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TNO report

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Euro VI technologies and costs for Heavy Duty vehicles
The expert panels summary of stakeholders responses

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Executive Summary

This report is the result of the work carried out under on the Europeans Commission's call for tender regarding "Technical support for the Commission DG Environment on the development of Euro 5 standards for light-duty vehicles and Euro VI standards for heavy-duty vehicles" (Reference: ENV.C.1/SER/2004/0039).
A consortium of TNO Automotive in Delft (project leader) in collaboration with LAT from Greece and Ricardo from the UK was selected to carry out the work. The work undertaken evaluates the technologies and associated costs involved to meet possible forms of Euro VI Heavy Duty vehicles emission legislation for both compression ignition and natural-gas vehicles. The evaluation was initially based on the responses from the Motor vehicles Emission Group (MVEG) to a questionnaire sent out by the Commission, asking for detailed technology and costs information related to a number of possible Euro VI limit values. These responses were bundled and assessed by the consortium (Euro VI panel).

The data supplied to the panel not only contained limited technical information but also in most cases did not cover all of the costs associated with the technology implementation on vehicles. Running costs and development costs were not supplied at all and are therefore not assessed in this report.

The initial information received therefore proved insufficient to provide detailed technology and costs data for all different Euro VI scenarios requested by the Commission.

In order to meet the terms of the contract, the panel first formulated different technology pathways to reach the Euro VI emission standards, following the different scenarios proposed in the MVEG. The pathways were built on the basis of information provided in the questionnaires but also on the basis of technical information collected from different sources and the own expertise of the panel. The pathways also proposed a low-high technology range to attain the emission requirements in each scenario.

The second element of the approach was to quantify the costs for each pathway. Due to the lack of such information in the original questionnaires, the panel arranged specific meetings with key respondents to obtain more data in order to build an, as far as possible, reliable cost model. This model enabled "scaling" of technologies and costs for several typical vehicle applications (swept volume dependent), based on some specific engine and vehicle data but extended to a range of vehicle classes and engine sizes.

The panel remains confident that despite the spread of information and the associated uncertainties in the ranges of the data supplied by different stakeholders, the technology and cost model developed to reach Euro VI when applied to the baseline technology assumptions (Euro IV) leads to a reliable estimate of the cost of future technologies and is reasonably consistent with the original data supplied to the Commission.

The model was used to predict the costs within a bandwidth of probable technology solutions to meet the EC specified Euro VI emission limit values scenarios. These solutions have been based on typical combinations of aftertreatment and engine measures. The combinations selected were based on the applicable limit values (for the scenarios) and technologies that were seen to be adequate to achieve these limits, based on the information supplied by the stakeholders to the panel.
Key issues and assumptions were:

- the use of cost assumptions for the year 2012 and beyond, based on 2004 costs and production volume data (with the exception of PGM price development and thrifting). This ignores the likely changes in costs due to technical progress and mass production;
- the assumption of a stable market price for automotive PGM compositions and a 30% reduction in PGM use (thrifting);
- the inability of the panel to effectively take into account LNT technology at the moment of the assessment;
- the inability of the panel to discriminate between cost for emission reduction and fuel consumption decrease;
- the fact that the costs and availability of urea (and distribution) for SCR technology on diesel vehicles have not been taken into account;
- not being able to take into account development costs.

Apart from these limitations, the output produced will also need some further processing before it can be used as input to simulations within the CAFE programme. In particular, assumptions will have to be made on:

- the correspondence of the engine swept volume (used in this report) to TREMOVE gross vehicle weight classes;
- the N1 class 2 vehicles within the HD limit values concept;
- market share distribution of stoichiometric and lean burn CNG (SI) engines
- the trade off between costs for Euro VI emission reduction and CO_2 emission reduction;

The panel cannot further elaborate on the assumptions to be made. It will be up to the Commission (and subsequent studies on scenario formulations for TREMOVE) to decide how to use the information presented here in the impact assessment of a proposal for a Euro VI standard. However in order to facilitate the choices of the Commission the cost for all CI Euro VI scenarios are presented in two ways (tables next): one with *all* cost allocated to Euro VI emission reduction and one with *only 50%* of the cost of “high pressure injection “ and “two stage turbo charging” allocated to Euro VI. The latter technologies being seen as possibly contributing to both to fuel consumption reduction as well as regulated emissions reduction.

In the following, the result of the Euro VI panel’s work is presented in 3 tables. The tables contain the technology scenarios and associated costs for respectively compression ignition (CI, *all* and *50%*), and NGVs (*stoichiometric* and *lean burn technology*).

Table A: CI (all cost allocated to Euro VI)

	limits g/kWh ETC*	Engine swept volume (L)	cost (€)		
			low	high	avg
scenario 1	PM: 0,030	6	297	533	415
scenario 1	NOx:2,00	9	346	935	640
scenario 1	THC: 0,55	13	428	1287	857
scenario 2	PM: 0,015	6	1131	1753	1442
scenario 2	NOx:1,00	9	1632	2315	1973
scenario 2	THC: 0,55	13	2116	3080	2598
scenario 3	PM: 0,015	6	1631	1853	1742
scenario 3	NOx: 0,50	9	2332	2415	2373
scenario 3	THC: 0,55	13	2816	3180	2998
scenario 4	PM: 0,025	6	2559	3255	2907
scenario 4	NOx: 0,40	9	3189	4218	3703
scenario 4	THC: 0,20	13	3778	5251	4515
scenario 5	PM: 0,010	6	3355	3553	3454
scenario 5	NOx: 0,40	9	4318	4615	4466
scenario 5	THC: 0,16	13	5351	5780	5566
scenario 6	PM: 0,020	6	3753	3753	3753
scenario 6	NOx: 0,20	9	4815	4815	4815
scenario 6	THC: 0,55	13	5980	5980	5980
	* NH3 10 ppm CO 4,0 g/kWh				

Table B: CI (50% of the costs for "high pressure injection" and "two stage turbo charging" allocated to Euro VI)

	limits g/kWh ETC*	Engine swept volume (L)	cost (€)		
			low	high	avg
scenario 1	PM: 0,030	6	297	533	415
scenario 1	NOx:2,00	9	346	935	640
scenario 1	THC: 0,55	13	428	1287	857
scenario 2	PM: 0,015	6	1131	1753	1442
scenario 2	NOx:1,00	9	1632	2315	1973
scenario 2	THC: 0,55	13	2116	3080	2598
scenario 3	PM: 0,015	6	1431	1853	1642
scenario 3	NOx: 0,50	9	2032	2415	2223
scenario 3	THC: 0,55	13	2516	3180	2848
scenario 4	PM: 0,025	6	2059	2755	2407
scenario 4	NOx: 0,40	9	2589	3618	3103
scenario 4	THC: 0,20	13	3078	4551	3815
scenario 5	PM: 0,010	6	2855	3053	2954
scenario 5	NOx: 0,40	9	3718	4015	3866
scenario 5	THC: 0,16	13	4651	5080	4866
scenario 6	PM: 0,020	6	3253	3253	3253
scenario 6	NOx: 0,20	9	4215	4215	4215
scenario 6	THC: 0,55	13	5280	5280	5280
	* NH3 10 ppm CO 4,0 g/kWh				

Table C: SI-NGV-costs for meeting Euro VI scenarios (Stoichiometric and lean burn)

		cost (€)					
6 cylinder, 9 litre NGV engine		Stoichiometric			lean burn		
	limits g/kWh ETC*	low	high	avg	low	high	avg
scenario 2	CO: 3,0 NMHC: 0,40 CH4: 0,65 NOx: 2,0 PM: 0,02	760	1240	1000	80	3570	1825
scenario 3	CO: 3,0 NMHC: 0,40 CH4: 0,65 NOx: 1,0 PM: 0,01	760	1240	1000	3580	4070	3825
scenario 4	CO: 4,0 NMHC: 0,20 CH4: 0,5 NOx: 0,4 PM: 0,01	1460	2190	1825	3980	4070	4025
scenario 5	CO: 4,0 NMHC: 0,16 CH4: 0,5 NOx: 0,4 PM: 0,01	1460	2190	1825	3980	4070	4025
* all NH3: 10 ppm							

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Appendices

1 Introduction

This report is the result of the work executed under Task 2 of a service contract for the Europeans Commission concerning “Technical support for the Commission DG Environment on the development of Euro 5 standards for light-duty vehicles and Euro VI standards for heavy-duty vehicles” (Contract no. 070501/2004/381669/MAR/C1).
The work has been carried out by a consortium of TNO Automotive in Delft (project leader) in collaboration with LAT from Greece and Ricardo from the UK. The work deals with the evaluation of the technologies and associated costs involved to meet possible forms of Euro VI Heavy Duty vehicles emission legislation.

1.1 Background

Within the framework of the Clean Air For Europe (CAFE) programme the European Commission has been preparing a Thematic Strategy to preserve air quality in Europe in line with the 6th Environmental Action Programme. The process followed should enable the determination of the optimal pollution reduction effort and the role of the main sources of pollution. A number of quantitative models are used to support the CAFE work, including the RAINS model which covers all emission contributing sectors, and more specialised models for some individual sectors. For the transport sector, the latest version of the TREMOVE model (amongst others) will be used.
The results of the model calculations will inform the process of setting new emission standards for vehicles sold in Europe.
The next set of new standards for Heavy Duty Vehicles (HDV’s) are commonly referred to as Euro VI.
For setting these new standards in an appropriate cost effective manner, detailed information on the availability of emission control technology and associated costs is required.
In order to obtain this information the Commission has sent out two questionnaires to specific members of the Motor Vehicles Emission Group (MVEG). These questionnaires aimed at collecting information on the necessary technologies and associated costs in order to meet a number of prescribed technology scenarios.

