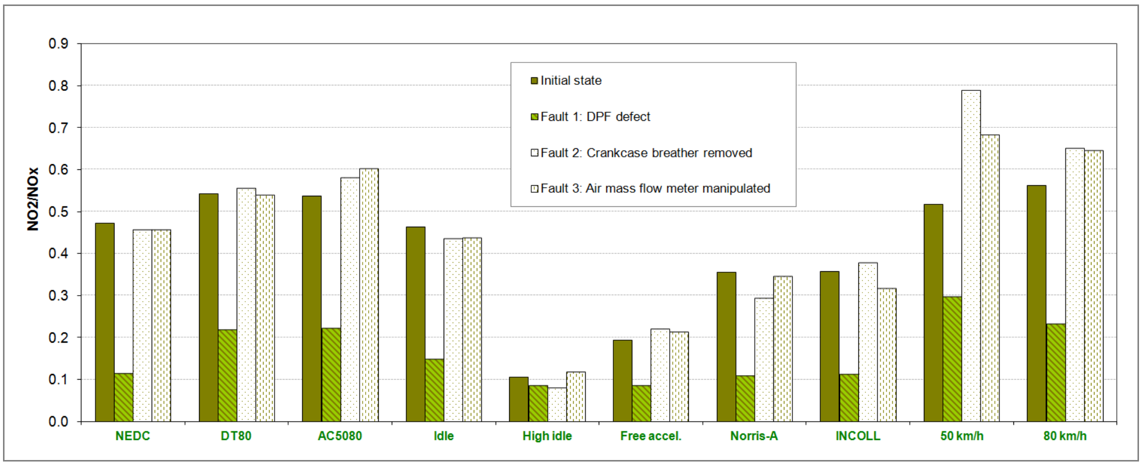

Figure 25: NO_2/NO_x ratio by test procedure and simulated fault, vehicle 1.

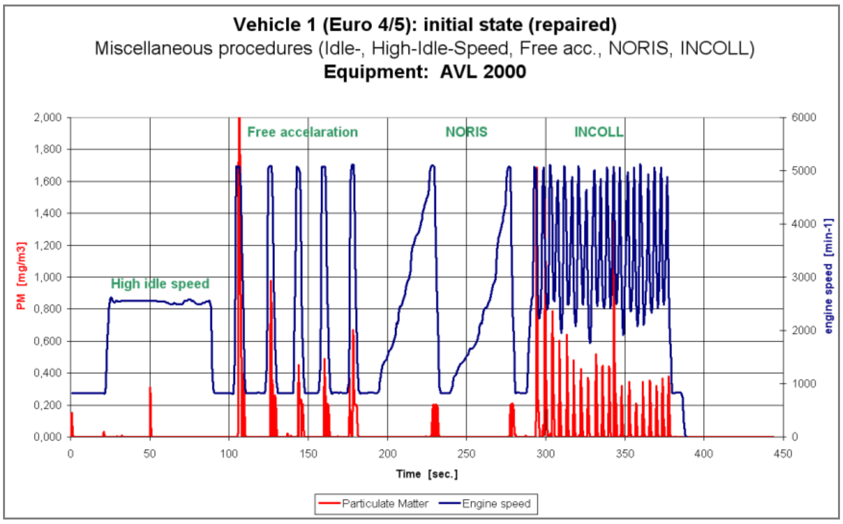

Figure 26: On-line measurements during test procedures, vehicle 1: initial state.

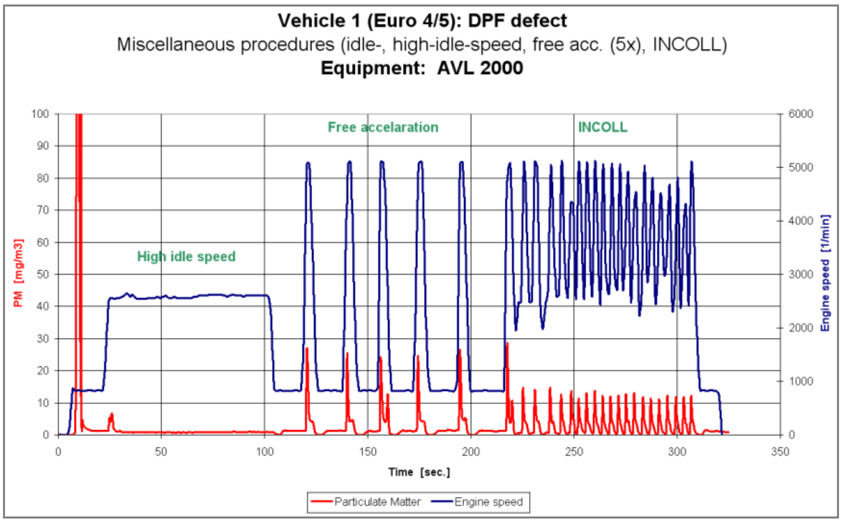

Figure 27: On-line measurements during test procedures, vehicle 1: DPF defect.

5.3.2 Vehicle 2

Figure 28, Figure 29and Figure 30 show the results for vehicle 2. The measurement methods used for vehicle 1 were also used for this vehicle. NO_x emissions over the NEDC were lower than those over the DT80 and AC5080, but in this case the difference was smaller. The results for the DT80 and AC5080 were divided by a factor of 2.

Fault 1 – The **damaged DPF** had little effect on NO_x emissions over the NEDC but a significant impact on PM emissions, and this was detected by several of the PTI procedures. Here, the picture was slightly different to that observed for vehicle 1, in that the clearest responses were found for the free acceleration, Norris-A and INCOLL tests. The NO_2/NO_x ratio decreased noticeably over the NEDC. This change was also detected by some of the PTI tests (notably the loaded tests) but not others.

Fault 2 – Unlike in the case of vehicle 1, the **removal of the crankcase breather** had little effect on NO_x and PM emissions over the NEDC. This is likely to be due to differences between the technologies used for the Euro 4 and Euro 5 vehicles. The PTI procedures did not register very large changes in NO_x or PM either. For the NO_2/NO_x ratio the picture was rather different; over the NEDC, fault 2 led to an increase in the NO_2/NO_x ratio, and some substantial changes – both increases and decreases – were observed for the PTI tests. It seems likely that there could be significant errors of commission if the NO_2/NO_x ratio is used alone.

Fault 3 – the **DOC defect** – gave broadly similar NO_x results to fault 2, with the exception that the Norris-A test led to an increase in NO_x which was not observed over the NEDC. In addition, no large changes in PM emissions were observed over the NEDC or the PTI tests. There was a slight increase in the NO_2/NO_x ratio over the NEDC, but larger increases were observed over the PTI tests. This again suggests the possibility of false failures if the NO_2/NO_x ratio is used alone.

OBD: In all cases the MIL was not triggered and no DTC was stored; again, the OBD was unable to detect that faults were leading to increased emission behaviour.

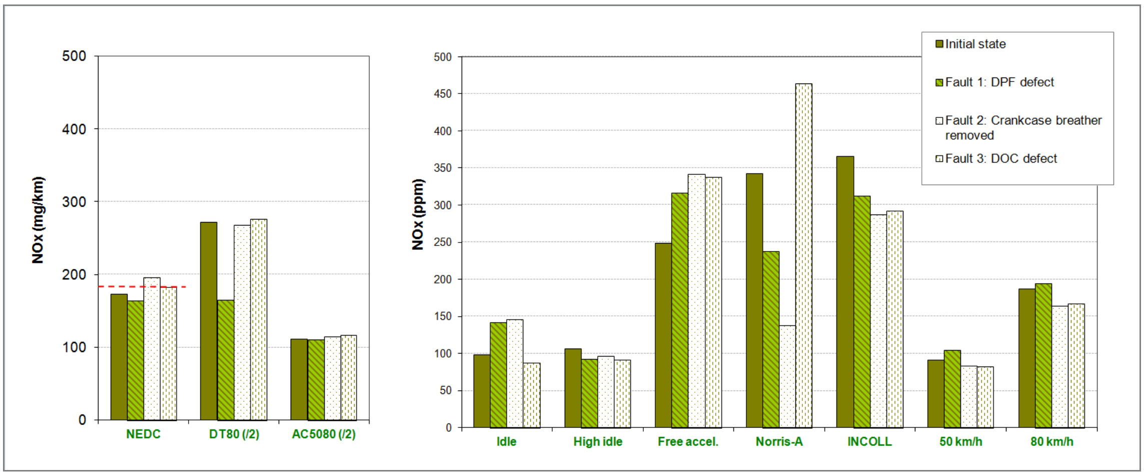

Figure 28: NO_x emissions by test procedure and simulated fault, vehicle 2. Dashed red line = Euro 5b type approval limit for NO_x.

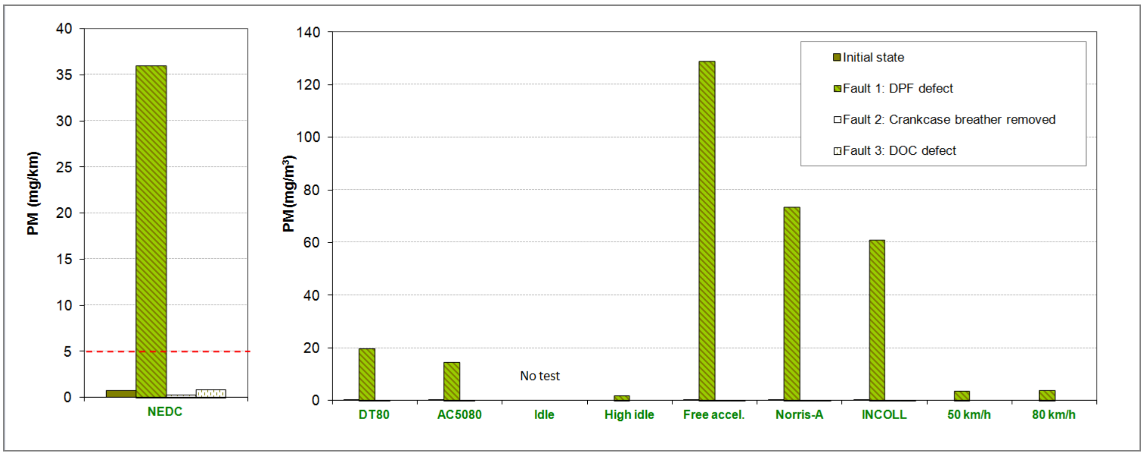

Figure 29: PM emissions by test procedure and simulated fault, vehicle 2. Dashed red line = Euro 5b type approval limit for PM.

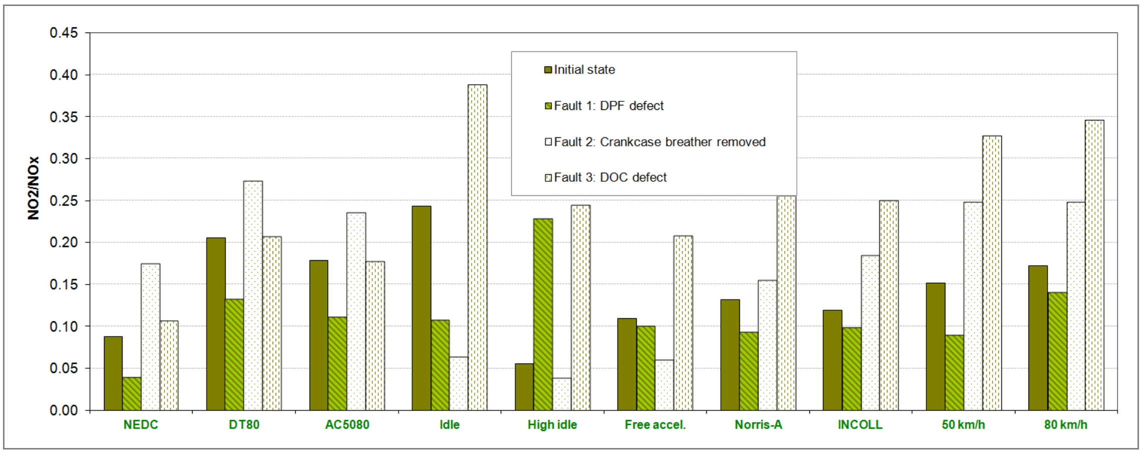

Figure 30: NO_2/NO_x ratio by test procedure and simulated fault, vehicle 2.

5.3.3 Vehicle 3

The results for vehicle 3 are given in Figure 31, Figure 32 and Figure 33. For PM, the DT80 and AC5080 tests were carried out using type approval measurement equipment, and hence the results in Figure 32 are given in mg/km. The free acceleration test was conducted using the AVL 2000 instrument, and therefore the results are given in mg/m³.

Fault 1 – The **unloaded DPF** had little effect on NO_x emissions over NEDC, DT80 and AC5080. There was an increase in PM over the NEDC, but emissions remained well within the Euro 5 limit. However, an increase in PM was only clearly identified by the AC5080 test. The PTI tests generally gave an increase in the NO_2/NO_x ratio, but the absence of substantial increases in NO_x and PM again indicate that the ratio alone is not a reliable indicator of faults.

Fault 2 – The **removal of the DOC** also had little effect on NO_x emissions over the NEDC. PM emissions over the NEDC increased slightly, the free acceleration test showed a large increase, suggesting that a false failure would be likely. Some of the PTI tests gave a large reduction in the NO_2/NO_x ratio.

Fault 3 – The **combined DPF and DOC fault** again had little effect on NO_x emissions over NEDC. However, it had a larger impact on PM emissions than either of fault 1 or 2 alone, although emissions remained within the Euro 5 limit. The higher PM values appeared to be due to very high HC emissions, with hydrocarbons attaching to solid particles and affecting the filter weight. The increased PM level was identified to some extent by the loaded transient PTI tests (with measurement in mg/km), but not by the free acceleration test (with measurement in mg/m³ based on LLSP[34]). The PTI tests also tended to give a decrease in the NO_2/NO_x ratio.

OBD: In all cases the MIL was not triggered and no DTC was stored; again, the OBD was unable to detect that faults were leading to increased emission behaviour.