The authors of this report formed an expert panel to analyse the responses to the Heavy Duty Vehicles (HDV) questionnaire. According to the contract, their task was (subtask 1b):

- forming an opinion on the factual correctness, plausibility and accuracy of the information provided in the responses to the MVEG questionnaire;
- analysing the degree of coherence between different responses received and highlighting any major differences;
- comparing the information received with outside information known to the members of the panel or made available to them by the Commission;
- identifying any significant gaps in the information provided through the responses to the questionnaire, and providing information to fill these gaps in the best possible way;
- communicating the findings of the panel in a report to the Commission.

The present report corresponds to these tasks.

The information received by the Commission in response to the questionnaires has come from several mostly independent sources, making it impossible to use this basic feedback directly as input for the model calculations. Therefore all the inputs have been summarised and checked for reason, degree of coherence and the completeness of the total information received. In order to meet the requirements of several stakeholders when supplying highly confidential information to the EC, confidential treatment of the information to be assessed was a major issue to and was taken satisfactorily into account.

Based on the information received and on other available information with the EC, an objective and coherent projection of possibilities and costs to meet the requirements of the submitted scenarios has been established by the panel.
This assessment will in the end lead to a custom fit input for running the TREMOVE model calculations.

1.2 Methodology and activities

Methodology
The key task of the work was to objectively assess a large amount of technical and highly confidential information, and report on the findings in a comprehensive way to the European Commission. This panel consisted of 4 specialists on the topics: engine- and exhaust gas after treatment technology, emission policy and legislation, emissions modelling and testing. The actual team consisted of Raymond Gense (project Leader) and Iddo Riemersma from TNO-Automotive, Chris Such from RICARDO and Leonidas Ntziacristos from LAT.

This expert panel has reviewed information supplied to them by the EC directly (through the questionnaires output), completed with information directly from the stakeholders. In addition international open literature (technical papers and reports) and was used for confirmation. The result of the assessment of all information is summarised in the following report. In order to preserve confidentiality concerning the information made available to the panel, this report at no point presents information from individual stakeholders. The experts have also refrained from using confidential information from other projects executed within their companies.

The methodology used for assessing the information made available has been one of disaggregating the information received, into technical sub packages with typical emission reduction rates and costs linked to each of the sub packages. For this purpose the panel has used a detailed cost calculation spreadsheet, which has been filled with the information received (see appendix A for spreadsheet structure). The end result is a range of cost specification for each of the possible legislative scenarios, with certain technology combinations linked to the scenarios.

Activities
The activities of the expert panel started after the EC had received back information from the stakeholders in answer to the HDV questionnaire that was sent out in the autumn of 2004. The stakeholders are the parties which participate in the MVEG group (Motor Vehicles Emission Group) of the EC http://europa.eu.int/comm/enterprise/automotive/mveg). The questionnaire contained specific questions about technologies, costs, durability and additional requirements for

meeting 11 emission limit scenarios (6 Compression Ignition and 5 for NGV) using the current type approval procedure as described in directive 88/77/EEC.

Official responses to the EC's request for information were submitted by ACEA, AECC (3 separate responses), ENGVA and UBA. ACEA and one of the AECC members actually replied using the Excel spreadsheet format. In addition to the Excel input and the written statements, additional information was supplied by the stakeholders in the form of relevant papers and notices.
All information received by the EC was handed over to the panel. This set of information was the starting point for the expert panel's work.

The next step for the panel was to assess the input on its coherence.
A first screening of the information made available to the panel showed that:

- questionnaires were filled out only partly
- Responses did not contain information on all scenarios
- limited explanations towards the technological background of the input were supplied (probably due to the way the questionnaire was structured), but in return additional information exchange was offered by several stakeholders, on condition of strictest confidentiality.
- different angles of looking at the topic were obvious between manufacturers and equipment suppliers, leading to gaps in the chain of technologies and assumptions used.

This resulted in a large bandwidth of technologies and related costs in order to fulfil the limit value scenarios under investigation.

At this point the expert panel decided to make use of the additional information exchange offered, and additional meetings between some stakeholders and the expert panel were organised:

- a meeting with ACEA (general background of questionnaire response and engine internal measures)
- a meeting with AECC (general background of questionnaire response and expected technologies combinations)
- a meeting with ENGVA (general background of questionnaire response)
- a general stakeholders meeting on the 24th of April 2006 (presenting the first findings of the panel to the stakeholders).

All information, ideas and explanations gathered were joined in a detailed technology- and costs spreadsheet, constructed for the purpose of the assessment by the panel. This spreadsheet identified sub-technologies and costs related to vehicle classes (fuel type and swept volume) that could be linked to each other in order to meet certain emission limitation scenarios (see appendix B).
Based on the material provided from the questionnaire, and on more detailed information obtained during stakeholder meetings, the panel was able to prepare specific sets of technology combinations required to meet certain scenario settings. From this analysis the costs related to the technology combinations are calculated. This output is the essential output of the underlying investigation and will be the input for the model calculations for the CAFE process.

In the next paragraphs the details (as far as can be displayed with the confidentiality agreements) of the panels work will be described.

- First the available technologies to further reduce heavy-duty vehicles regulated emissions from Euro IV onwards will be described.
- Secondly the current and reference Euro IV baseline will be described, also taking into account special topics such as, CO_2 emission reduction and real world operation emissions.

Based on this current baseline and available technologies, the selected range (low and high) of technology applications will be described.

2 Technology options for Euro VI HDV Review of Technologies to Reduce Vehicle Emissions

2.1 Introduction

Emissions reduction is generally a complex area with many interactions between technologies, impact on fuel economy, driving performance and costs and a complete review is beyond the scope of this report. However, this section provides an overview of the key technologies in research and development focusing on current critical issues.

In general, emissions reduction measures can be divided into 2 main areas:

- Combustion system developments to reduce engine-out emissions
- Emission control technologies using "aftertreatment" of the exhaust gas post-combustion

For Heavy Duty diesel engines, the key emissions challenges have generally been NO_x and particulate matter (PM). However, techniques to reduce NO_x and PM often lead to an increase in unburned hydrocarbon (HC) and carbon monoxide emissions (CO) which present additional challenges and can be a limiting factor in how far particularly NO_x emissions can be reduced.

For Compressed Natural Gas (CNG) engines, emission control technology at present is dominated by three-way catalysis (TWC) which has proved to be very effective. However, this requires the combustion system to operate at stoichiometric (chemically correct) air to fuel ratio, which limits combustion efficiency and can introduce pumping losses at part load. Recent developments to improve combustion efficiency, reduce pumping losses and improve fuel economy through lean or stratified charge operation have required more complex lean emission control technologies to control NO_x and this has been a key area of research in recent years.

The main development routes are thus:
-C*ombustion control systems*
-*Aftertreatment technologies*

Since diesel and NGVs are, to a large extent different technologies, these will be addressed separately.

2.2 Diesel Engines

2.2.1 Combustion System Developments

In the following, the possibilities to reduce emissions by using combustion system developments are discussed. The measures discussed give a general overview of technical possibilities. The actual application of these measures in order to achieve Euro V level emissions depends largely on the development strategy of the individual manufacturer. The measures from this portfolio possibly used under the Euro VI regime are further referred to as Engine Internal Measures

2.2.1.1 *Developments in engine internal measures*

The most significant challenge in Heavy-duty diesel engine development is to cost effectively reduce NO_x emissions without increasing fuel consumption. Cost effective in the HD context means low additional vehicle sales price, high durability and low fuel cost.

The most effective internal measure is to use Exhaust Gas Recirculation (EGR) to control NOx by diluting the charge with gaseous combustion products. Due to the relatively even distribution of engine load in the Heavy-duty emission cycles, EGR is required over most of the operating range, including full load. Good control of mixing of fuel, air and recycled exhaust gas is essential to provide a favourable local air/fuel ratio in order to minimise soot. In the case of Euro IV, some 15-18% (averaged over the test cycle) of the charge consists of recycled exhaust gas, and this must be supplied efficiently to avoid an increase in fuel consumption and CO_2 emissions.

In future, rather than a step change in technology, a number of incremental developments will lead to progressive benefits. Operation at increased rates of EGR leads to challenges in transient control, combustion stability and engine durability.

Research work has shown that reduced emissions are possible, but the practical and robust demonstration, subject to production variation is a much more difficult challenge. To meet lower NO_x levels, a new generation of control systems will be necessary. New sensor technology and advanced model based control must be realised to enable improved combustion control and robustness.

The main technologies to reduce engine out NO_x from the Euro IV baseline are as follows:

- Increased exhaust gas recirculation (EGR) rates (cooled)
- Advanced fuel injection systems with higher pressures and multiple injection
- Increased Flow Range Turbocharging
- Model Based Combustion Control Using New Sensor Technology

2.2.1.2 *Increased EGR rates*

Cooled EGR is used by some manufacturers for Euro III and Euro IV. Cooling the recirculated exhaust gas allows a higher mass of exhaust gas to be recirculated for a given volume, allowing higher in-cylinder mass for a given boost pressure and enabling EGR use at high loads, without significantly compromising the A/F ratio. e manufacturers who plan to continue with EGR for Euro V will increase EGR rates and EGR cooling. In order to achieve suitable air/fuel ratios, higher levels of boost pressure will be required, which will increase the cost of the single stage turbocharger and in some cases will lead to the use of two stage turbochargers. Changes to the vehicle cooling system (radiator, cooling fan) will be needed in order to cope with the increased heat rejection to coolant, due to the higher exhaust volume which needs to be cooled by the EGR cooler.