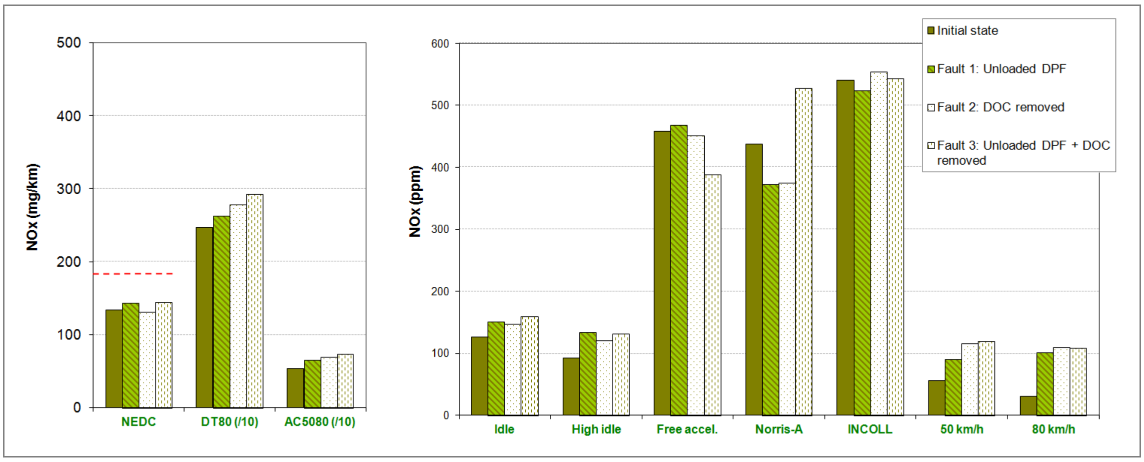

Figure 31: NO_x emissions by test procedure and simulated fault, vehicle 3. Dashed red line = Euro 5b type approval limit for NO_x.

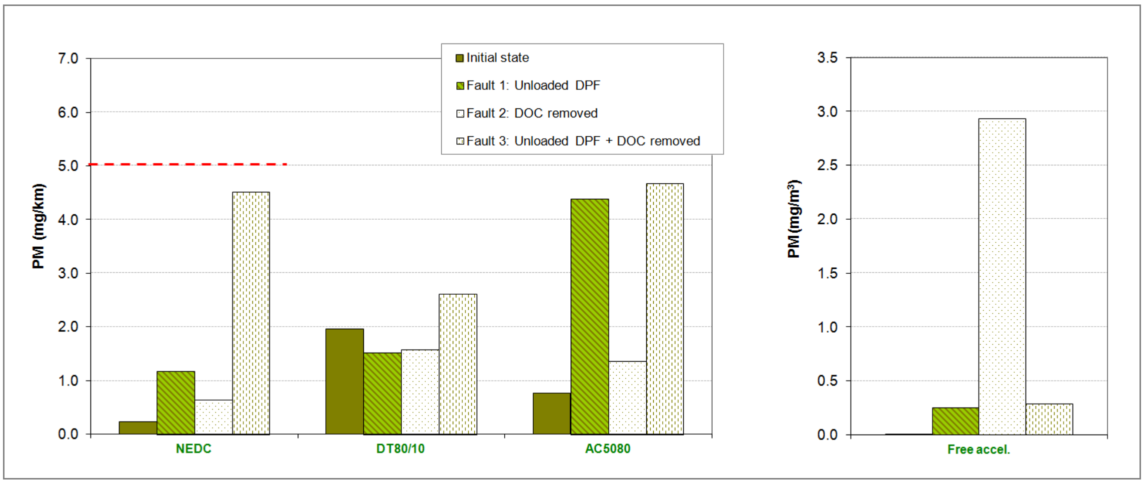

Figure 32: PM emissions by test procedure and simulated fault, vehicle 3. Dashed red line = Euro 5b type approval limit for PM.

[34] The wavelength of the light used in LLSP instruments, and the fact that the measuring cells are heated to at least 70°C, are potential explanations for the HC-component of PM not being detected in the free acceleration test.

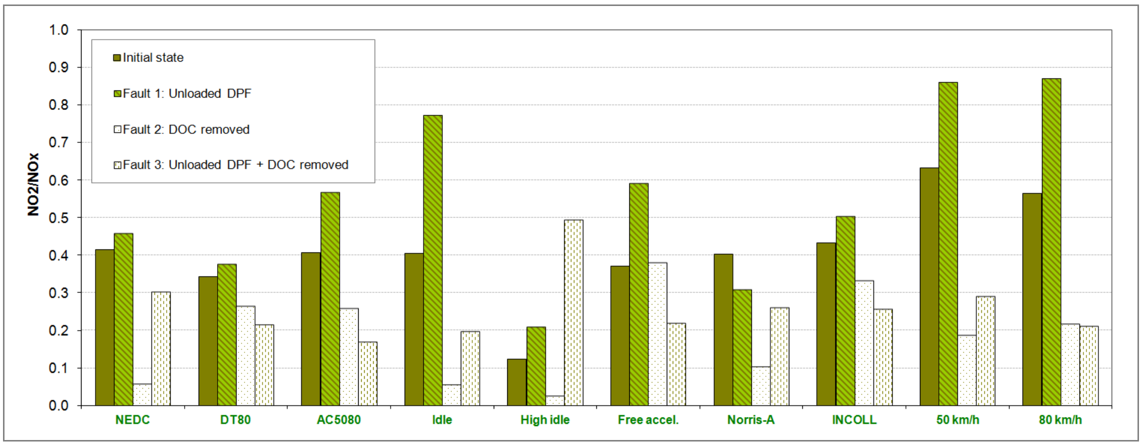

Figure 33: NO_2/NO_x ratio by test procedure and simulated fault, vehicle 3.

5.3.4 Vehicle 4

The results for vehicle 4 are given in Figure 34, Figure 35 and Figure 36. For this vehicle measurements were made for the NEDC, the free acceleration test, the Norris-A test and the INCOLL test. The PM measurements over the PTI tests were made with the AVL 2000 instrument.

None of the simulated faults had a pronounced effect on NO_x emissions. The results for the NO_2/NO_x ratio were very variable and difficult to interpret. The PM results are summarised below.

Fault 1 – The **unloaded DPF** had little effect on PM emissions over NEDC.

Fault 2 – The **unloaded DPF and removed DOC** had a larger impact on PM emissions over the NEDC than the unloaded DPF alone. However, the emission level remained within the Euro 5 limit and the increase was not clearly identified by the PTI tests. It is again likely the high HC emissions for this condition was the cause for this discrepancy (see vehicle 3, fault 3).

Fault 3 – The **mechanical DPF defect** gave a much larger increase in PM emissions over NEDC, and resulted in an exceedance of the Euro 5 limit value. This effect was similar to that observed for vehicles 1, 2 and 4). This increase was also identified more clearly by the PTI tests, and in particular the free acceleration test.

OBD: In all cases the MIL was not triggered and no DTC was stored; again, the OBD was unable to detect that faults were leading to increased emission behaviour.

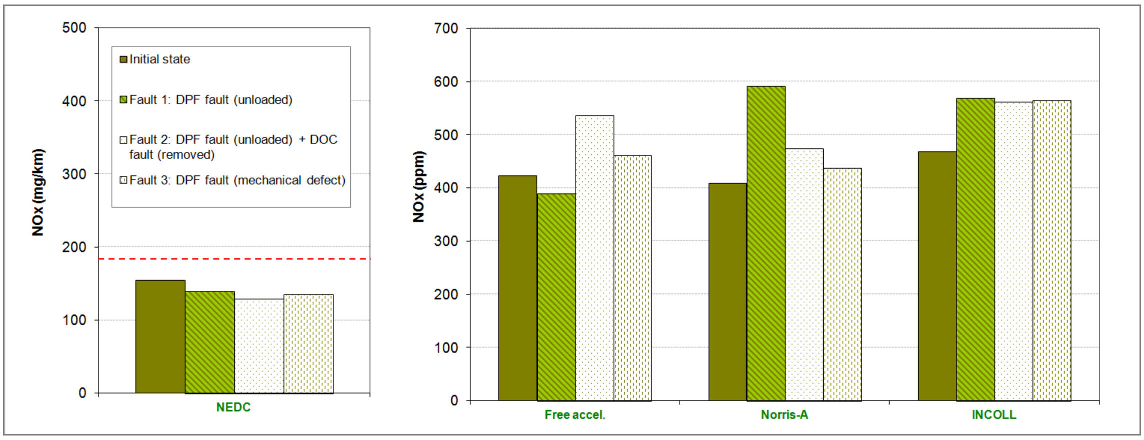

Figure 34: NO_x emissions by test procedure and simulated fault, vehicle 4. Dashed red line = Euro 5b type approval limit for NO_x.

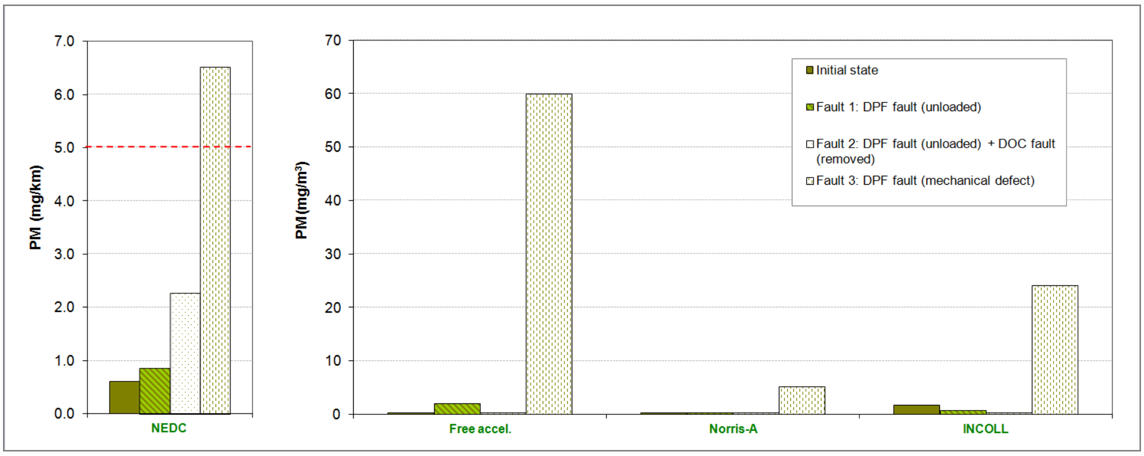

Figure 35: PM emissions by test procedure and simulated fault, vehicle 4. Dashed red line = Euro 5b type approval limit for PM.

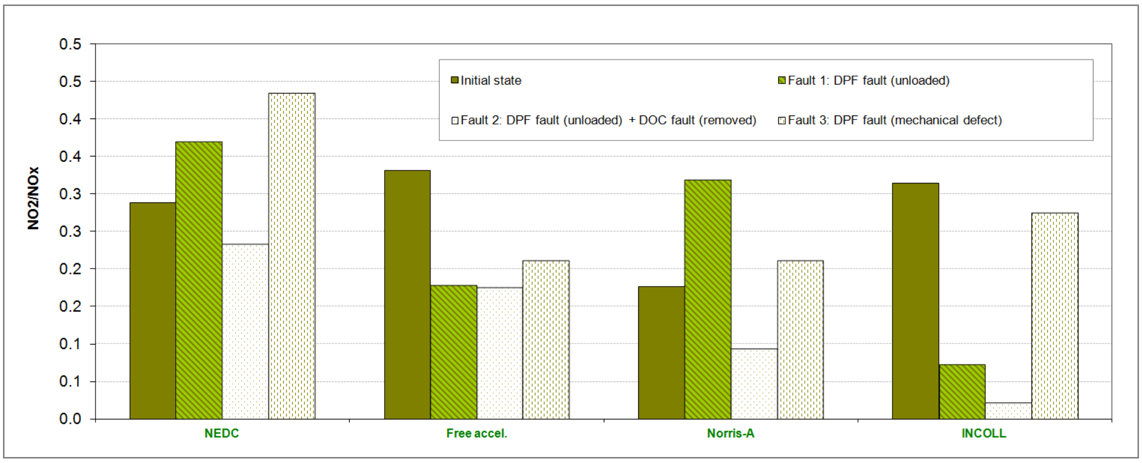

Figure 36: NO_2/NO_x ratio by test procedure and simulated fault, vehicle 4.

5.3.5 Vehicle 5

The results for vehicle 5 are summarised in Figure 37, Figure 38 and Figure 39. The data for PM over the PTI tests are taken from the MAHA MET 6.1 measurements.

For this vehicle NO_x emissions over the NEDC were higher than those over the AC5080. Measurements were not made using the DT80 test, as the vehicle was fitted with an engine speed limiter (the engine speed was limited to around 2,500 rpm if the wheels did not rotate), which meant that the rates of acceleration in the DT80 could not be achieved. In any case, the measurements on vehicles 1-3 showed that there were no substantial differences between results over the DT80 and AC5080, and therefore the use of the AC50 alone was considered to be sufficient.

However, it is important to recognise that tests involving free acceleration could not be performed on this vehicle. For the free acceleration tests in this project the vehicle was set to 'dynamometer mode'[35] and driven at 20 km/h. Under these conditions the engine speed limit was around 4,200 rpm, which was the nominal engine speed (for maximum power) of the engine, but not the cut-off speed. As the engine load for free acceleration test depends on the acceleration and the cut-off speed, it is assumed that the emission values would be higher if the engine accelerates to the 'real' cut-off speed (around 5,500 rpm).

The results for the simulated faults were as follows:

Fault 1 – For the **DPF defect (mechanical damage)**, there was a substantial increase in NO_x emissions over the NEDC, resulting in an exceedance of the type approval limit value. This increase in NO_x was not, however, systematically observed in the PTI tests, although it was replicated quite well by the AC5080 and free acceleration tests. The fault resulted in a large increase in PM emissions over the NEDC (type approval limit well exceeded), and this was detected by all the PTI procedures (in particular the free acceleration test). The NO_2/NO_x ratio did not provide consistent information, with the effect over the PTI tests being the opposite of that over the NEDC.

Fault 2 – Rather surprisingly, the **ageing of the SCR catalyst** resulted in a smaller increase in NO_x emissions over the NEDC than fault 1. Here the increase in NO_x was observed in most of the PTI tests, but not clearly so. The PM and NO_2/NO_x data did not provide any clear indication of the fault.

Fault 3 – The **damaged SCR catalyst** also resulted in a smaller increase in NO_x emissions over the NEDC than fault 1, and indeed in this case the type approval limit was not exceeded. As with fault 2, the PM and NO_2/NO_x data were quite variable and the fault was not clearly identified.

OBD: In all cases the MIL was not triggered and no DTC was stored; again, the OBD was unable to detect that faults were leading to increased emission behaviour.

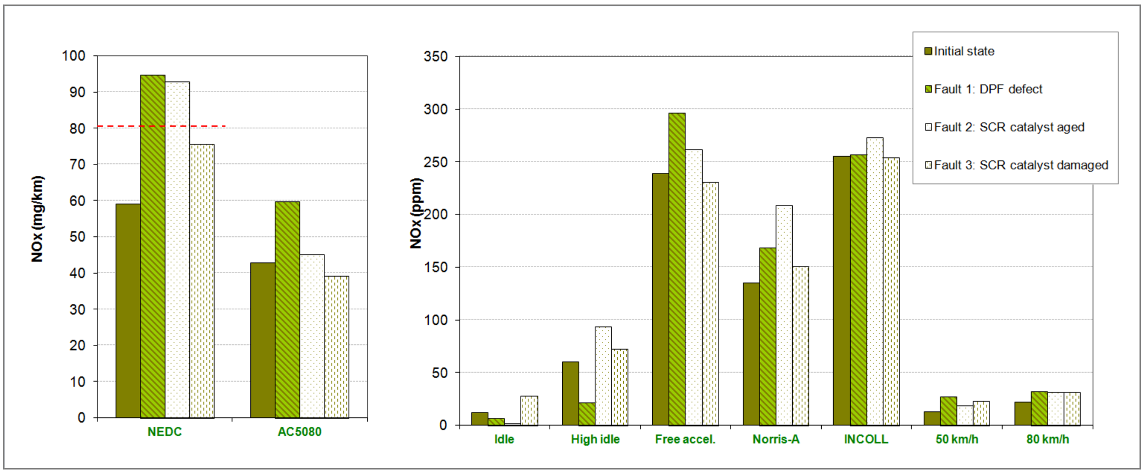

Figure 37: NO_x emissions by test procedure and simulated fault, vehicle 5. Dashed red line = Euro 6 type approval limit for NO_x.

[35] This involved switching on the ignition, and with the emergency light on pressing the accelerator pedal five times then starting the engine.

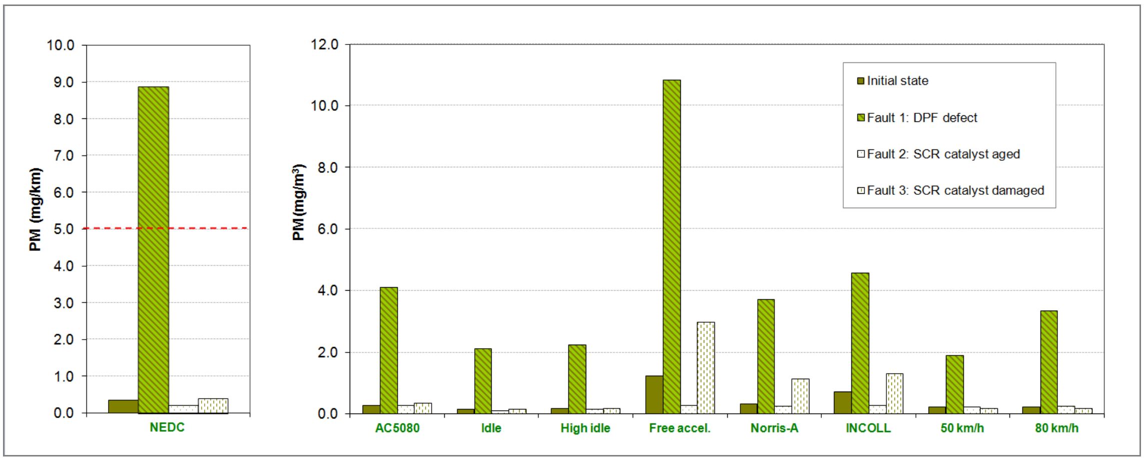

Figure 38: PM emissions by test procedure and simulated fault, vehicle 5. Dashed red line = Euro 6 type approval limit for PM.

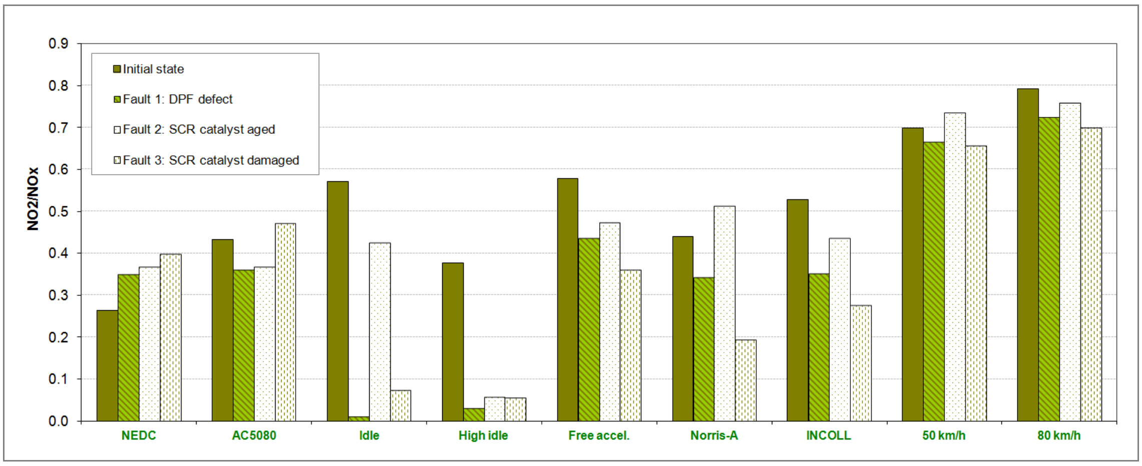

Figure 39: NO_2/NO_x ratio by test procedure and simulated fault, vehicle 5.

5.3.6 Heavy-duty engine

In the case of the heavy-duty engine the emphasis was on faults which affected NO_x emissions and the NO_2/NO_x ratio, rather than PM.

The NO_x results for the heavy-duty engine, measured using a chemiluminescence detector, are shown in Figure 40. The effect on NO_x of the simulated faults broadly reflected the extent to which the urea dosing system of the SCR was manipulated. The changes in NO_x over the steady speed/torque tests closely matched those observed over the ETC. However, none of faults could be identified from the results of the idle and free acceleration tests. The SCR system does not work efficiently at the low exhaust temperatures associated with low load conditions. Consequently, faults tend to result in little change in emissions over unloaded tests (*e.g.* free acceleration) as the SCR system is not working.

Figure 41 shows PM emissions from the engine over the ETC. Emissions were within the Euro V limit value in the initial state and with the simulated faults. The simulated faults had little effect on emissions over the ETC and opacity over the free acceleration test.

The NO_2/NO_x ratio was consistently very low (always less than 0.05, and generally less than 0.02), and was therefore not considered to be useful for identifying faults.

During the tests the simulated SCR faults were detected by the OBD system, and the following fault codes were stored:

- Intermittent reagent dosing: P042D
- Empty reagent: P203F
- Diluted reagent: P14AA, P1956, P1951

The scope of the study did not extend to cover engine faults. It would be of interest in subsequent work to investigate engine-related problems which have an impact on PM emissions, such as faulty injectors.

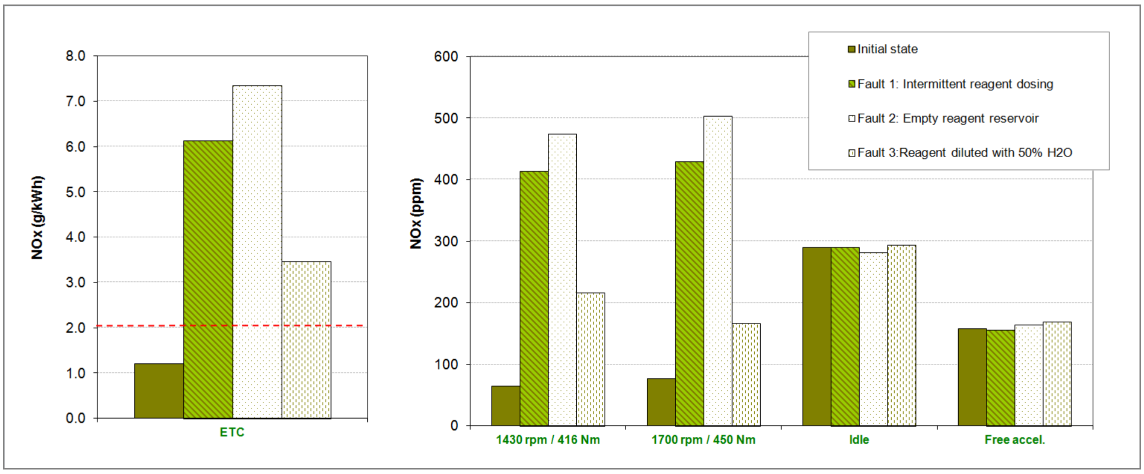

Figure 40: NO_x emissions by test procedure and simulated fault, heavy-duty engine.
Dashed red line = Euro V type approval limit for NO_x.

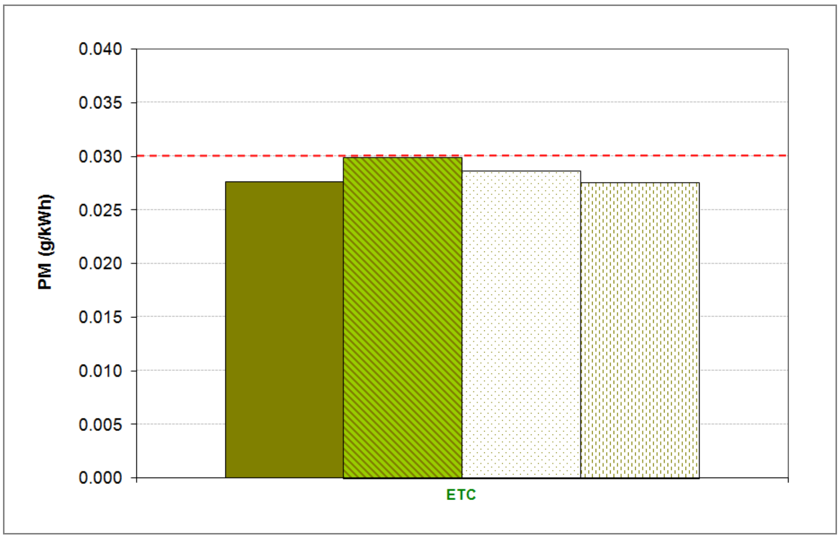

Figure 41: PM emissions from heavy-duty engine over ETC.
Dashed red line = Euro V type approval limit for PM.

5.3.7 Performance of measuring instruments

Whilst the emphasis in this part of the work was on the test procedures, the performance of the different PTI instruments was also given some consideration. For example, the NO and NO_2 performance of different PTI instruments was investigated for several PTI tests (see Appendix H).

Some, but not all of the larger changes in NO_x emissions and the NO_x/NO_2 ratio associated with the faults were detected by the PTI equipment. This reinforces the need for the further development of the PTI instruments.

The effects of the DPF fault could clearly be seen with both the MAHA MET 6.2 and AVL 2000 instruments, suggesting that instruments which rely upon scattered light technology are able to detect emission-related faults. The AVL 439 did not register a large change in opacity, but the opacity values were near the lower limit of its measurement range.

Key points from this chapter

Cars

1. For the cars, faults leading to increases in NO_x emissions (large increases in some cases) were not systematically detected by the PTI tests. Whilst some faults were detected, the overall results did not provide sufficient evidence to support the use of NO_x measurement during PTI.
2. The faults which led to large increases in PM emissions were, on the whole, detected by the PTI tests. Again, there were exceptions, but generally the results were much better than those for NO_x. Of the unloaded tests, the free acceleration test tended to be the best indicator of faults.
3. The results for the NO_2/NO_x ratio were too variable and inconsistent to enable them to be used reliably for identifying faults in specific components.
4. For all five cars tested the OBD system was unable to detect that faults were leading to increased emissions. In all cases the MIL was not triggered and no DTCs were stored.

Heavy-duty engine

5. Because the engine was not equipped with a DPF and had inherently low engine-out PM, the simulated faults were designed to affect NO_x emisisons.
6. The SCR-related faults led to increases in NO_x, but none of the faults could be identified from the results of the idle and free acceleration tests, primarily because the SCR system does not work efficiently under the low load conditions associated with these PTI tests.
7. As expected, the SCR faults had little effect on PM emissions and opacity. In future tests PM-related faults should be simulated.
8. The OBD system was able to identify the faults with the urea dosing of the SCR, and DTCs were stored.

6 Data analysis and PTI method

6.1 Overview

The aims of this part of the work were to analyse the data from the measurement programme and to propose an improved PTI method and potential amendment to Directive 2010/48/EC, bearing in mind the limitations of the study.

The following aspects were considered in the analysis:

- The ability of PTI methods to identify a vehicle with high emissions resulting from a damaged exhaust after-treatment system.
- The ability of PTI methods (and limit values) to give low errors of omission and commission.
- The possibility of determining the proper operation of catalytic after-treatment devices using the NO_2/NO_x ratio.
- The improvement of the opacity measurement using new PM measurement devices and methods.
- The evaluation of EOBD failure codes relevant to components of the exhaust emission after-treatment system.

6.2 Evaluation method

The suitability of PTI short test methods for identifying faults which result in high 'real-world' emissions of NO_x or PM was evaluated by comparison with type approval results, as shown in Figure 42. Emissions for the type approval test are shown on the *x*-axis, and emissions for the PTI test are shown on the *y*-axis.

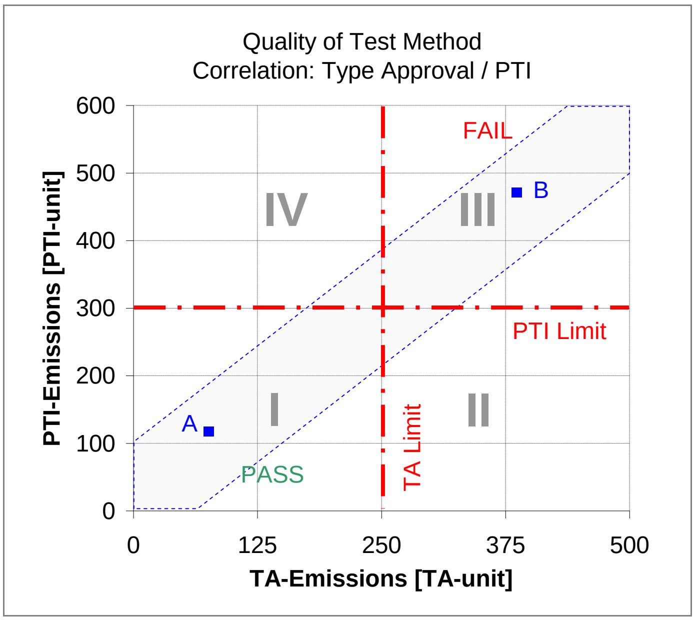

Figure 42: Evaluation of PTI short tests by comparison with type approval test.