2.2.1.3 *Advanced fuel injection systems with higher pressure and multiple injection*

Improvements in EGR tolerance (reduced NO_x without a corresponding increase in PM emissions) can be obtained through improved atomisation by increasing the injection pressure and reducing the nozzle hole size. However, in combustion system design there is a trade-off between full load and part load operation. The nozzle hole size must be selected so that fuelling at rated power can be maintained within an acceptable crank angle period. Increased injection pressures allow nozzle flow rate reductions to improve the part load emissions without sacrificing full load performance as the increased pressure allows the use of smaller nozzle holes whilst achieving the maximum injection period allowed at full load. Furthermore, more responsive injectors using Piezo actuated control valves offer the potential to more accurately control the injection characteristics and quantity. Improved opening and closing characteristics and multiple injections (up to 5) will be beneficial to emissions, fuel consumption and combustion noise through improved mixing and better overall control of the injection characteristics. New fuel injection systems with very high injection pressure potential (in the range of 2000 – 2500 bar) are expected to become available for Euro V. These systems will also have enhanced flexibility in terms of multiple injection capability.

The new fuel injection systems currently under development have the potential to improve fuel consumption as well as emissions.

Innovations in nozzle technology may also provide an opportunity to improve the compromise between part load and full load operation. In particular, variable nozzle area or spray angle offer benefits. The application of a narrower cone angle offers the potential to reduce the amount of fuel impingement on the cylinder wall during early and late injection strategies. These concepts are at an early development stage and there have been problems in maintaining spray quality with variable area nozzles. As such, it is difficult to predict if and when such concepts could be introduced to the market.

2.2.1.4 *Increased flow range turbocharging*

Advanced turbocharging offers the potential to enhance performance, emissions and fuel consumption. For manufacturers using cooled EGR, high levels of boost pressure are needed in order to control particulate emissions. This is especially important in Heavy-duty engines, because of the need to use EGR at high loads. Whilst single stage turbochargers are being continuously developed to provide high boost levels over a wide flow rate, the most practical approach to significantly enhance air supply in Heavy-duty diesel engines is via two stage turbocharging. This consists of a high-flow turbocharger and a low-flow turbocharger in series, with either one or both turbines waste gated. The first application of this technology to the Heavy-duty market in Europe has been by MAN on the mid range truck engines. Further applications are expected for Euro V and beyond.

The two stage turbocharger has the potential to improve fuel consumption as well as providing the level of charge air needed for high EGR rates.

2.2.1.5 *Model based combustion control using new sensor technology*

As emissions legislation tightens, achieving consistently robust and repeatable results in all production engines is a major challenge. To meet this need, control system developments will be essential. This is likely to be achieved through the combination of new sensor technology and improved processing capability. New sensors will provide direct feedback indicating combustion characteristics to the control system and when coupled with model based control of the air and EGR systems will enable adaptive control of the engine variables. Such systems also provide improved on-board diagnostic (OBD) capability. This technology is at an early stage and significant development is required. Advances in model based control will be an essential enabler for low NO_x strategies, which operate much closer to engine combustion limits.

2.2.1.6 *HCCI*

Homogeneous charge compression ignition (HCCI) is a distinct combustion mode in which a premixed charge of air, fuel and combustion products is compressed until it auto-ignites. Lean air/fuel ratios or high amounts of recycled combustion products are used to limit the heat-release rate and to promote low reaction temperatures. The combustion reaction is thought to simultaneously initiate at multiple locations, expand rapidly and does not contain localised high-temperature regions or flame-fronts.

HCCI combustion offers the potential for simultaneously producing low NO_x and PM emissions due to the low peak temperature achieved and lean mixtures. However, several technical limitations must be overcome in order to make HCCI feasible for on road applications, including controlling the combustion phasing over a range of engine speeds and loads.

HCCI combustion is in the early stages of development but shows good potential for NO_x and PM reductions. Control over the combustion process, durability and cost are still major issues that need to be addressed and therefore pure HCCI engines are not expected to be on the market within the time frame of the underlying study.

Recent research suggests that, at light loads, the combination of high EGR levels and retarded injection timings results in a wholly premixed combustion, which could be termed partial HCCI (pHCCI), and which results in very low levels of NOx and PM, at the expense of increased fuel consumption. It has not been possible to achieve pHCCI much above 25% of full load. Due to the relatively even distribution of engine loads in the emission test cycles, the use of HCCI or pHCCI is not currently seen as being significant for the Heavy-duty Euro VI engine. Research work is continuing, and it seems possible that this new combustion technology may play a role in the round of emission legislation after Euro VI.

2.2.2 *Aftertreatment Technologies*

This section describes the key functions of current and future NO_x and Particulate emissions control technology. As is the case for the Engine Internal Measures (EIM), the after treatment (or emission control) technologies presented give a general overview of possibilities. The actual application of certain technologies (or combinations of technologies) under the Euro VI regulations is largely dependent on the individual manufacturers development strategies.

There are two main strategies for NO_x reduction using catalysis: (1) continuous reduction, and (2) storage with periodic reduction. Continuous reduction requires a constant feed of reductant. Periodic NO_x reduction is required for NO_x trap type catalysts.

2.2.2.1 *Continuous NO_x Reduction*

Continuous lean NO_x conversion can be achieved by using ammonia and a Selective Catalytic Reduction (SCR) catalyst, or hydrocarbons and a Lean NO_x Catalyst (LNC) as explained next.

2.2.2.2 *Lean NO_x Catalysis*

Hydrocarbon as a reductant is delivered either from the engine or by exhaust fuel injection. To achieve optimum NO_x conversion using hydrocarbons, a HC: NO_x ratio of ~6:1 is required. Therefore, a specific engine calibration or injection of fuel into the exhaust is required to give the desired ratio. Hydrocarbon reduction of NO_x is generally called Lean NO_x Catalysis (LNC). LNC offers a relatively low NO_x conversion efficiency (~10%). To improve the efficiency, non-thermal plasmas can be used to produce a more reactive hydrocarbon based species. The plasma is housed pre LNC and partially oxidises the hydrocarbons, which then react with NO_x over the catalyst. The plasma enables higher NOx conversion efficiencies (~50 – 70% over limited cycles) but has an associated fuel penalty. LNC fuel consumption penalty is generally 2-5% but there is currently no information on the associated plasma fuel consumption penalty. Over an LNC hydrocarbons react with NO_x in the following manner.

$$HC + NO_x + O_2 \rightarrow N_2 + H_2O + CO_2$$

LNC have durability issues and can be reversibly poisoned by fuel and oil sulphur. Degradation will be dependent on fuel and oil sulphur level, as well as thermal influences. Sulphur related poisoning will obviously diminish with low sulphur levels, but is still of concern due to general poor durability of this technology overall.

2.2.2.3 *Ammonia Based Selective Catalytic Reduction*

Selective catalytic reduction using ammonia as a reductant utilises the injection of urea into the exhaust. The urea hydrolyses to form ammonia and carbon dioxide. Ammonia can also be delivered to the exhaust through ammonium carbamate. Ammonium carbamate ($NH_2CO_2NH_4$) is a solid which sublimes > 60°C to give ammonia and carbon dioxide.

Over an SCR catalyst, ammonia reacts with NO_x according to the following reactions:

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \quad (1)$$
$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O \quad (2)$$
$$4NH_3 + 2NO_2 + O_2 \rightarrow 3N_2 + 6H_2O \quad (3)$$

Reaction 2 is more facile and occurs at lower reaction temperatures than either reaction 1 or 3. Thus, if the NO_x is present in a 1:1 ratio of $NO:NO_2$, the SCR system will perform with the highest efficiency at low temperatures.

SCR can provide high NO_x conversion efficiencies over a wide operating range (~ 60 - 80%). However, it has a lower temperature limit of ~180 – 200°C. This is not so much a problem on the current European emission cycles, but in service conditions such as busses in Scandinavia, it represents a limitation on NOx conversion. Packaging may also be an issue for SCR on some smaller vehicles where space is at a premium.

Urea consumption at Euro V levels is likely to be equivalent to about 5% of diesel fuel consumption. On heavy trucks, the urea tank will be 50 – 70 litres, which means that the truck operator will be required to fill up the urea tank at about the same frequency as the diesel tank.

The calibration of urea dosing into the exhaust system is carried out taking into account the NOx levels emitted by the engine, the temperatures at the entry to the SCR catalyst, and any transient effects, which may result in storage of the urea in the catalyst. If too much urea is injected, there is a risk that ammonia will slip through the SCR catalyst. To counteract ammonia slip, an oxidation catalyst is fitted downstream of the SCR (so called “slip catalyst”) which limits the ammonia emitted to a few parts per million.

To provide the degree of control needed for very low NOx levels and to comply with OBD legislation, closed loop control of urea dosing is expected to be introduced using a NOx sensor fitted on either side of the SCR catalyst.

As an alternative to urea solution, ammonia can also be delivered to the exhaust through ammonium carbamate ($NH_2CO_2NH_4$), which is a solid that sublimes above 60°C to ammonia and carbon dioxide. Ammonium carbamate has the major advantage of requiring only 28% of the volume of liquid urea to deliver the same mass of ammonia, which gives it a major packaging advantage. The main disadvantage is that ammonium carbamate requires a heated container (above 60°C) to ensure delivery of ammonia over all climatic driving conditions. At this stage, the generally adopted strategy is to use liquid urea solution, instead of solid urea, and this is expected to continue as the urea infrastructure is introduced in the near future.

2.2.3 *NO_x Storage with Periodic Reduction*

There are two main NO_x storage catalysts currently under development, Lean NO_x Trap (LNT) and Four Way Catalyst (4WC).A 4WC is an LNT formulation coated on a Diesel Particulate Filter (DPF), to provide a one brick solution for NO_x and PM control.

LNT and 4WC work on the principle of storing NO_x under lean operation and periodically releasing and reducing the stored NO_x. The NO_x is removed by provision of a rich gas mixture, which subsequently reduces the NO_x. The rich gas mixture can be produced in three main ways, from in-cylinder means, exhaust fuel injection and by the application of a fuel reformer. Figure 1 shows the operation of LNT.

In-cylinder reductant formation uses a calibration, which changes the injection timing and quantity to produce a rich gas mixture from the combustion chamber. This can have an impact on engine durability, but produces a high quantity of CO, which is a better NO_x reductant than hydrocarbons.

Exhaust injection of fuel into the exhaust system is used to produce a rich gas mixture, which does not interact with the base engine calibration. In this case, neat fuel or partially combusted fuel is used as the reductant. Exhaust fuel injection has a low impact on engine durability but does not provide the optimum gas mixture for NO_x reduction.

The use of a fuel reformer with exhaust injection is being investigated as a way to provide an optimised reductant with minimal impact on base engine durability. The reformer utilises neat fuel and reforms it into CO and Hydrogen (H_2). CO and H_2 are excellent reductants for NO_x. Fuel reformer technology is in its infancy and development work is required to provide a production ready solution.

NO_x storage and reduction based catalysts give high NO_x conversion efficiencies (65-80%) depending on temperature. Low temperature NO_x storage is limited by NO_2 formation which occurs at ~200°C. The upper temperature limit is a function of the formulation but is in the range 400 – 500°C. NO_x storage and reduction catalysts are reversibly poisoned by fuel and oil sulphur. Any sulphur seen by the LNT will be stored and thus there will still be a need for removing the sulphates from the trap (so called DeSOx), even with low sulphur fuels and oils. Low sulphur fuels and oils enable the performance of the LNT to be extended and hence the period between DeSOx to be increased – thus minimising fuel consumption associated with DeSOx. Removal of sulphur requires high temperatures (~650°C) and rich conditions. However, high temperatures can thermally deactivate NO_x storage and reduction catalysts. LNT and 4WC have the major advantage that they require no external reductant supply, unlike SCR.

Durability data is scarce but there is evidence that recent LNT formulations are more durable than previously. However there are still serious concerns about the ability of LNT to maintain performance over the mileages required on Heavy-duty engines (equivalent to 500,000 km) even with low sulphur fuels.

In summary, LNT is seen as potentially a good technical solution for the lowest levels of Euro VI Scenarios, but the technology is not yet mature, and its impact on cost is impossible to estimate with any accuracy.

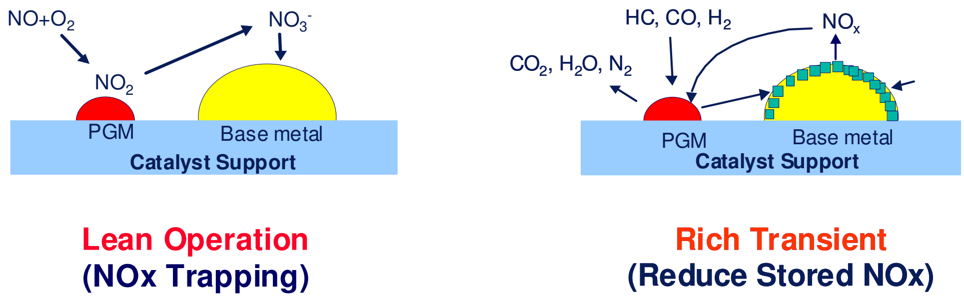

Figure 1. – LNT NO_x Storage and Reduction

2.2.4 *Particulate Filter Technologies*

Diesel Particulate Filters (DPF) have to-date been fitted to engines in certain Heavy-duty applications, mainly for retrofit rather than factory-fit. These have been full flow DPFs, in which case the full exhaust flow passes through the walls of the filter (referred to as closed DPF below).

For Euro IV and V, the first manufacturer to introduce filter technology was MAN, with their open type of metallic, non-blocking filters used on engines with cooled EGR.

2.2.4.1 *Closed DPFs*

The ceramic materials commonly used in DPFs are cordierite, silicon carbide and silicon nitride. The main advantage of ceramic wall flow filters is their high trapping efficiency for carbonaceous particles. The disadvantage is that blockage will occur unless the soot is burned off in the so-called ‘regeneration’ process.

For the ceramic wall flow filters, controlling regeneration can be assisted by the use of fuel borne catalysts, catalytic coating on the filter or an upstream diesel oxidation catalyst (DOC), combined with post-combustion fuel injection.

For Heavy-duty engines, soot regeneration is achieved by either catalytic coating or by upstream oxidation catalyst; fuel borne catalysts are not considered at this stage mainly due to concerns of ash build up in the filter.

Catalysed DPF (CDPF) consists of a ceramic filter coated with a catalytic wash coat. The catalyst wash coat generally contains platinum (Pt) as the precious metal. The catalytic coating reduces the combustion temperature of the soot. Due to the precious metal requirement of CDPF there is an associated cost increase. CDPF must be maintained, typically at annual intervals, due to the build up of ash from the lubricant in the filter.

A DOC followed by uncoated DPF (as in Johnson Matthey Continuously Regenerating Trap (CRT) applications) uses nitrogen dioxide (NO_2) for soot oxidation. The DOC oxidises nitrogen oxide (NO), which is the main constituent of NOx, to NO_2. NO_2 oxidises soot and is itself reduced to NO. Oxidation of soot with NO_2 can take place at usual exhaust gas temperatures but requires a high NO_2 to soot ratio. DOC-based DPF can lead to an increase in measured roadside NO_2 (not overall NO_x) concentrations and thus increase the chance of limit values being exceeded.

Sintered metal filters have high trapping efficiencies for both mass and number, like ceramic wall flow filters. Sintered metal filters can be formulated with catalyst-coating in a way to reduce the soot combustion temperature. Disadvantages are similar to wall flow ceramic filters: back pressure increases with soot accumulation, large volume requirements, packaging constraints and regeneration control.

2.2.4.2 *Open flow DPFs*

MAN has recently introduced open-flow metal filters for reducing PM on Euro IV engines with cooled EGR. The open-flow metal filters have lower soot trapping efficiencies than the wall-flow DPFs and PM number counts from open-flow filters may be several orders of magnitude higher than those from wall-flow DPFs. The advantage of the open-flow DPF is that it can operate with a lower back pressure, hence achieve potentially lower fuel consumption, and does not need regeneration.

2.2.4.3 *Ceramic Fibre, Ceramic Foam and Electrostatic Filter*

Other filter systems have been developed using fibres, foam and electrostatic devices, however, they are not expected to become mainstream PM removal technologies. They may be used on niche applications. Their filtration efficiencies are generally lower than wall flow filters for both mass and number.

2.2.4.4 *Particulate Filter Regeneration for wall-flow DFPs*

Soot accumulated on a closed DPF must be periodically removed as the restriction in flow rate and increase in back pressure will lead to significant performance degradation. Overload of soot in the filter can also lead to thermal degradation where uncontrolled soot combustion leads to excessive temperatures, damaging the substrate. Generally, combustion of the accumulated soot is achieved by raising the temperature of the gas stream to 400-550°C, depending on whether a catalytic coating is used. On Heavy-duty vehicles where exhaust temperatures are relatively low in urban driving, active regeneration strategies are required. Active regeneration must be optimised to maintain the integrity of the DPF, whilst minimising the fuel consumption penalty associated with the regeneration event. Active regeneration will require the use of pressure and temperature sensors to aid the understanding of soot loading, when to trigger regeneration and to monitor the regeneration event. The calibration challenge is a major issue to ensure that DPF regeneration can be achieved over the majority of the operating map, especially for vehicles used in low speed stop/start driving patterns and cold climates. Exhaust temperature increases are obtained through modified fuel injection strategies such as post injection late in the cycle. Post injection also increases unburned hydrocarbons, which can be oxidised in a pre-DPF catalyst creating an exotherm, further raising the exhaust temperature at the inlet to the DPF.

Post injection tends to increase lubricant dilution by fuel due to fuel spray impingement on the cylinder walls. An alternative under investigation is the use of an additional injector in the exhaust system, fuelled by diesel and operating at low pressure.

Concerns still exist regarding the durability of oxidation catalysts for HC/CO control when subjected to repeated exotherms during DPF regeneration. Similar durability issues may also be experienced by other NOx reduction technologies such as SCR systems if they are repeatedly exposed to the high temperature caused by HC based exotherms, in the case of the SCR being located downstream of a closed DPF.

Fuel consumption is generally increased by the closed DPF, due to increased exhaust back pressure and the need for regeneration.