The Figure is divided into four areas, defined by the limit value for the type approval test (*e.g.* 250 TA-units) and for the PTI test (*e.g*. 300 PTI-units).

The points A and B within the shaded area of Figure 42 are examples of results for a suitable test method with a good correlation between PTI values and type approval values. Point A represents a low emitting vehicle with an emission level over the NEDC which is lower than the type approval limit value, and an emission level over the PTI test which is lower than the PTI limit value. Point B represents a high emitting vehicle with emission levels which exceed both the type approval and PTI limits over the respective tests. Both vehicles have been identified successfully by the PTI tests.

Results could be rated according to their location in the graph:

- Area I: The result indicates a PASS in the type approval test and a PASS in the PTI test. Vehicles with low emissions over the type approval test are correctly identified as low-emitting vehicles in the PTI test. Vehicles in this area of the graph may still have emission-relevant failures, but these failures do not result in an exceedance of the type approval limit.
- Area II: The result indicates a FAIL in the type approval test and a PASS in the PTI test. Vehicles with high emissions over the type approval test are incorrectly identified as low-emitting vehicles in the PTI test. This is known as an error of omission, and is a concern from an environmental perspective. It is also thought to be common in current PTI testing.
- Area III: The result indicates a FAIL in the type approval test and a FAIL in the PTI test. Vehicles with high emissions over the type approval test are correctly identified as high-emitting vehicles in the PTI test.
- Area IV: The results indicate a PASS in the type approval test and a FAIL in the PTI test. Vehicles with low emissions over the type approval test are incorrectly identified as high-emitting vehicles in the PTI test. This is known as an error of commission, and is a concern from a time and cost perspective, because the vehicle cannot be repaired to meet the PTI thresholds as there is no fault.

The PTI tests and faults investigated were summarised in chapter 5.

6.3 Analysis of passenger car data

6.3.1 Opacity/PM

Opacity for PTI tests vs PM for NEDC

Different PTI tests showed different responses to the different simulated faults. In addition, the number of repeated accelerations performed affected the PTI test results. Increasing the number of free accelerations generally resulted in lower mean PTI short test values (see the decreasing emission values in Figure 26).

Figure 43 shows the comparison between the opacity (*k* value) results for the PTI tests and the corresponding PM results over the NEDC. The different symbols represent the different measuring instruments used in the TEDDIE measurement programme. It can be seen that the PTI tests and opacity instruments could not differentiate between vehicles with and without faults for type approval PM values lower than around 5 mg/km. This situation causes a high error of commission.

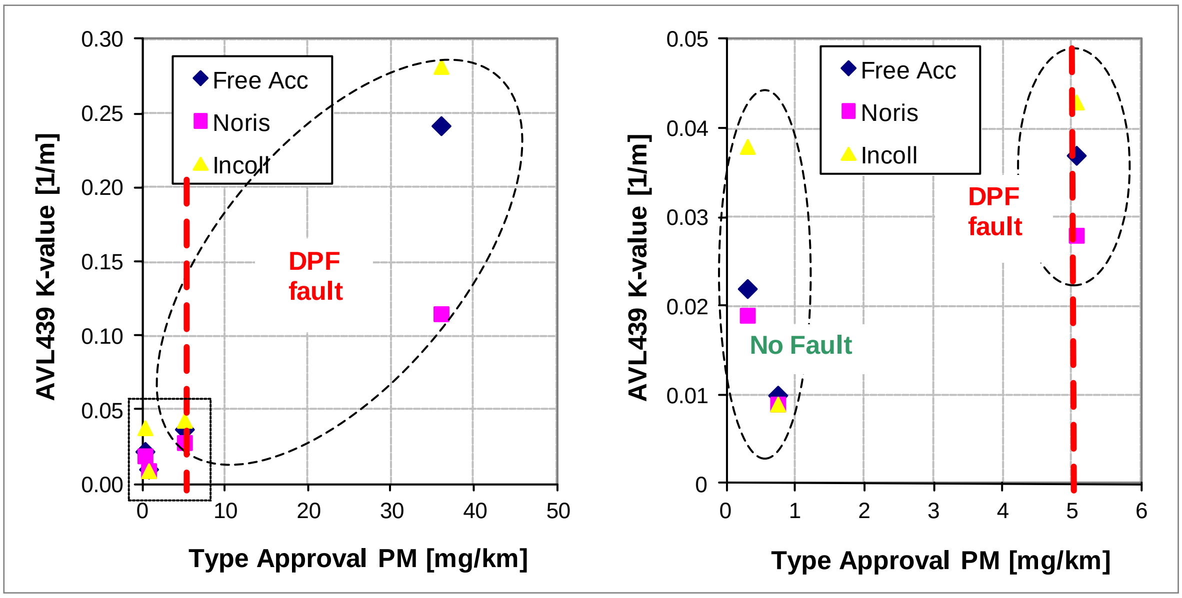

Figure 43: Opacity for PTI short tests compared with PM for type approval test. The right-hand graph shows the detail at lower values.

PM for PTI test vs PM for NEDC

Figure 44 shows the comparison between the PM concentrations (in mg/m³) measured using the PTI procedures and PM emissions (in mg/km) over the type approval test. Again, the different symbols represent the different instruments used in the TEDDIE measurement programme. The PTI instruments for measuring PM showed a better discrimination and more significant response compared with opacity measurements. The PM equipment was capable of a higher differentiation for PM type approval values of about 5 mg/km and a successful detection of DPFs with faults.

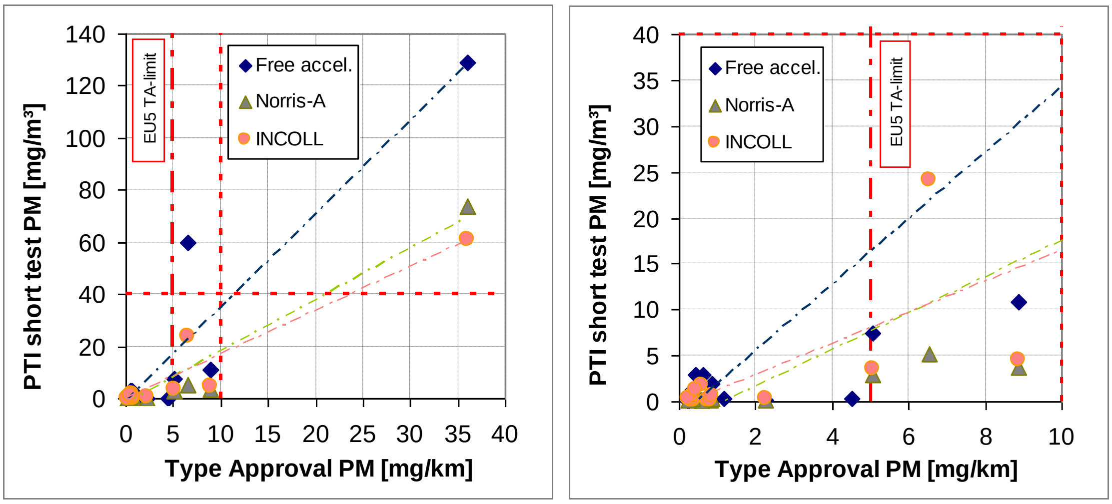

Figure 44: PM results for PTI short tests compared with PM results for NEDC. The right-hand graph shows the detail at lower values.

Proposal for PM test

Based on the limited amount of data collected in the project, it appears that the combination of the free acceleration test and the new PM instruments for PTI meets the following requirements:

- A significant response to defective exhaust after-treatment systems, thus allowing the identification of high-emitting vehicles.
- The correlation between PM emissions in PTI tests and PM emissions over the type approval test (NEDC) seems to be acceptable.
- The PM measurement from the PTI instruments (in mg/m^3) shows acceptable discrimination between different vehicles and an acceptable response to low PM emissions over the type approval test (NEDC).

In Figure 45 the left dashed vertical red line shows the Euro5 type approval limit for PM of 5 mg/km. This value could be used to define a PTI short test limit of around 20 mg/m^3 using the correlation shown for the free acceleration test. However, to avoid a high error of omission it might be more useful to use a higher PTI test limit value of about 40 mg/m^3 for the free acceleration test, equating to a PM type approval value of 10 mg/km for high emitting vehicle.

A further approach might also be to use vehicle-specific PTI limit values, as in the case of opacity in the current legislation. Given the limited number of vehicles used in TEDDIE, the final limit values should be based on a wider field study representing current and future vehicle fleets.

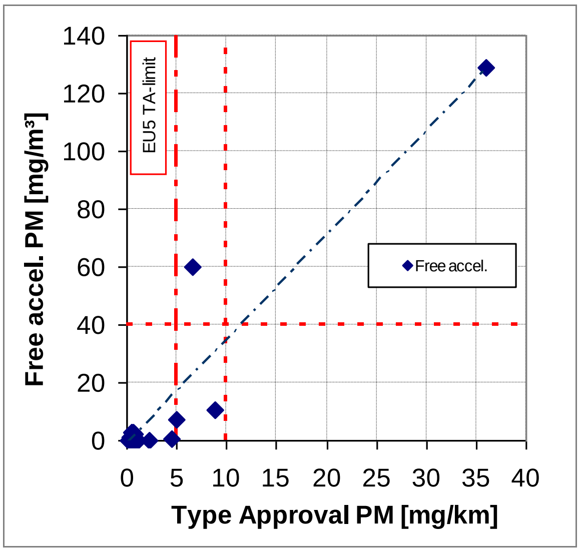

Figure 45: Evaluation of limit values for free acceleration test.

This proposal is limited to Euro 5 and Euro 6 vehicles with current exhaust after-treatment technology such as wall-flow-type DPFs (closed systems). For future type approval procedures for Euro5b and Euro 6 legislation, the current gravimetric PM measurement method will be extended to include particle number measurement. The implications of this change, and issues associated with the new measurement equipment, are not addressed here.

6.3.2 NO, NO_2 and NO_x

The metrics investigated here were the NO_2/NO_x ratio and total NO_x. The reasons for this were as follows:

- It has previously been suggested that the functioning of catalytic after-treatment devices (DOCs) can be determined by examining the NO/NO_2 ratio. The assumption here is that the oxidation of HC and CO is directly related to the formation of NO_2 in the DOC. HC values are mainly influenced by cold-start emissions and the conversion rate of the catalytic coating of the exhaust after-treatment components, and so it might be a possibility to use CO emissions to identify defect catalytic coatings.
- The functioning of NO_x-reduction technologies (SCR, NO_x trap) can be evaluated using NO_x emissions. NO_x emissions are also regulated at type approval.

NO_2/NO_x ratio for PTI test vs NOx for NEDC

Comparisons were made between the NO_2/NO_x ratio (as a percentage) for various PTI procedures and simulated faults, and NO_x emissions (in mg/km) over the type approval test and using the type approval equipment. The results are shown in Figure 46 and Figure 47 for loaded and unloaded tests respectively for the test vehicles and simulated faults. The NO_x limits at type approval for Euro 4 and Euro 5 vehicles are shown as dashed red lines.

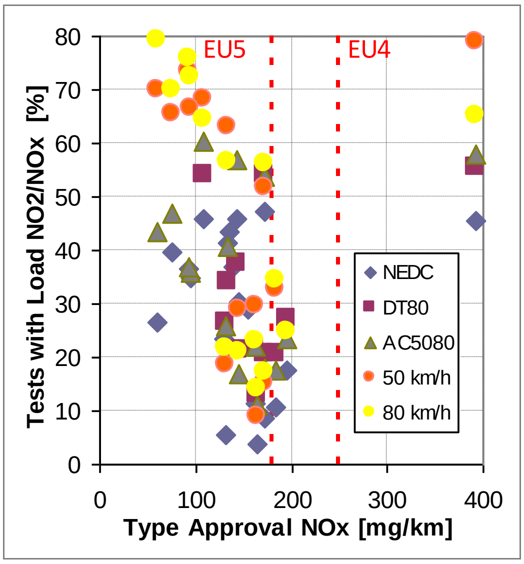

Figure 46: NO_2/NO_x ratio for loaded PTI short tests vs NO_x for type approval test.

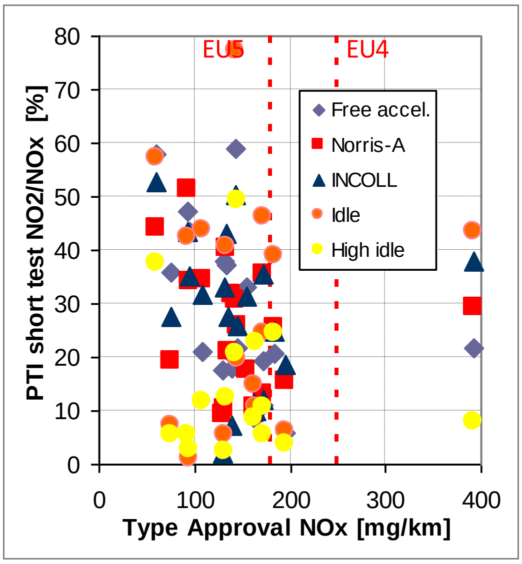

Figure 47: NO_2/NO_x ratio for unloaded PTI short tests vs NO_x for type approval test.

Interpretation: The faults could not be detected using any of the test procedures, including the type approval test itself. The use of the NO_2/NO_x ratio from the PTI tests and NO_x type approval values does not therefore meet the main criteria for an effective test method, since:

- Faults do not result in a significant response in the NO_2/NO_x emission ratio. The identification of damaged NO_x after-treatment components is not possible.
- The correlation between the results over the type approval test (NEDC) and the PTI tests was low.