2.3 NGV's

Natural Gas heavy duty vehicles (NGVs) became available in Europe after the establishment of the Enhanced Environmentally friendly Vehicles (EEVs) definition by regulation 1999/96/EC. NGVs were characterized by much lower PM emissions than equivalent technology diesel vehicles and could therefore benefit from lower taxation compared to diesels. This counterbalanced the additional cost associated with NGVs, which originated from the additional engine components (ignition system), the fuel bottles and the body reinforcement and the higher maintenance costs. For a diesel vehicle to meet the same environmental performance as the NGV, this would mean fitting a diesel particle filter (DPF) on the vehicle exhaust, which is again an extra cost element and suffers from reliability issues. NGVs are limited only to urban busses due to the need for dedicated NG fuel stations which are not widespread outside cities.
The new emission standards considered for Euro VI supersede the EEV emission standards, at least with regard to scenarios 2-5. In order to meet these new targets, new technological solutions need to be found for NGVs as well. This questions whether NGVs will therefore continue to be competitive against the diesel vehicles, taking into account the waiving of the taxation benefits and the higher fuel costs. The response to this question needs to take into account the two separate NGV technologies which are available today, i.e. the stoichiometric and the lean burn engine.

2.3.1 Stoichiometric operation

Stoichiometric engines operate similarly to common passenger car gasoline ones and benefit from very low emission levels especially compared to diesel engines (typically used for HD purposes). In principle, one might expect that all of the proposed scenarios for Euro VI may potentially be reached by stoichiometric engines with technologies which are more or less available today. These include a closed loop three way catalyst, oxygen sensors upstream and downstream of the catalyst (also used for OBD purposes) and a multipoint injection system. According to the position paper from ENGVA, an additional catalyst might be required to reach the particularly stringent NOx emission limits for scenarios 4/5. Scenario 6 is even more demanding but one should expect that engine tuning, precise air-to-fuel ratio control and EGR at particular engine modes will be sufficient to attain even these very stringent standards. Although there are no stoichiometric HD NGVs that can reach these targets today, based on the passenger car experience, one should expect that these are still feasible engineering targets with today's available technology. To put it on a different perspective, stoichiometric engines and three way catalysts should be in the position to reach as good or even better NOx levels as tuned diesel vehicles with SCR aftertreatment. Stoichiometric NGVs though show a poor fuel economy compared to diesel vehicles. They share the same technology (combustion efficiency) and maintenance schedules with gasoline vehicles and only benefit from the lower carbon content of CNG compared to diesel. This however gives similar green house gas emissions than diesel, but in general higher running costs. Moreover, NGVs require a dedicated fuel supply system and are even more expensive than diesel vehicles due to the reinforced fuel tanks carried. This makes stoichiometric NGVs a rather remote option for fleet operators today, which may only change if the increasing diesel prices favor natural gas as a fuel and if the cost and the complexity of advanced diesel aftertreatment systems make stoichiometric NGVs a cheaper to run and more reliable option.

2.3.2 *Lean-Burn operation*

The second technology available today is based on a full-range or part-range lean burn operation. Full-range lean burn means that the engine operates under lean mode over the entire engine map. Some systems have also appeared today which utilize stoichiometric operation at low loads to reduce emissions and lean mode at higher loads to improve efficiency (part-range lean mode). The benefit of lean mode is the higher combustion (fuel) efficiency, which approaches the diesel one, and therefore makes these vehicles a viable option for fleet operators (without neglecting of course the extra cost associated with the different fuel and the fuel ignition system). PM emissions also remain low – at a similar level to the stoichiometric NGV engine. The main issue with lean burn combustion is the high NOx emissions, due to the excess oxygen and the inability to reduce with a three-way catalyst. Hence, engine out NOx emissions compare to those of diesel vehicles (they are practically somewhat lower due to the lower compression ratio). In principle, this would mean that emission levels below 2 g/kWh will be difficult to attain without particular NOx aftertreatment – in principle SCR, utilizing urea. SCR can be implemented similarly to a diesel vehicle and can achieve low NOx emission levels, due to the lower engine-out levels and higher exhaust gas temperatures of the lean-burn NGV. Obviously, the particular issues that arise for diesel (ammonia slip, sulfur control, etc.) appear in the case of CNG as well and similar control measures will be required (ammonia slip guard catalyst). The low natural sulfur content of natural gas is also a benefit in this case.

Another technique which may be promising for NOx reduction from NGVs involves selective catalyst reduction using methane (instead of ammonia) as an agent. Such DeNOx systems are usually referred to as Lean NOx catalysts (see also diesel). In these systems, a special catalyst formulation is used which enables the reduction of nitrogen oxides with a hydrocarbon to produce carbon dioxide, nitrogen and water. Although this principle can be applied to diesel vehicles as well, NGVs have the additional benefits of relative abundance of methane in the exhaust gas and higher exhaust gas temperatures. Both conditions lead to a higher conversion efficiency, the former due to its known chemical structure and activity which enables a better tuning of the system and the latter just because the conversion is promoted as the temperature increases. Laboratory experiments [See Appendix A] have shown that over zeolite-based palladium catalysts NOx conversion efficiencies can reach 60-85% at temperatures normally encountered for lean-burn NGVs. Although this technique is still at an experimental level for NGVs at least, it is promising because it can achieve significant reductions without the need and the additional cost of the urea supply.

Finally, a technique which is mainly considered in US for post-2007 standards involves storage of NOx under lean conditions over an alkali adsorber and its desorption and reduction over rich conditions. The rich conditions are periodically produced with methane injected downstream of the engine outlet and upstream of the aftertreatment systems and last for 1-10s as opposed to 30-120 s for the lean mode. Park et al. [See Appendix B] achieved NOx emission levels in the order of 0.12 g/kWh using such a technique on a conventional lean burn engine operating under steady state conditions. Currently, this method is also associated with various issues though, such as its complexity and the number of separate catalyst stages required (oxidation, reforming, storage/reduction), its effect on fuel consumption due to the methane post-injection (effect 1-5%), the narrow temperature range for efficient NOx storage and good utilization of methane (325-550°C), the methane slip downstream of the aftertreatment system and its high sensitivity on sulfur poisoning (even at the trace levels currently found in natural gas). These conditions pose significant limitations to the commercial application of such a system, at least for the time being. Even when most of the issues are resolved, cost – due to the complexity and various catalyst systems - will remain a significant element though.

3 The 2004 (Euro IV) technology baseline

The starting point of the assessment made in this report is the technology baseline at the beginning of the Euro IV timeframe at the end of 2004.

Since Euro IV involves two principally different engine technologies: compression ignition (CI diesel)) and spark ignition (SI natural gas), the definition of the Euro IV baseline is split in two.

Based on the information received by the panel and knowledge available within the panel this technology baseline can be described as follows:

3.1 Euro IV baseline CI (Diesel):

This CI baseline proved to be not as well defined as could be foreseen in 2004 when setting out the questionnaire. When setting up the Euro IV limit values it was expected that the limit values would be met using Exhaust Gas Recirculation (EGR) in combination with a Diesel Particulate Filter (DPF). This solution however could be accompanied with a potential fuel economy deficit, increasing the running cost of the vehicles. Since Euro V, with an even more stringent NOx emission limit value, was already in view, some Heavy Duty vehicle manufacturers decided to go an alternative route for Euro IV. In view of the Euro V requirement the SCR DeNOx technology had been rapidly matured and gave good opportunities to meet Euro IV emission standards without fuel economy deficits.
This baseline therefore comprises two vehicle technology sets sold under the Euro IV legislation.

- ***The ‘EGR” route, with:***
  - Cooled EGR
  - Open flow DPF (without an oxidation catalyst)

- ***The “SCR” route, with:***
  - SCR DeNOx (with dosing unit and sensor suite)
  - Oxidation catalyst (still some uncertainty about necessity)

In both baseline options no major base engine modifications are required, nor significant recalibrations of the engine.

In the following the baseline technology scenarios for Euro IV are presented in a tabular format.

Table 1. Technology scenarios for CI base line Euro IV

SC 0 (Euro IV)	technology	cost baseline Euro IV-1	cost baseline Euro IV-2
Nox 3,5 PM 0,03	Cooled EGR		x
	DPF sensor suite		
	Ad-Blue dosing unit	x	
	Nox sensor suite	x	
	HPI		
	2 stage turbo		
	Enhanced cooled EGR		
	active DPF regeneration		
	Advanced AT control		
	DPF closed		
	DPF open		x
	SCR cat	x	
	LNT cat		
	Oxicat	x	
	slip cat		

3.2 Euro V baseline CI (Diesel)

Although the questionnaire stipulated Euro IV to be the baseline for the Euro VI assessment, at the moment the actual assessment of the Euro VI limit value setting will take place (2006) Euro V has become a well established technology suite by itself. In order to facilitate possible assessment work by the Commission in relation to Euro V, the panel developed a Euro V baseline as well. This baseline could however be developed for CI engines only (since for SI (NGV) vehicles the data supplied were not sufficient in detail to allow/justify a separate Euro V baseline).

As is the case for Euro IV, for Euro V there are in fact 2 possible main scenarios:

- ***The 'advanced EGR" route, with:***
  - Advanced cooled EGR
  - Open flow DPF (with an oxidation catalyst)

  For those manufacturers which are intending to use **EGR**, the change from Euro IV to Euro V will involve the increase in EGR from typically 15-18% EGR at full load to 22-25% EGR at full load. Slightly increased fuel injection pressures and open DPF with DOC upstream will be used to control PM. Increased charge air pressures will be adopted to give acceptable air/fuel ratios at full load. Increased heat rejection to coolant will require larger radiators and heat exchangers, which will tend to increase fuel consumption. It is likely that a pressure sensor, or differential pressure sensor, will be used to indicate that the filter is fitted in the DPF can, for OBD reasons (in order to avoid tampering).

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- ***The "SCR" route, with:***
  - SCR DeNOx (with dosing unit and sensor suite and increased volume and dosing rate compared to Euro IV)
  - Oxidation catalyst (still uncertainty about necessity)
  - NH_3 slip catalyst

  For manufacturers with **SCR**, the engine will be kept without major changes, and an improved catalyst and urea dosing unit will be mounted. A DPF is not required. In cases where a slip catalyst was not used at Euro IV, it is likely that a slip catalyst will need to be added for Euro V.

In the following, the baseline technology scenarios for Euro V are presented graphically. “low” and “high” options reflect two most feasible options to meet the emission limit values, with the “low” option achieving this at lower cost than the “high” option.

Table 2. Technology scenarios for CI Euro V

SC 1 (Euro V)	technology	low	high
Nox 2,0 PM 0,03	Cooled EGR		
	DPF sensor suite		**x**
	Ad-Blue dosing unit	**x**	
	Nox sensor suite	**x**	
	HPI		
	2 stage turbo		
	Enhanced cooled EGR		**x**
	active DPF regeneration		
	Advanced AT control		
	DPF closed		
	DPF open		**x**
	SCR	**x**	
	LNT		
	Oxicat	**x**	**x**
	slip cat	**x**	

3.3 Baseline SI (NGV):

For spark ignited Natural Gas Vehicles a distinction has to be made between stoichiometric technology and lean/stratified technology. A distinction into different swept volume classes was not possible (based on the limited amount of information supplied). Such a differentiation in fact is not really necessary because NG engines are used almost only in city distribution circumstances in which a typical 6 cylinder 9 litre 200-250 kW engine is a more or less common application. This type of engine has been used as a basis for the assessment of the panel.
In case of stoichiometric combustion, high efficiency, durable and sulphur insensitive, 3-way catalyst technology is applied successfully in high numbers for many years now. The lean/stratified technology has better fuel consumption and moderate engine out NOx emissions, leading to oxidation catalyst technology being sufficient for exhaust gas clean up, in scenarios with NOx limit values higher then 2 g/kWh. Appropriate lambda control however is needed for optimal lean combustion control.
Apart from stoichiometric and lean concepts, mixed concepts are used as well, involving a 3-way catalyst and wide range lambda control.

It must be noted however that Euro IV technology for NGV's during the last years was overshadowed by EEV (Environmentally Enhanced Vehicles) equivalent technology that was being brought on the market in increasing numbers (in order to profit from tax incentives for these NGV's on several markets). The 1999 EEV standard is equivalent to the – rather unambitious – Euro V limit value for NOx and slightly more stringent than Euro V for PM (but PM being not an issue for these NGV's). The challenge for NGV's in relation to EEV lies in the CH_4 limit value being almost twice as stringent as Euro IV and V. Using optimised fuelling and highly active catalyst technology, meeting EEV however proved possible.
However for the sake of the consistency with the rest of the Euro VI assessment the Euro IV baseline will be actually described in the following.

Based on the description above, the Euro IV baseline technology scenarios can be described as follows:

Stoichiometric:
- Multi point intake manifold fuel injection
- Closed loop, close coupled 3-way catalyst

Lean/stratified:
- Multi point intake manifold fuel injection
- Closed loop, 3 way catalyst for Stoichiometric_mode working in oxidation mode during lean operation (no NOx aftertreatment needed because of lean combustion)
- State of the art sensor technology (linear lambda sondes)

4 Technology maps for Euro VI scenarios

The process of assessing technology options and related costs for Euro VI Heavy Duty Vehicles is based on the eleven emission limit scenarios provided by the EC. There are six for CI engines and five for Natural Gas engines. The scenarios are graphically presented below:

Figure 2 . CI (Diesel) emission scenarios (Scenario 0 corresponds to Euro IV and scenario 1 to Euro V).

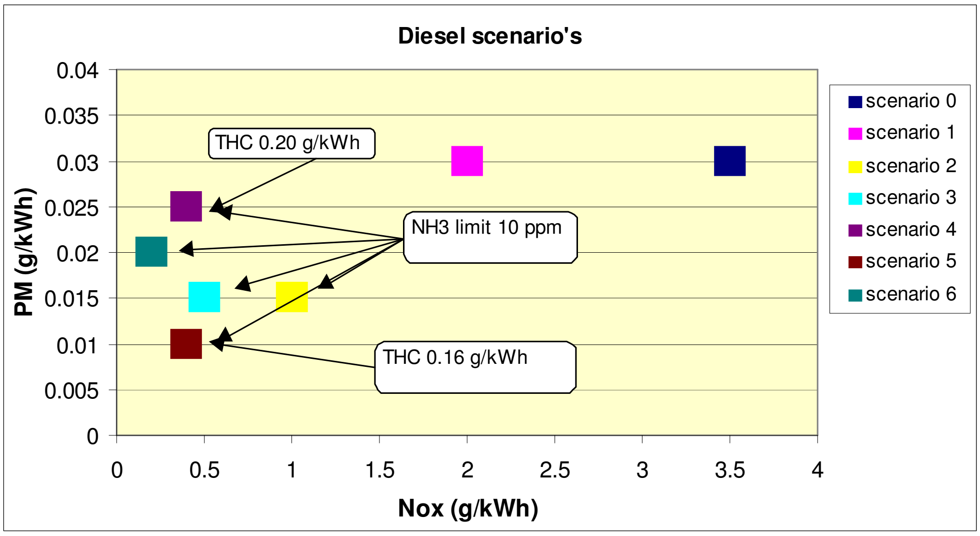
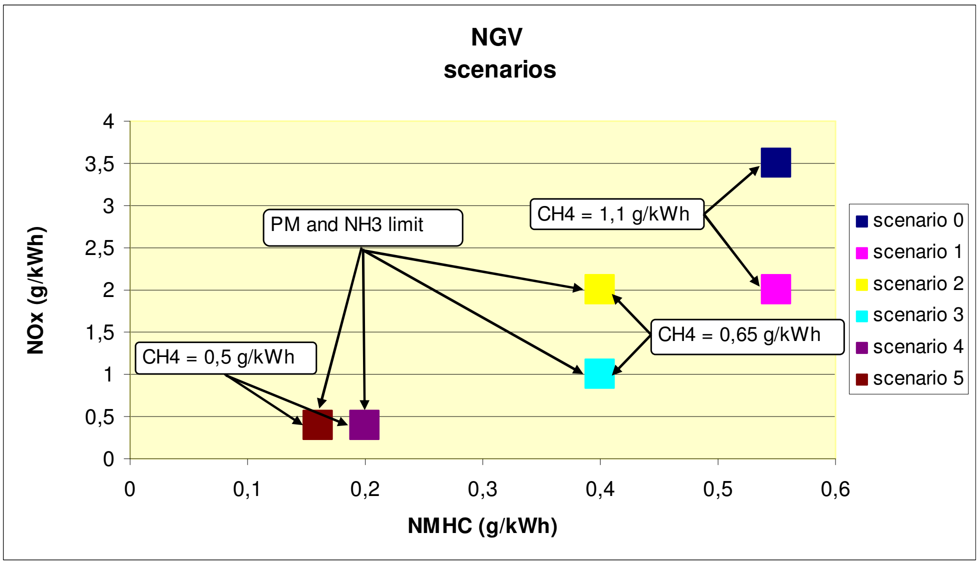


Figure 3. SI (NGV) emission scenarios (differences compared to Euro IV)



In order to comply with the different scenarios, some of the earlier mentioned technologies have to interact with each other. How this interaction will be brought into practice is very much dependent on the individual manufactures technology baseline and development strategies. Based on the information received from the stakeholders the panel has developed low and high interaction applications. The “low” can be applied in case of a sophisticated, low engine out emissions base engine. The “high” will have to be applied in case of a base engine that has limited potential to be upgraded further than Euro IV. “low” and “high” applications have been developed for each vehicle type and Euro VI scenario. The assumptions behind the technology application choices are presented in the following.

4.1 General approach

In order to be able to as correctly as possible assess the technologies that could be applied to live up to the Euro VI scenarios under investigation, the panel made a set of assumptions, which are:

- The technology combinations being used are dependent on the respective emission limit value setting. The swept volume of the engines is not taken into account in the way the technology combinations are set up. The swept volume is in fact an important parameter in relation to the combination of technologies that will enable meeting certain scenarios, but the information made available to the panel was insufficient in its level of detail in order to substantiate such distinctions. At the same time the vehicles classification used in the questionnaire (N 1-3 and M 1-3 for M<7,5, 7,5<M<16 and M>16 tonnes), leads to a large number of possible technology/vehicle combinations which can not be addressed in detail within the context of the panel’s work and the amount of detail in the input received.
- Based on the mentioned low level of detail of the input, but acknowledging the fact that the swept volume is an important parameter when designing an engine and its exhaust gas aftertreatment system, the component costs have been established by assuming that the component cost (aftertreatment and engine measures) was related to this swept volume. In order to best fit the vehicles/technologies that are sold on the market, the panel used a distinction between 6, 9 and 13 litres of swept volume. This categorisation can rather easily be linked to the vehicle categories (mentioned above) that are used in scenario models.
- The selected technology combinations are based on 13 litre engines. Smaller swept volumes in general may lead to other (less sophisticated) technology combinations, which implies that the costs for the case of 9 and 6 litre engines will be on the high end (worst case) of the scale. A further detailing of the technology combinations of the two lower swept volume classes is possible in principle, but would require a much more detailed set of input information from the stakeholders. Therefore the panel chose not to differentiate the technology scenarios between the different swept volume classes, since this in their opinion would lead to a false sense of accuracy that is not supported by the available data. Engine internal measures will play an important role in achieving Euro VI emission levels, but will in almost no case be sufficient to reach the Euro VI limit proposal in the different scenarios. Therefore in most cases additional aftertreatment measures will have to be taken. Thus a combination of both engine internal measures and after treatment will be used by the industry. The required effectiveness of each type of measure in reducing pollutants is highly dependent on the base engine used and on the balance a company uses between engine measures and aftertreatment. Therefore the companies’ typical development strategies (past and future) will in the end possibly lead to different

technical solutions. In order to deal with this issue, the high and low applications chosen by the panel reflect probable combinations of engine measures and after treatment.