NO_2/NO_x ratio for PTI test vs CO for NEDC

Figure 48 and Figure 49 show similar plots, but this time using CO emissions over the type approval test (in mg/km) on the *x*-axis. The loaded tests showed a high NO_2/NO_x ratio for very low CO values over the NEDC, and low NO_2/NO_x ratios for the higher CO values over the NEDC associated with ineffective catalytic coatings. The results in the circled area in Figure 48 represent properly working exhaust after-treatment systems which are designed to meet the Euro 5 type approval limit values. In comparison to older CRT systems with a high NO_2 conversion rate for passive DPF regeneration, these systems have a different type of coating (e.g. less platinum) as they involve active thermal DPF regeneration.

For the unloaded PTI tests Figure 49 does not show any of the effects described above. A reason for this might be that the NO_2 conversion is dependent upon exhaust temperature, as shown in Figure 50, and for the unloaded PTI tests the required temperature might not be reached.

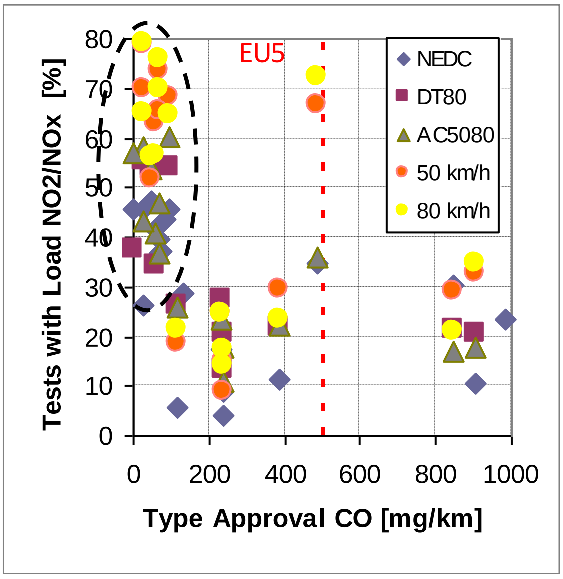

Figure 48: NO_2/NO_x ratio for loaded PTI short tests vs CO for type approval test.

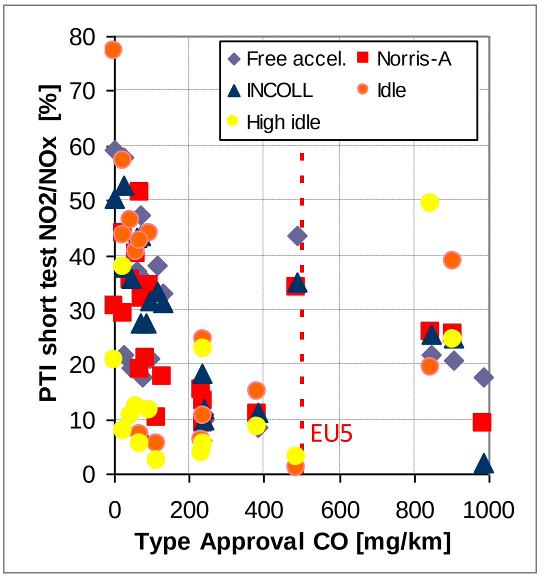

Figure 49: NO_2/NO_x ratio for unloaded PTI short tests vs CO for type approval test.

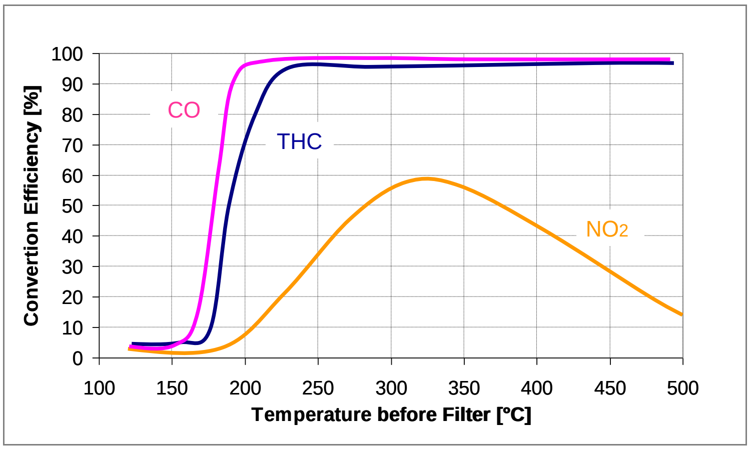

Figure 50: Catalytic conversion in a DOC. Reduction and formation of exhaust components as a function of exhaust gas temperature for a typical CRT system.

Interpretation: The use of the NO_2/NO_x ratio from the PTI test and CO from the type approval test does not meet the main criteria for an effective test method, since:

- There were significant responses for CO emissions in the case of defective catalytic coatings for CRT systems, but the identification of such defects was only possible for these systems.
- The correlation between the results over the type approval test (NEDC) and the PTI tests was poor.

Comparison NOx type approval test vs. NOx PTI short test

Comparisons were made between absolute NO_x measured using the different PTI methods and NO_x emissions over the type approval test, including the vehicles tested and the simulated faults. The results for the loaded and unloaded PTI tests are shown in Figure 51 and Figure 52 respectively. For the loaded PTI tests the NO_x data are given in mg/km, whereas for the unloaded PTI tests the NO_x data are given in ppm.

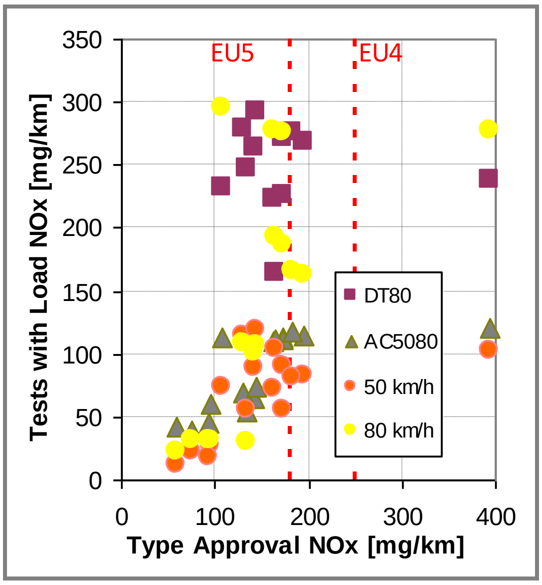

Figure 51: NO_x for loaded PTI tests vs NO_x for type approval test.

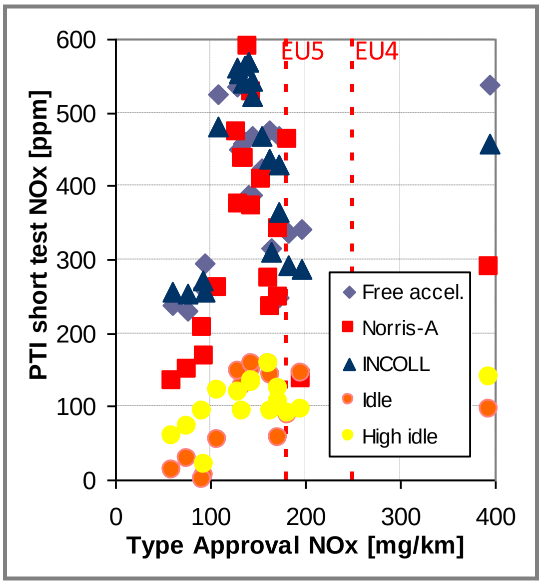

Figure 52: NO_x for unloaded PTI tests vs NO_x for type approval test.

The type approval limit was exceeded with the simulated DPF defect, but this result could not be reproduced using the PTI procedures.

Interpretation: The evaluation of NO_x values does not meet the main criteria for an effective test method, since:

- The simulated faults could not be detected using any of the test methods. However, the faults did not have a significant effect on NO_x emissions and did not lead to exceedances of the type approval limit.
- There was no significant correlation between the NO_x values measured during different PTI test procedures and NO_x emissions over the NEDC.

Figure 53 shows a detailed graph with different simulated faults for the different test vehicles. The influence of the test vehicle was, in general, greater than the influence of the simulated fault. In this Figure the vehicle-specific type approval limit values are also shown in the same colour as the corresponding vehicle. In several cases the vehicle-specific values were not exceeded following the introduction of the simulated faults. The vehicle-specific type approval limits are shown in Table 33.

With reference to Figure 42 the simulated failures cannot be detected with acceptable errors of omission and commission, even if vehicle specific type approval values are used as limit values. This means that exhaust emission measurement alone seem not to be able to detect failures in the NO_x after-treatment system, and might have to be extended (*e.g.* with component testing). OBD might be an option in this respect, but current systems are not designed for this purpose (no OBD failure codes occurred).

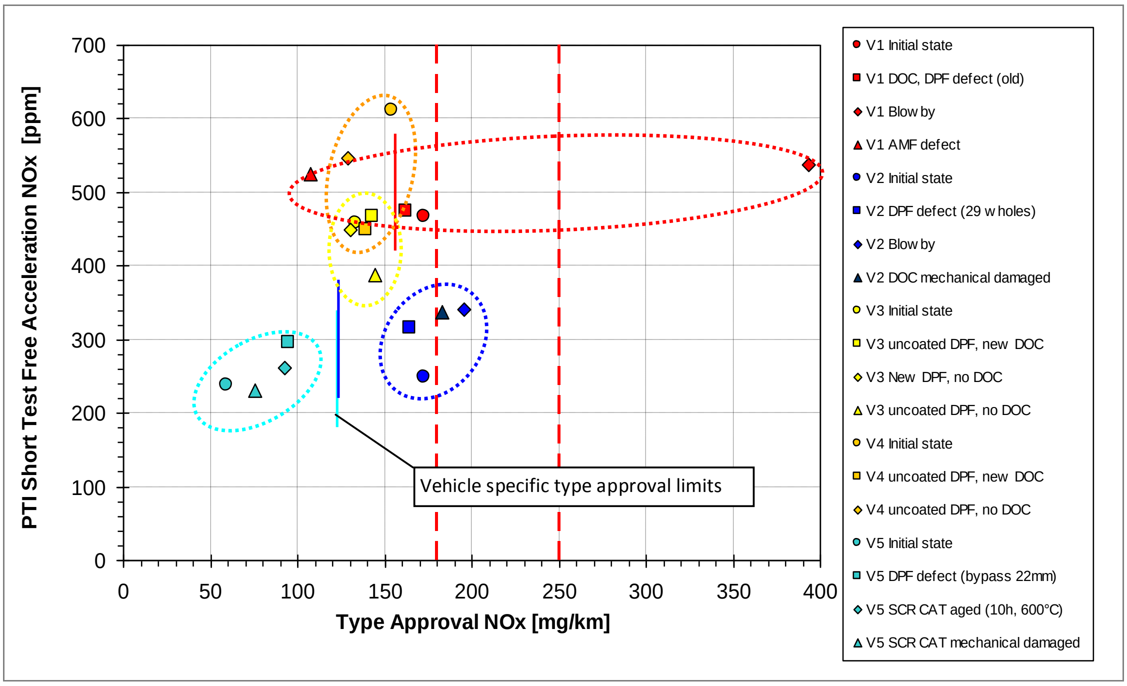

Figure 53: NO_x emissions over free acceleration test and type approval test, with different simulated faults and test vehicles.

Table 33: Type approval values (type-I test) and deterioration factor (DF) for the specific vehicle models tested.

Test vehicle	NO_x (mg/km)	DF	PM (mg/km)	DF
Vehicle 1	156.0	1.0	1.00	1.2
Vehicle 2	123.4	1.0	0.15	1.0
Vehicle 3	-	-	-	-
Vehicle 4	-	-	-	-
Vehicle 5	122.6	1.0	0.00	1.0

Proposal for NO_x test

A suitable emission test for NO, NO_2 or NO_x could not be identified. A better approach may be to identify failures in the NO_x-reduction system using OBD surveillance (where this involves direct measurement using sensors) in combination with stringent OBD limit values, but this requires further investigation.

6.4 Analysis of heavy-duty engine data

6.4.1 Opacity/PM

The engine had no DPF, and the simulated faults did not result in any changes in exhaust opacity. PM emissions measured with PTI devices were not available for the PTI tests.

6.4.2 NO, NO_2 and NO_x

The engine had no DOC, and NO_2 emissions were less than 0.1 g/kWh or less than 3% of total NO_x emissions. The NO_2/NO_x ratio was therefore not relevant for the indication of faults.

Figure 54 shows the comparison between NO_x type approval emissions in g/kWh and PTI NO_x concentrations in ppm. The correlation for tests with load was very strong. For the unloaded PTI tests there was no correlation.

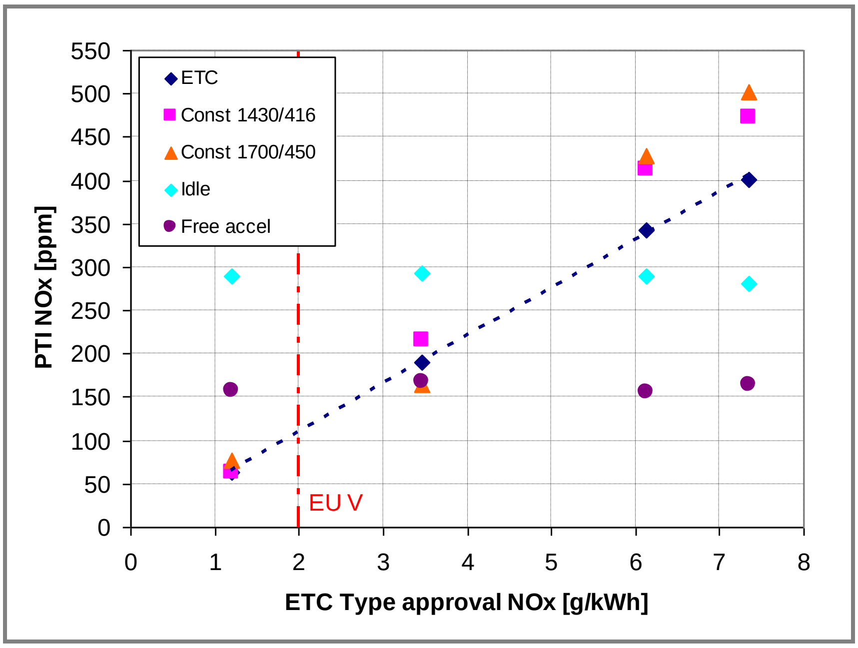

Figure 54: Type approval NOx for ETC vs. NOx PTI short test for unloaded tests and tests with load

Key points from this chapter

Cars

1. For the cars, the PTI tests and opacity instruments could not differentiate between vehicles with and without faults for type approval PM values lower than around 5 mg/km. The PTI instruments for measuring PM (in mg/m^3) showed a much better discrimination between different vehicles and an acceptable response to low PM emissions over the NEDC.
2. It appears that the combination of the free acceleration test and the new PM instruments meets the requirements of a PTI emission test. This combination showed a significant response to defective exhaust after-treatment systems, thus allowing the identification of high-emitting vehicles. To avoid a high error of omission a limit value around 40±10 mg/m^3 for the free acceleration test would be appropriate, but this would need to be evaluated in a large-scale field trial.
3. A further approach might be to use car-specific PTI limit values, as in the case of opacity in the current legislation. Again, the final limit values would be determined from a wider field trial.
4. A suitable emission test for cars using NO, NO_2 or NO_x could not be identified.