- For every selected category a high and a low technology package has been established. “high” and “low” reflect the level of sophistication of technologies used and the costs related to this level. This distinction has been made to reflect the effect of the differences in base engine (Euro IV), development status and philosophies to reduce emission between the different manufacturers. It is assumed that both technology packages will in the end be equivalent in emissions and meeting the emission legislation scenario.
- The chosen technology scenarios are set up with (as far as possible) fuel neutrality compared to the baseline in mind. This approach was chosen by the stakeholders (ACEA), because of the fact that in their view the market demands low emissions being accompanied with lowest fuel consumption. Therefore the only realistic technology scenarios are those that incorporate low emissions and lowest fuel consumption.
- No additional technical-or cost application has been added for N1 class 2, vehicles because these vehicles are in fact not HDV, but very large passenger cars, with passenger car like technology. The additional costs can be established by using the M1 > 2 l large class from the M1 Euro 5 report.
- The high and low technology packages are built up based on 2 basic items:
  - **Engine internal measures** (further optimisation of mostly existing technology like EGR, turbo charging, valve timing, injection timing-and pressure)
  - **Aftertreatment measures** (adding additional components like a NOx-or PM trap, or optimised catalysts)

In addition to these main assumptions, additional assumptions have been made typically for CI (Diesel) or SI (NGV) technology.

4.2 Compression Ignition (CI) engine assumptions

For taking CI (compression ignition) engines from Euro IV towards Euro VI, emissions of NOx and PM have to be reduced and NH_3 emissions have to be kept low. Especially the reduction of the NOx emissions is a challenge for the industry, since further NOx emissions reduction (using engine measures) is counter productive with low fuel consumption, one of the main market drivers for HD vehicles. In this light the industry stressed that the technology choices that would be actually made, would be dictated by meeting Euro VI emission limit values, without (as far as possible) sacrificing Euro IV fuel consumption achievements, and that these fuel consumption achievements were the main reason why Euro V vehicles equipped with SCR-DeNOx were on the market in 2006.

Taking into account all information received by the panel, the following basic assumptions towards technology pathways were made:

- In the case of aftertreatment devices, scaling in relation to engine swept volume is applied based on commonly known (and specified by AECC) parameters. Scaling of engine measures is much more difficult, since every hardware part has a basic price almost independent of its size (offset) but will become more expensive with increasing size (this size being related to the swept volume again). The panel tried to cope with this sizing/costing issue by using a fixed base size/cost and linearly increasing the cost for bigger swept volumes on top of this base cost. The panel acknowledges that this approach is not very sophisticated, but because of lacking detailed input from the stakeholders, no more detailing was possible.

- One of the basic principles that drives the technologies used towards Euro VI is the trade-off between engine out PM and NOx. This trade-off enables manufacturers to choose between engine out emission optimisation for one component and aftertreatment for the other (or both). The driving forces behind the choices made are: fuel consumption, durability and production cost. The technology scenarios used by the panel reflect choices to be made taking into account the three main driving forces mentioned. The following main assumptions have been used while setting up technology combinations:
  - At a NOx limit value (ETC) below 0.5 g/kWh DeNOx aftertreatment will be inevitable.
  - At a PM limit value (ETC) below 0.02 g/kWh a PM trap will be inevitable
  - At PM limit values (ETC) above 0.02 g/kWh PM traps can be used in order to be able to optimize the engine out NOx emissions (and thereby fuel economy). In these cases (dependent on the strategy followed) it is the assumption of the panel that, because of their easier integration into the total emission control concept and possible lower fuel consumption penalty, the open flow filters could have a significant market share under Euro VI.
  - In order to improve the efficiency of the exhaust gas aftertreatment oxidation catalysts can be added
  - Using advanced cooled EGR will in principle enable meeting 0.5 g/kWh NOx levels (in combination with DPF) but at the cost of significantly increased fuel consumption.
  - Driven by the low limit values of most Euro VI scenarios, NOx after treatment will be applied. In principle NOx after treatment for HD engines is available as SCR (Selective Catalytic Reduction using urea). LNT (Lean NOx Trap) shows promising developments (LD) at this moment but for Heavy Duty has not proven to be a mature solution at this moment. Successful SCR implementation on the other hand is largely dependent on the availability of some kind of urea (liquid or solid) supply infrastructure. This problem has been largely solved with the introduction of Euro IV SCR trucks. The panel's choice has been to use SCR DeNOx for the assessment, since applicability and cost for (serial production) of LNT are not known at this moment.
  - A large variety of the efficiency of SCR DeNOx systems is possible by changing the reactor volume and/or the accuracy of the reactant dosing system.
  - Highest SCR DeNOx efficiencies (involving close to stochiometric reactant dosing) can lead to a NH_3 slip in dynamic load situations. This leads to the inevitability of an additional catalyst having to be mounted in order to reduce NH_3 emissions.
  - For lower emission limit values than 0.5 g/kWh NOx a fuel consumption penalty (compared to Euro IV) is almost inevitable. Above this limit value a fuel consumption penalty can (and will) be avoided by making certain technology choices. These choices which the industry will make (in order to preserve their market position) are taken into account in the panel's technology choices as well.

Based on these assumptions the following five actual technology applications have been linked to the EC's limit value scenarios.

Scenario 2

For those manufacturers which are intending to use **EGR**, the change from Euro IV to Euro VI will involve the further increase in EGR from 15 – 18% to over 25% at full load. Further increases in fuel injection pressures and closed DPF with DOC upstream will be used to control PM. Increased charge air pressures will be adopted to give acceptable air/fuel ratios at full load. Increased heat rejection to coolant will require larger radiators and heat exchangers, which will tend to increase fuel consumption. A DPF regeneration system will be introduced, with additional temperature sensors, and changes to the fuel injection calibration or the use of an exhaust mounted fuel injector.

For manufacturers with **SCR**, the engine will be kept without major changes, and the urea dosing strategy will be revised. A DPF will be needed upstream of the SCR, most likely of the wall-flow type, with regeneration system.

Scenario 3

At this stage it seems unlikely that Scenario 3 NOx levels can be achieved with cooled **EGR** in the time available, although further developments in combustion research combined with advanced High Pressure Injection systems may show that it is possible. There would be very serious effects on fuel consumption and CO_2 emissions due to the high levels of EGR required.

The alternative strategy to use **SCR** plus wall-flow DPF would appear to be more feasible, although it may be necessary to adopt some cooled EGR to achieve the NOx targets.

Scenario 4

To achieve the Scenario 4 NOx limit will require both highly cooled **EGR and SCR**. Together with advanced developments of the combustion system, fuel injection and turbocharging technology, it seems feasible to meet the PM limit with a DOC or an open DPF. Fuel consumption is likely to increase compared with the Euro IV baseline.

Scenario 5

To achieve the Scenario 5 NOx limit will require both cooled **EGR and SCR**. Together with an advanced development of the combustion system, fuel injection and turbocharging technology, it seems feasible to meet the PM limit with either an open-flow DPF or a wall-flow DPF. Fuel consumption is likely to increase compared to the Euro IV baseline, especially in the case of a wall-flow DPF.

Scenario 6

To achieve the Scenario 6 NOx limit will require both cooled **EGR and SCR**. At this NOx level, a wall-flow DPF will be needed to meet the PM limit value. Fuel consumption is likely to increase significantly compared with the Euro IV baseline.

The above presented five actual technology pathways for Euro VI are presented graphically below. The “low” and “high” options reflect the two most feasible options to meet the emission limit values, with the “low” option achieving this at lower cost than the “high” option. In one case (scenario 6) there is only one technology set up that is foreseen to meet the limit values.