Heavy-duty engine

5. The simulated faults did not affect PM emissions, and therefore no conclusions could be drawn concerning a PM test. However, the results for the passenger cars indicated that PM measurement is important for identifying faults in PM-control systems, and it is likely this will also be the case for heavy-duty engines. Nevertheless, this assumption should be tested in further laboratory work.
6. For NO_x there was a strong correlation between the results from the type approval test and the loaded PTI tests, which suggests that it would be possible to identify an appropriate loaded test procedure. However, loaded tests were excluded as a practical option for PTI. Unloaded tests were not found to be suitable for detecting the simulated NO_x faults. Consequently, a PTI test for NO_x involving emission measurement could not be proposed. Further investigations are recommended.
7. The engine had no DOC, and NO_2 emissions were less than 0.1 g/kWh or less than 3% of total NO_x emissions. The NO_2/NO_x ratio was therefore not relevant for the indication of faults.
8. For identifying failures in NO_x-reduction systems a potentially useful alternative to the measurement of NO_x emissions at the tailpipe may be the use of OBD surveillance in combination with stringent OBD limit values as a additional measure in combination with PM measurement, but this also requires further study.

7 Cost-benefit analysis

7.1 Overview

This chapter of the report provides a cost-benefit analysis (CBA) of the proposed PTI procedures. The CBA involved the estimation of benefits associated with the introduction of new emission testing methods at PTI, and was based on the TEDDIE measurements.

CBA is an appropriate socio-economic assessment approach for determining the overall impact of the proposed PTI emission test procedures. It provides an undisputable methodological background, and the absence of a weighting scheme leads to objective results. The calculation procedure in CBA can also be used for other evaluation methods. CBA can provide input to financial analyses, cost-effectiveness analyses, break-even analyses, multi-criteria analyses and business case calculations.

The overall result of CBA is a benefit/cost ratio; ratios greater than one – which means that benefits exceed costs – prove that the system implementation is profitable for the whole of society.

Figure 55 shows how, in general, roadworthiness strategies can lead to a reduction of accident costs, time costs, vehicle operating costs, air pollutant emission costs (of relevance here), CO_2 costs, and vehicle breakdown costs. An improved PTI emission test for diesel vehicles could clearly lead to environmental improvements (and hence cost savings). In order to quantify these savings it is necessary to determine how the current emission situation would be affected by introducing a new emission test method.

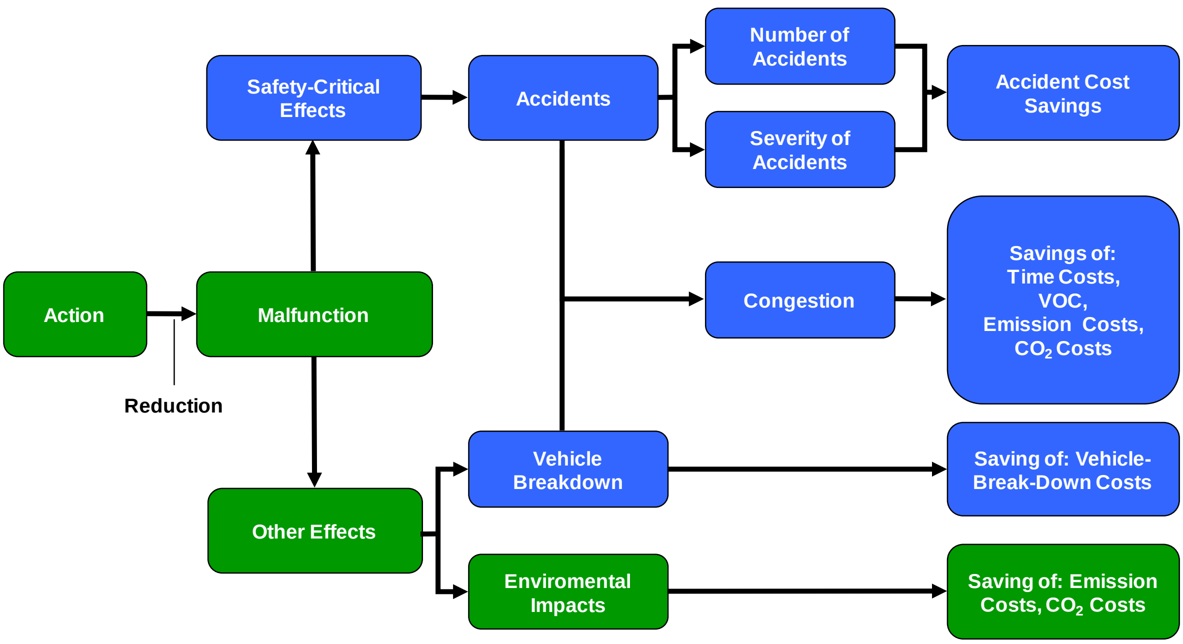

Figure 55: General impact channels of vehicle inspection measures on economical costs.

7.2 Methodology

7.2.1 Identification of benefits, costs and steps in CBA

CBA determines the change in a current situation (the 'without' case) following the introduction of something new (the 'with' case), such as a measure or policy. Within any CBA it is crucial to distinguish between the benefit terms and the cost terms

Within the framework of the CBA, monetary values can only be assigned to the use of resources. Thus, taxes and profits are not considered as costs associated with the measure or policy. Furthermore, the costs to other stakeholders (such as vehicle owners) are not considered. This is a point that is sometimes raised by critics of the CBA approach. A new procedure for emission testing means that more defects can be detected. For the car owners who are affected additional repair costs will arise. This leads consumer organisations and/or politicians to the argument that measures should avoid imposing extra costs on the user. This argument has two flaws:

- Firstly, a car owner is required by law to maintain his vehicle in a roadworthy condition. He has to undertake repairs when the vehicle does not fulfil the legal requirements. Therefore, the owner must pay the costs of guaranteeing the functioning of his car. In a perfect world the car user will always have information about the condition of his car; the car owner knows everything and emission testing is not needed. In the real world the car owner does not have this information. Therefore, control and testing is needed. The repair costs are not the result of the tests - they are the result of the legal requirements.
- Secondly, counting the repair costs is economically incorrect. Counting repair costs means that the cost-side is enlarged without taking into account the fact that spending money on repairs leads to benefits for the repair industry. So repairing is, in the general economic sense, only a shift of money from the consumer (car owner) to the car repair centre and automotive industry. The overall economic balance does not change. One's loss is another's gain. The inclusion of repair costs makes it necessary to consider the profits on the other side as benefits. Repair costs have no resource effect.

The CBA followed the steps shown in Figure 56 to calculate the benefit/cost ratios for the proposed new PTI methods and threshold criteria. The methodology was used to show whether the proposed test method would have a benefit for the European Member States. This economic modelling approach has previously been approved for various other evaluations.

NB: The calculations focused on passenger cars, as a reliable CBA for HGVs was not possible due to the limited nature of the TEDDIE measurements.

The steps were as follows:

1. In the first step the 'with' and 'without' cases were defined. The 'without' case represented the current approach to measuring exhaust emissions at PTI in Europe. This meant that the 'without' case was a situation without adaptation to new technology and procedures. Therefore the 'without' case was essentially a 'do-nothing' scenario, which consequently meant that gross polluters would not be recognised by the PTI scheme. Gross polluters are passenger cars with elementary defects of the exhaust system.
2. In the second step the relevant traffic, environmental and vehicle data for the various 'with' cases were obtained. In addition, the causes and effects had to be determined on an empirical basis from the TEDDIE measurement programme. This enabled the quantification of the possible resource savings.

3. The third step quantified the physical effects and benefits for both the 'with' and 'without' cases. The results were the quantitative changes in the resource amount. In this case, the resources affected by new testing methods were emissions of NO, NO_2, CO, THC and PM. On the cost side, the relevant cost categories were identified and the related production quantities were determined. The relevant costs were the additional costs for the new testing methods.
4. In the fourth step the quantities for the benefits and costs were transformed using cost/unit rates into monetary values. The monetary transformation allowed the addition of the different quantitative effects.
5. In step 5 the monetary benefits were compared with the costs to determine the benefit/cost ratio.
6. Finally, a sensitivity analysis was conducted.

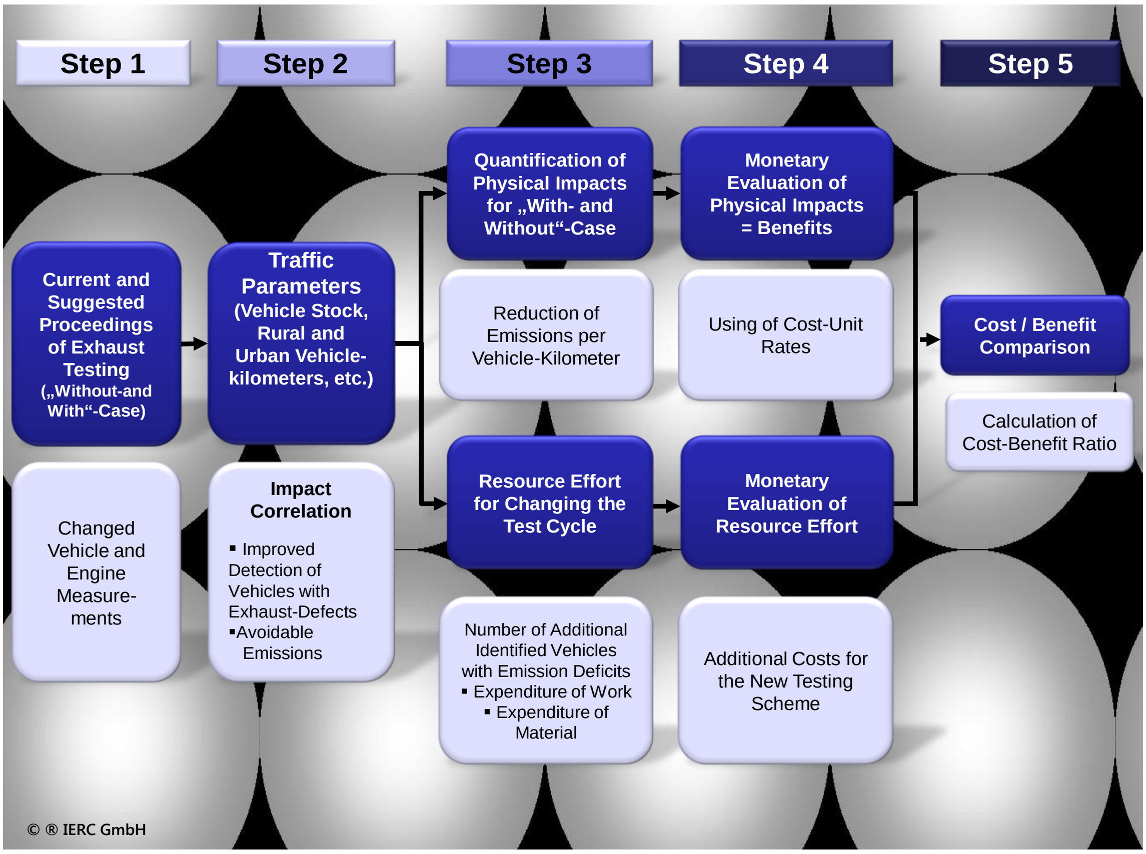

Figure 56: Steps in the TEDDIE cost-benefit analysis.

7.2.2 Monetary evaluation

The economic cost-benefit analysis model used here has previously been applied in the following projects:

- HEATCO, Developing Harmonized European Approaches for Transport Costing and Project Assessment, Deliverable 2, State-of-the-art in project assessment (HEATCO, 2005).
- SEiSS (Exploratory Study on the potential socio-economic impact of the introduction of Intelligent Safety Systems in Road Vehicles. Study for the Directorate-General Information Society) (SeiSS, 2006).
- AUTOFORE (Study on the Future Options for Roadworthiness Enforcement in European Union, Study for the Directorate-General for Transport and Energy) (AUTOFORE, 2007).
- eIMPACT (Assessing the Impacts of Intelligent Vehicle Safety Systems, Contract no: 027421, Sixth Framework Programme DG Information Society and Media) (eIMPACT, 2008a;2008b).
- Handbook on estimation of external costs in the transport sector. Produced within the study Internalisation Measures and Policies for All external Cost of Transport (IMPACT), Version 1.1, Delft 2008 (Maibach 2007; 2008).
- Ökonomische Bewertung von Umweltschäden, Methodenkonvention zur Schätzung externer Umweltkosten (UBA, 2007).
- Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles.

This experience ensures that the results of the CBA will be comparable with other national and European analyses, and will represent the current scientific state-of-the-art.

7.3 Modelling

7.3.1 Calculation Model

Figure 57 presents the calculation model, which consisted of three modules:

- The first module was the vehicle and engine measurement calculation procedure. It focused on the kinds of emission-related fault that could be additionally detected by the new testing methods.
- The second module was the vehicle stock module, which was based on the TREMOVE-model[36]. TREMOVE is a policy assessment model which is used to study the effects of different transport and environment policies on the transport sector for all European countries.
- The third module covered resource effects. Emission factors, toxicity factors and unit cost rates were used to calculate the monetary values of the emissions. This module was based on Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles.

[36] Version 3.3.2 (http://ec.europa.eu/environment/air¬/pollutants/models/tremove.htm).

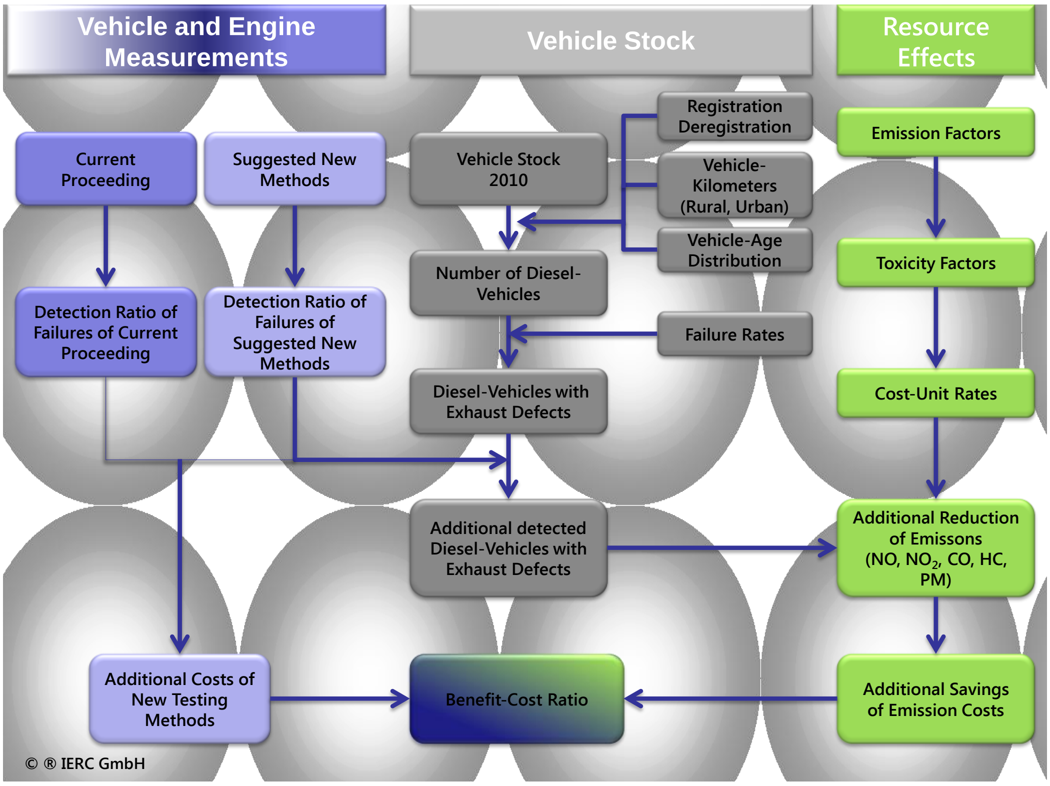

Figure 57: Calculation Model.

7.3.2 Vehicle stock and activity

Table 34 shows the vehicle stock and activity for diesel cars in each EU Member State, from which the average vehicle-kilometres per car were calculated. The last column shows the number of diesel cars inspected each year in each country.

7.3.3 Resource effects

As result of the investigation of PTI procedures in TEDDIE, eight defects that could be detected using the new testing methods were considered to be relevant:

- DPF defect (Case 1)
- Crankcase breather removed (Case 2)
- Air mass flow meter manipulated (Case 3)
- DOC fault (Case 4)
- DOC removed (Case 5)
- DOC removed, unloaded DPF (Case 6)
- SCR catalyst aged (Case 7)
- SCR catalyst damaged (Case 8)

The emission results from the investigation of PTI test procedures, and the expectable changes in emissions were the new measurement methods to be introduced, are given in Appendix I. It can be seen that the emission results were not complete for each of the tested vehicles, because not each fault was tested in every case. However, the five vehicles should be representative of the European fleet of diesel passenger cars.

Table 34: Vehicle stock of diesel cars, total and average vehicles-kilometres per diesel car and yearly inspected diesel cars in the EU-27.

EU Member States		Diesel car stock (vehicles)	Diesel car activity (million vehicle-kilometres	Average activity per car (vehicle-kilometres)	Yearly inspected diesel cars (vehicles)
Belgium	BE	3,239,111	71,251	21,997	1,619,556
Denmark	DK	352,107	14,444	41,021	176,054
Germany	DE	12,608,478	271,576	21,539	6,304,239
Greece	EL	48,498	3,365	69,380	24,249
Spain	ES	11,563,454	269,438	23,301	5,781,727
France	FR	18,634,436	358,599	19,244	9,317,218
Ireland	IE	368,446	8,379	22,742	184,223
Italy	IT	15,844,613	216,842	13,686	7,922,307
Luxembourg	LU	218,966	5,669	25,890	109,483
Netherlands	NL	1,499,019	61,641	41,121	749,509
Austria	AT	2,471,284	50,719	20,523	1,235,642
Portugal	PT	1,448,807	34,066	23,513	724,404
Finland	FI	390,594	15,938	40,805	195,297
Sweden	SE	311,227	17,174	55,182	155,613
United Kingdom	UK	8,377,921	220,780	26,353	4,188,960
Czech Republic	CZ	1,032,896	24,341	23,566	516,448
Estonia	EE	108,933	956	8,772	54,466
Cyprus	CY	38,576	280	7,249	19,288
Latvia	LV	197,609	2,543	12,871	98,805
Lithuania	LT	491,848	5,461	11,104	245,924
Hungary	HU	523,228	9,358	17,885	261,614
Malta	MT	66,880	272	4,068	33,440
Poland	PL	2,591,654	42,380	16,353	1,295,827
Slovenia	SI	250,779	5,228	20,848	125,390
Slovakia	SK	167,653	5,896	35,165	83,826
Romania	RO	752,128	10,628	14,130	376,064
Bulgaria	BG	615,675	13,232	21,492	307,837
Total EU 27		**84.214.820**	**1.740.456**	**20,667**	**42,107,410**

7.4 Emission effects

The assumptions that were made for the calculation of emission effects were as follows:

- It was assumed on the basis of empirical findings (ZDK, 2008; DEKRA, 2009) that 10% of the inspected vehicles would have exhaust defects which could be only detected by the new roadworthiness emission test. Furthermore, it was assumed that the detected defects would be completely repaired so that the emissions of vehicles would return to their design levels.

- The empirical data on the emission reductions which could be achieved were derived for the five vehicles tested in TEDDIE. These five vehicles were considered to be broadly representative of Euro 5/6 technologies in terms of their response to faults.
- Vehicle 1 was assumed to represent 40% of the European diesel passenger car fleet. Vehicles 2, 3, 4 and 5 were taken to represent 30%, 10%, 10%, and 10% of the fleet respectively.
- Emissions of CO, HC, NO and NO_2 were transformed using toxicity factors into NO_x-equivalents. The toxicity factors were: HC 1.5; CO 0.003; NO and NO_2: 1.
- Positive values represented emission savings. Negative values were the result of side-effects which led to an increase in emissions. Some defects had unexpected side-effects, in that emissions of some pollutants were reduced. However, emissions of other pollutants increased.

Changes in emissions for each fault case are given in Appendix I.

7.5 Benefits

The calculation of benefits was based on following cost unit rates for 2010:

- NO_x-equivalent: 4,680 euro per tonne.
- PM: 92,546 euro per tonne.

These cost rates for emissions from road transport were based on EC Directive 2009/33. In accordance with the Directive, the cost unit rates were adjusted for inflation using the Harmonised Index of Consumer Prices (HICP). For the time period 2007 to 2010 the average price increase was 2% per year.

The achievable benefits under the assumption that each defect was dominant are tabulated in Appendix I. However, the average benefits could also be calculated using the probability of each defect. Table 35 shows how the average benefits of introducing new measurement methods were calculated. The probabilities of each defect were independent, and therefore the overall probability of combined defects can be greater than 100%.

Table 35: Total emission benefits per year.

Defect	Probability	Benefits in million euro per year for each defect with a theoretical probability of 1 per defect	Average benefits in million euro per year for each defect weighted by the empirical probability
Case 1	0.80	1,051.3	841.0
Case 2	0.20	17.3	3.4
Case 3	0.05	-6.1	-3.1
Case 4	0.30	39.5	11.9
Case 5	0.30	4.1	1.2
Case 6	0.50	11.4	5.7
Case 7	0.30	1.5	0.5
Case 8	0.20	1	0.2
Total	--	1,120.4	860.8

The expected average benefit per year of the new roadworthiness emission tests for diesel engines was calculated to be **864.4 million euro**. This means that for each tested diesel car a benefit of 20 euro can be achieved. Other criteria apart, this benefit itself is significant and sufficient to allow an immediate regulatory switch to the new roadworthiness emission tests.

7.6 Cost-benefit results

For the calculation of the benefit/cost ratio the costs of introducing the new methods were relevant. As argued in section 7.2.1, the repair costs were not relevant for the overall economic perspective of CBA, but they will be relevant at the stakeholder level. For the CBA the following costs had to be considered:

1. The costs of the measurement equipment. The way in which these costs have to be considered depends primarily on the market introduction strategy, and two extreme cases are possible:
   (a) All existing testing equipment will have to be replaced at once. This will definitely lead to highest costs because at a cut-off date the new method will be mandatory.
   (b) The new methods will be introduced using the given depreciation cycle of the current testing equipment. The relevant costs are then the cost difference between the current testing equipment and the new equipment. This will lead only to additional costs
2. For both case the additional labour costs for performing the tests are relevant.

For the first case the following were assumed:

- The market price (without tax) of the equipment was 5,000 euro. The market price regularly has to be lowered by the profit margin. For this calculation a conservative approach was used, and no profit reduction was included.
- The depreciation period was 5 years.
- The market interest rate was set to 5%.
- 80,000 testing devices were needed (CITA, 2006; Nolte, 2010).

The total annual cost of such a strategy to replace the devices immediately was found to be 92.4 million euro, and the benefit/cost ratio was 9.

For the second case the following assumptions were made:

- The price difference between old and new devices was 1,000 euro.
- The depreciation period was 5 years.
- The market interest rate was 5%.
- 16,000 testing devices per year would have to be replaced over five years.
- The inflation rate was 2% per year.

The total annual cost of this strategy was found to be 22.2 million euro per year, and the benefit/cost ratio was 39.

From a theoretical economic point of view the second market introduction strategy is - given the high benefit/cost ratio - the preferable strategy. However, compared with general benefit/cost ratios in the transport sector, the first strategy also results in an impressive benefit/cost ratio, and implementation would also be justified.

7.7 Sensitivity Analysis

A sensitivity analysis was conducted to examine the effects of changes in the vehicle share. Other parameters were not investigated because they were either empirical (*e.g.* emission changes), official values (*e.g.* unit cost rates) or led to directly proportional changes in the results (*e.g.* failure rates).

For this purpose vehicle-share elasticities of benefit were derived. This kind of elasticity was defined as follows:

$$E(B, S_i) = \frac{\frac{dB}{B}}{\frac{dS_i}{S_i}} \quad (5)$$

where:

E = elasticity
B = benefits
S = share of vehicles
i = vehicle category (i = 1, 2, 3, 4, 5)

Firstly, an isolated change in the vehicle share was examined. It was assumed that, for example, the share of vehicle 1 was 100%, and the effects of a 10% reduction in the share were examined. At this stage the shares of vehicles 2 to 5 remained unchanged to fulfil the ceteris-paribus condition. For each vehicle category the following elasticities were derived:

- E(B, Svehicle1) = 1.0
- E(B,Svehicle2) = 1.0
- E(B,Svehicle3) = 1.0
- E(B,Svehicle4) = 1.0
- E(B,Svehicle5) = 1.9

The above elasticities indicate that a 10% change in the share of vehicles 1-4 leads to a change in the benefits of 10%. The situation for vehicle 5 is better, in that a 10% increase in the share of this vehicle will lead to ~20% increase in benefits through the use of new techniques for exhaust measurement.

Secondly, it was assumed that in the base case the vehicle shares were all equal to 20%. The share of each vehicle in turn was increased by 10%, and the other shares were each reduced proportionally. For each vehicle category the following elasticities were derived:

- E(B, Svehicle1) = -0.21
- E(B,Svehicle2) = 0.71
- E(B,Svehicle3) = -0.17
- E(B,Svehicle4) = -0.17
- E(B,Svehicle5) = -0.11

Some of the elasticities were negative. For example, a 10% increase in the vehicle 1 share reduced the possible benefits of new exhaust measurement methods by around 2%.

Key points from this chapter

1. The average benefit per year of the new roadworthiness emission test for diesel engines was calculated to be 864 million euro. This meant that for each tested diesel car a benefit of 20 euro could be achieved. Other criteria apart, this benefit would be sufficient to allow an immediate regulatory switch to the new roadworthiness emission test.
2. A strategy to replace opacity measurement devices immediately was found to have a cost of 92 million euro, and a benefit/cost ratio of 9. Implementation of this strategy would also be justified.
3. A strategy to replace opacity measurement devices over a five-year period was found to have a cost of 22 million euro, and a benefit/cost ratio of 39. Implementation of this strategy would also be justified and preferable.
4. The sensitivity analysis showed that the vehicles which were selected would be broadly representative of Euro 5/6 technologies.

8 Conclusions and recommendations

The conclusions and recommendations from this study are provided below by topic. A stakeholder meeting was held towards the end of the project to ensure that these recommendations also reflected the wider consensus, and the outcomes of this meeting are summarised in Appendix J.

8.1 Instruments for measuring NO, NO_2 and NO_x

Conclusions from review

1. Instruments which are suitable for measuring NO or NO_2 during PTI emission tests are based on electrochemical cells or NDUV spectroscopy, although the latter are currently more expensive. Due to water vapour cross-sensitivity, NDIR and FTIR instruments (especially for the measurement of NO_2) will not fulfil the requirements of PTI testing.
2. Prior to TEDDIE there have been relatively few studies in which NO/NO_2 instruments specifically designed for PTI have been evaluated. NDUV analysers have been evaluated in several PEMS studies, and seem to have a high correlation with chemiluminescence analysers. Electrochemical cells have been evaluated with calibration gases (especially NO), but no studies have involved comparisons with other instruments on dynamometers.

Conclusions from TEDDIE programme

1. The NDUV instrument (Sensors Inc. SEMTECH-DS) used in TEDDIE was in an advanced state of development and generally performed well in the tests, with the exception of dynamic response. However, this can be optimised by the manufacturer according to the test procedure. The instrument is therefore technically suitable for use in PTI tests but, as noted above, my be excluded on cost grounds.
2. The instruments based on electrochemical cells performed inconsistently in the TEDDIE tests, and can only be considered as prototypes in relation to their use in emission tests. Whilst the instruments generally meet the cost requirements, their performance must improve if they are to be certified for use in PTI.

Recommendations

1. It is anticipated that instrument development will continue, especially if the demand for such instruments increases. Specifically, improvements are required to electrochemical cells in the following areas:
    - Calibration procedures. For measuring low emissions it is necessary to calibrate instruments with low-concentration calibration gas. To maintain accuracy over a wide measurement range, calibration should be conducted for a minimum of two points.
    - Long-term stability, especially for NO_2 measurement.
    - Reduced cross sensitivity to other exhaust components (CO, CO_2, HC, O_2). The results for the MAHA instrument showed that this is possible.
    - Optimisations of delay time of the sensors for dynamic test procedures.

    Following such developments, instruments using electrochemical cells might be able to meet PTI requirements.
2. Developments in measuring instrument technology should be monitored, and further evaluation studies conducted where the developments are significant.

8.2 Instruments for measuring PM and opacity

Conclusions from review

1. Many instruments are available for characterising particles in vehicle exhaust during PTI, including standard and advanced opacimeters, reflectometers, light-scattering (LLSP) meters, quartz crystal microbalances and escaping current sensors.
2. In previous studies the correlation between opacity measurements and gravimetric PM measurements (in g/km) was found to be poor, especially over unloaded tests. Filter paper reflectometry and advance opacimeters have higher sensitivities than the standard opacimeter, although the practical application of the reflectometry method is more difficult.

Conclusions from TEDDIE programme

1. All the instruments used for PM measurement in TEDDIE (three LLSP instruments and one escaping current sensor) are essentially prototypes, but the level of development can be considered to be higher than that of the NO and NO_2 instruments.
2. LLSP instruments provide measurements which are sufficiently accurate and stable, and have the necessary dynamic response characteristics and resolution, for testing modern vehicles in PTI programmes. Both high emissions (above 3 m^{-1}) and very low emissions (within the measurement range of conventional opacimeters) can be detected very well.
3. Excessive PM emissions can clearly be identified using LLSP instruments, and the correlation with results from type approval tests is significantly better than for opacimeters.
4. The cost of LLSP instruments is comparable to that of conventional opacimeters, and in some cases can be lower. In addition, the instruments are easy to handle and their practical use during PTI emission tests does not appear to be a problem.
5. The escaping current sensor (the Pegasor PPS-M) is an early prototype, and the measurement procedure is slightly more complicated than for LLSP instruments.

Recommendations

1. For LLSP instruments a practicable calibration procedure is still required. This is currently being addressed by the manufacturers and by the German PTB.
2. A certification procedure for the use of LLSP instruments in PTI emission tests should be established.
3. Escaping current sensors will probably undergo further development, and should be re-evaluated for use in PTI. Purchase costs and operational costs may also fall.
4. Any other developments in measuring instrument technology should be monitored, and further evaluation studies conducted where the developments are significant.

8.3 PTI test procedures – review, measurement and analysis

Conclusions from review

1. At present all EU countries perform a diesel emission test during PTI. None of the Member States check exhaust components other than smoke opacity.
2. Opacity is measured during idle and free acceleration according to Directive 2009/40, except in the Czech Republic, Germany (where there are no measurements on post-2005 diesel vehicles

which have no OBD DTCs and correctly set RCs) and Slovenia. None of the Member States check other exhaust components.

3. The free acceleration smoke test is also the main test used for diesel vehicles outside the EU. Different loaded tests are used to measure NO_x and PM. A free acceleration test is only used to measure NO_x at one location (Beijing).
4. OBD offers a potential alternative to emission measurement, and is used in PTI emission testing in France and Germany. However, a number of issues with OBD, and its use in PTI tests, have been identified. These include thresholds which are set too high for the latest emission standards, and an inability to consistently detect problems with all after-treatment devices.

Conclusions from TEDDIE programme

The conclusions from the TEDDIE programme are arranged in relation to the questions posed in chapter 5:

5. *Can faults in NO_x-control systems be detected using NO_x measurement during PTI tests?*

   For the cars the correlation between the PTI and NEDC results was poor for NO_x. Faults leading to increases in NO_x emissions (large increases in some cases) over the type approval test were not systematically detected by the PTI tests. Whilst some faults were detected, a suitable emission test cannot be identified and the overall results do not provide sufficient evidence to support the use of NO_x measurement during PTI. On the other hand, some of the faults did not lead to emission levels above the vehicle-specific limits, and therefore such faults would not have been identified in the type approval test itself. This shows that exhaust emission measurement alone is not sufficient for finding faults in the NO_x-control systems of modern diesel vehicles. Additional component testing might be an option for detecting failures during PTI with a low error of omission and commission

   For the heavy-duty engine only SCR faults were investigated. Whilst these faults led to increases in NO_x over the type approval test, none were identified by the PTI tests (idle and free acceleration), primarily because the SCR system does not work efficiently under the low load conditions associated with such tests. Therefore, the overall results do not provide sufficient evidence to support the use of NO_x measurement during PTI.

6. *Can faults in PM-control systems be detected using PM measurement during PTI tests?*

   For the cars the PTI tests and opacity instruments could not differentiate between vehicles with and without faults for type approval PM values lower than around 5 mg/km. The PTI instruments for measuring PM (in mg/m^3) showed a better discrimination between different vehicles, and an acceptable response to low PM emissions over the NEDC.

   The faults in the cars which led to large increases in PM emissions, such as major defects in 'closed' DPFs, were, on the whole, detected by the PTI tests. In general the results for measuring PM were better than those for NO_x. Of the unloaded tests, the free acceleration test tended to be the best practical indicator of faults.

   Therefore, the combination of the free acceleration test and the PM instruments is appropriate for identifying defective exhaust after-treatment systems and high-emitting vehicles. To avoid a high error of omission a general PTI test limit value of about 40 mg/m^3 for the free acceleration test would be appropriate.

   A further approach might be to use car-specific PTI limit values, as in the case of opacity in the current legislation.

   The SCR faults in the heavy-duty engine had little effect on PM emissions.

7. *Can faults in emission-control systems be detected using the NO_2/NO_x ratio?*

   The results for the NO_2/NO_x ratio were too variable and inconsistent to enable them to be used reliably for identifying faults in specific components. Whilst this metric might have been useful for identifying faults in CRTs fitted to Euro 3 and Euro 4 vehicles, in Euro 5 and Euro 6 vehicles the ratio is affected by several different components of the emission-control system. The ratio is therefore very sensitive to the actual after-treatment technologies and coatings used in different vehicles, and cannot be said to provide a reliable indication of the failure of any given component.

   The heavy-duty engine had no DOC, and NO_2 emissions which were less than 0.1 g/kWh, or less than 3% of total NO_x emissions. The NO_2/NO_x ratio was therefore not relevant for the indication of faults.

8. *Can faults in emission-control systems be detected using OBD?*

   For all cars tested the OBD system could not detect the simulated faults. The MIL was not triggered in any test, and no DTCs were stored. One reason for this was that the measurements were generally lower than the OBD thresholds, though in some cases the thresholds were greatly exceeded and the MIL was still not triggered. Therefore, if OBD were used to identify emission faults a large number of vehicles with unacceptably high emissions would not be identified as having faults.

   However, OBD did not respond to the faults that were simulated, and for cars OBD - in combination with stringent OBD limit values - may still be a useful additional means of identifying failures in the NO_x-reduction system. This requires further investigation.

   For the heavy-duty engine the OBD system was able to identify the faults with the urea dosing of the SCR, and DTCs were stored.

   In general, the performance of the OBD systems in TEDDIE highlighted once again the need for direct measurement of exhaust pollutants.

Recommendations

NB: It should be noted that the following recommendations are somewhat tentative given the limited size of the test programme, the variability in the results and, to some extent, the unexpected effects of some of the simulated faults.

1. The combination of the free acceleration test and new PM instruments measuring in mg/m^3 should be considered to represent a viable option for future PTI emission testing.
2. Field trials should be conducted to determine:
   a. Whether the combination of the free acceleration test and new PM instruments can accurately detect real-world faults in PM-control systems.
   b. Whether general PTI limit values for PM – such as the suggested 40 mg/m^3 - can be used or vehicle-specific limit values are more appropriate.
3. The measurement of NO_x emissions (or the NO_2/NO_x ratio) during PTI emission tests, and the identification of EGR and SCR faults, requires further investigation. No specific recommendations are possible at this stage.
4. The use of OBD to identify NO_x-related faults requires further investigation in field tests. It would also be of interest to study how drivers react to OBD warnings.
5. There will be a need to address the use of engine speed limiters (rpm and rpm gradient). A solution to this should be identified with ACEA, otherwise dynamometer-based testing may

be required for PTI. Engine protection limits will need to be discussed with OEMs.

6. The TEDDIE study did not cover engine faults for heavy-duty vehicles. It would be of interest in subsequent work to investigate engine-related problems, such as faulty injectors or EGR valves, as well as after-treatment faults, which have an impact on PM emissions,.

8.4 Cost-benefit analysis

Conclusions

NB: The cost-benefit analysis only covered diesel passenger cars. It did not include petrol cars or any other class of vehicle.

1. The average benefit per year of the new roadworthiness emission test for diesel cars (*i.e*. free acceleration with new PM instruments) was calculated to be 864 million euro. This meant that for each vehicle tested a benefit of 20 euro could be achieved.
2. A strategy to replace opacity measurement devices immediately was found to have a cost of 92 million euro, and a benefit/cost ratio of 9.
3. A strategy to replace opacity measurement devices over a five-year period was found to have a cost of 22 million euro, and a benefit/cost ratio of 39.

Recommendations

1. Other criteria apart, the estimated benefits would be sufficient to allow an immediate regulatory switch to the new roadworthiness emission test.
2. Implementation of a strategy to replace opacity measurement devices over a five-year period would be economically preferable to immediate replacement.

8.5 EU PTI legislation

Conclusions

Several limitations of the current PTI emission test in the legislation (Directive 2010/48/EC) have been identified, notably for modern diesel vehicles. Updates to the existing legislation, instruments and procedures therefore seem appropriate.

Recommendations

NB: Considering the limited numbers of vehicles and engines tested in this study, it would be premature to modify the legislation without further evidence. Nevertheless, the following preliminary recommendations should be considered:

1. The evidence from TEDDIE suggests that the **free acceleration test**, as currently defined in the legislation, remains a suitable procedure for modern diesel cars.
2. Consideration should be given to how **engine speed limiters** are addressed in the legislation, so that the free acceleration test can be conducted for all vehicles. For example, it must be clear how engine speed limiters are deactivated for PTI tests, and it must be possible to accelerate the engine in an appropriate manner (*i.e.* in less than 2 seconds).

3. In the current legislation the diesel emission limits[37] are stated as *k* values in m^{-1}, which are the units of conventional opacimeters. Consideration should be given to a changeover to the measurement of the **mass concentration of PM (in mg/m³)** for new vehicles meeting a specific emission standard. The existing regulation 72/306/EC should be updated replacing k values by mg/m3.
4. Should such a changeover be adopted, the legislation[38] would need to make an allowance for the use of **appropriate PM-measurement devices** (such as LLSP instruments).
5. There would also be a need to define a **correlation between PM values in mg/m³ and *k* values in m^{-1}** to be used in the measurement devices. This is currently being investigated by the manufacturers and the German PTB. A provisional generic correlation curve has also been developed by EGEA (Figure 58) using measurements from various different LLSP instruments and opacity values up to 0.5 m^{-1}.
6. **Limit values for PM** during PTI tests can be defined in accordance with the existing legislation, using the plate values for opacity from type approval in conjunction with a correlation function such as the one developed by EGEA.
7. General limit values for PM (or any adjustments to plate values) should be based on the findings of **field trials**.
8. Pending the results of further studies, **the extension of the use of OBD** in the legislation should be considered for the evaluation of emissions and other parameters which are relevant to PTI tests (*e.g.* engine speed).
9. **Hybrid petrol-electric and diesel-electric vehicles** are not currently addressed by the EC PTI legislation. The revision of the legislation to include hybrid vehicles, and appropriate test methods, should be considered. For Hybrid vehicles PTI test mode, to operate the engine on a dedicated level of load might be needed.
10. The implementation of the revised procedures and instruments in terms of **application by date or emission standard** will need to be agreed.
11. The implications of any of the above changes to the **type approval legislation** will need to be considered.

[37] Regulation 72/306/EEC specifies a 'corrected absorption coefficient', defines the measurement, the procedure and the calculation of the relevant value (m^{-1}). This regulation will be replaced in January 2013 by the regulation (EC) 715/2007 (type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6)) and its regulation for implementing (EC) 692/2008. This regulation specifies the vehicle plate value in an analogous way to regulation 72/306/EEC, and refers to the procedure and calculation of the relevant value in UN/ECE regulation No. 24.

[38] Regulations (EC)692/2008 and/or UN/ECE No.24.

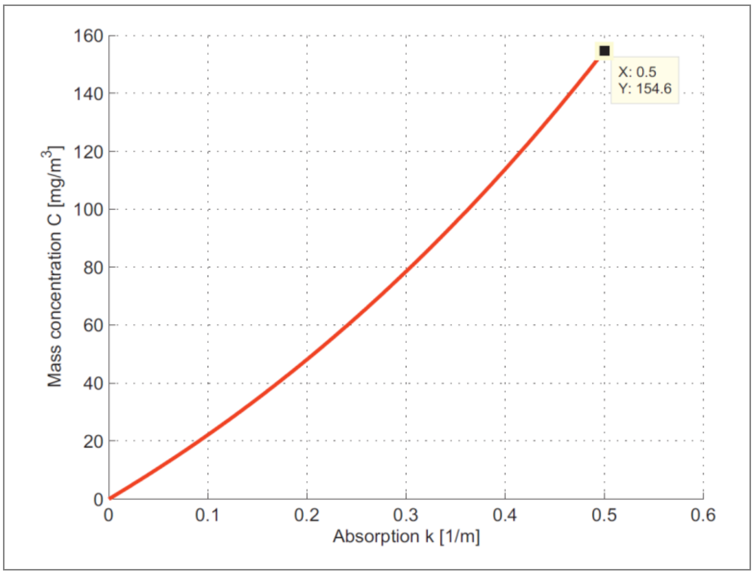

Figure 58: Correlation between PM mass concentration and *k* value (Hahn, 2011).

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