Table 3. Technology scenarios for CI Euro VI

SC 2	technology	low	high
Nox 1,0	Cooled EGR		
PM 0,015	DPF sensor suite	x	x
	Ad-Blue dosing unit		x
	Nox sensor suite		x
	HPI		
	2 stage turbo		
	Enhanced cooled EGR	x	
	active DPF regeneration	x	x
	Advanced AT control	x	x
	DPF closed	x	x
	DPF open		
	SCR		x
	LNT		
	Oxicat	x	x
	slip cat		x
		v	v
SC 3	technology	low	high
Nox 0,5	Cooled EGR		
PM 0,015	DPF sensor suite	x	x
	Ad-Blue dosing unit		x
	Nox sensor suite		x
	HPI	x	
	2 stage turbo		
	Enhanced cooled EGR	x	
	active DPF regeneration	x	x
	Advanced AT control	x	x
	DPF closed	x	x
	DPF open		
	SCR		x
	LNT		
	Oxicat	x	x
	slip cat		x
		v	v
SC 4 (NRMM st IV)	technology	low	high
Nox 0,4	Cooled EGR		
PM 0,025	DPF sensor suite		x
	Ad-Blue dosing unit	x	x
	Nox sensor suite	x	x
	HPI	x	x
	2 stage turbo	x	x
	Enhanced cooled EGR	x	x
	active DPF regeneration		
	Advanced AT control	x	x
	DPF closed		
	DPF open		x
	SCR	x	x
	LNT		
	Oxicat	x	x
	slip cat	x	x
		v	v
SC 5	technology	low	high
Nox 0,4	Cooled EGR		
PM 0.01	DPF sensor suite		x
	Ad-Blue dosing unit	x	x
	Nox sensor suite		
	HPI	x	x
	2 stage turbo	x	x
	Enhanced cooled EGR	x	x
	active DPF regeneration	x	x
	Advanced AT control	x	x
	DPF closed		x
	DPF open	x	
	SCR	x	x
	LNT		
	Oxicat	x	x
	slip cat	x	x
		v	v
SC 6	technology	low	high
Nox 0,2	Cooled EGR		
PM 0,02	DPF sensor suite	x	x
	Ad-Blue dosing unit	x	x
	Nox sensor suite	x	x
	HPI	x	x
	2 stage turbo	x	x
	Enhanced cooled EGR	x	x
	active DPF regeneration	x	x
	Advanced AT control	x	x
	DPF closed	x	x
	DPF open		
	SCR	x	x
	LNT		
	Oxicat	x	x
	slip cat	x	x

4.3 Spark Ignition (NGV) engine assumptions

For taking SI (NGV) engines from Euro IV toward Euro VI, mainly the emissions of NOx and HC (as CH_4) have to be reduced without increasing PM and NH_3 emissions. Furthermore the manufacturer will have to find the right balance between low emissions and low fuel consumption. Stoichiometric engines (using TWC technology) offer good opportunities to build low emitting engines, but (compared to lean burn engines) at the cost of lower fuel economy. Building highly fuel economic and clean lean burn engines involves the application of sophisticated technologies (like SCR-DeNOx). As both possible technology routes can meet Euro VI emission limit settings, they are discussed separately.

Different than for CI engines, scenario 1 (Euro V) is not really a practical scenario for SI engines (NGV). With the EEV standard being in use already during the Euro IV legislative period, NGV engines have been developed to meet this EVV standard and create a market advantage (via tax incentives) for the NGV engines. Because of this development route, Euro V engines (not as clean as EEV) are not actually on the market and it is expected that they will not come on the market during the Euro V period. Because of the (market) development, scenario 1 (Euro V) is not taken into account in the elaborations.

Taking into account the limited information received by the panel, the following basic assumptions towards technology applications were made:

4.3.1 SI stoichiometric concepts

The following assumptions toward technology applications for Euro VI SI stoichiometric concepts were made:

- The reduction of particulate matter for stoichiometric concepts is not necessary, since data from current Euro III and IV vehicles show levels below 0.01 g/kWh and engine technology will not change in a manner that will affect PM emissions. This leads to no actions on this point under Euro VI, except for constant attention for low lubricant oil consumption.
- Lw and high technology applications have been established in which “low” being purely optimisation of the catalyst efficiency, without any change in the engine control and its calibration. The “high” application would be a combination of optimised catalyst efficiency and further sophistication of the Euro 4 combustion control (and air management)
- Lowering NO_x and HC emissions by using catalyst technology only is achieved by increasing the activity of the catalyst by increasing the relative precious metal loading (with fixed total catalyst volume, but via an increase in cell density if required) in relation to the base case (Euro IV).
- Lowering NO_x and HC emissions via sophistication/optimisation of the engine is achieved by means of improved injection quality (atomisation and timing), variable valve timing and improved lambda/fuelling control (with linear lambda sondes).
- Reducing CH_4 emissions is and will be a challenge, since CH_4 emission reduction with current catalyst technology is rather ineffective (compared to other components) and will lead to high catalyst volumes in combination with exhaust gas heat management.

4.3.2 *SI lean concepts*

The following assumptions toward technology applications for Euro VI SI lean concepts were made:

- A reduction of particulate matter emissions for lean concepts is not necessary, since data from current Euro III and IV vehicles show levels below 0.01 g/kWh and engine technology will not change in a manner that will affect PM emissions. This leads to no actions on this point under Euro VI, except for constant attention for low lubricant oil consumption.
- At NOx emission limit values (ETC) below 2 g/kWh, SCR DeNOx will have to be applied. Dependent on the actual emission limit value setting more advanced SCR control will have to be applied.
- Lean NOx Trapping (LNT) may be used in the future (as for LD purposes some systems are already on the market), but the technology is not sufficiently mature to be taken on board in the panels assessment. Nor durability (under HD conditions) nor cost can be estimated correctly at this moment. Therefore only SCR DeNOx is used in the technology scenarios.
- low and high technology applications have been established in which "low" is optimisation of the lean combustion concept in combination with SCR DeNOx. and improved CH_4 reduction. The "high" technology applications have been established by further optimisation of the combustion and SCR DeNOx control. This engine optimisation would include optimised air management.

Based on these assumptions the following technology applications have been linked to the EC's limit value scenarios for NGV lambda 1 and lean SI engines.

Table 4. SI NGV technology scenarios

Technology scenarios for CNG 6 cyl 9 l engine	**Stoichiometric**				**lean burn**			
	scenario 2	**scenario 3**	**scenario 4**	**scenario 5**	**scenario 2**	**scenario 3**	**scenario 4**	**scenario 5**
CO (g/kWh)	3,0	3,0	4,0	4,0	3,0	3,0	4,0	4,0
NMHC (g/kWh)	0,40	0,40	0,20	0,16	0,40	0,40	0,20	0,16
CH_4 (g/kWh)	0,65	0,65	0,50	0,50	0,65	0,65	0,50	0,50
NO_x (g/kWh)	2,0	1,0	0,4	0,4	2,0	1,0	0,4	0,4
NH_3 (ppm)	10	10	10	10	10	10	10	10
PM (g/kWh)	0,02	0,01	0,02	0,01	0,02	0,01	0,02	0,01
Additional technolgies per engine compared to Euro IV								
Additional cost for optimised multipoint injection fuel system	x	x	x	x				
Pre-cat UEGO	o	o	o	o	x	x	x	x
Improved CNG stochiometric catalytic converter 0,65 g/kWh CH_4	x	x						
Improved CNG stochiometric catalytic converter 0,50 g/kWh CH_4			x	x				
second downstream stochiometric catalyst w/control system			o	o				
Lean-burn closed loop lambda control					x	x	x	x
Inlet manifold optimisation	o	o	x	x	o	o	x	x
Standard SCR system (dosage system + catalyst)					o	x	x	x
SCR improved control system						x	x	x
No_x sensor					o	o	o	o
	x = low technology level, x+o is high technology level							

5 Additional topics

This chapter is not strictly speaking necessary for the completion of Task 2, the validation of the stakeholder responses to the HDV questionnaire. However, the panel feels that the topics addressed below need to be kept in mind when interpreting the results obtained and when using them for the preparation of new emission limit values. This input can be seen as part of the work under task 3 (general information requested by the EC) of the contract.

5.1 Effects on CO_2 emissions of the discussed Euro VI emission standards

The response to the questionnaire included statements on fuel consumption (CO_2 emission) neutrality for CI scenarios 1 and 2. For scenario 3 an inevitable fuel consumption increases by 1-1,5 % were predicted and for scenarios 4,5 and 6 a further increase in fuel consumption by 3 to 5 % was predicted. These statements were based on the fact that the automotive industry feels that running cost are so important for their customers that despite of whatever limit value setting is applied they will do everything technically possible to achieve fuel neutrality compared to the baseline.

In line with this position the answers from the industry in relation to technology scenarios implicitly contained fuel consumption reduction measures.

5.2 Influence of the test procedure

The evaluation of the panel is based on a questionnaire set up which had the Euro IV test procedure as a baseline. Therefore all information was based on ETC testing only. However meanwhile relevant changes in the test procedure are foreseen in order to improve the effectiveness of the post Euro IV legislation. Items like Not To Exceed limits approach (NTE), the introduction of the WHDC (World Heavy Duty Test Cycle) and advanced OBD are the most important developments and will therefore be addressed next in the context of the effects of such legislation on the technology scenarios (and related cost) for Euro VI regulations.

5.2.1 *Background of the Not-To-Exceed limits approach*

In an attempt to limit pollutant emissions from heavy duty engines under real-world operating conditions, the off-cycle emissions (OCE), i.e. emissions occurring outside of the operating conditions corresponding to the legislated test cycles need to be considered. The Not-To-Exceed (NTE) limits have already been introduced in the US legislation as an additional instrument to make sure that heavy-duty engine emissions are controlled over the full range of speed and load combinations commonly experienced in use. The NTE approach establishes an area (the “NTE zone”) under the torque curve of an engine, where emissions must not exceed a specified value for any of the regulated pollutants. The NTE test procedure does not involve a specific driving cycle of any specific length (mileage or time). Rather it involves driving of any type that could occur within the bounds of the NTE control area, including operation under steady-state or transient conditions and under varying ambient conditions. Emissions are averaged over a minimum time of thirty seconds and then compared to the applicable NTE emission limits. A proposal for a Global Technical Regulation (GTR) recently issued by the OCE working group of the International Association of Motor

Vehicles Manufacturers (OICA), proposes NTE emission limits expressed as a proportional increase of the respective legislated cycle limits [See Appendix B]. Both the current US legislation, and the proposed GTR by OICA adopt the NTE procedure as a supplement to the standard certification procedure using test cycles.

5.2.2 *WHDC*

The type approval for new HD diesel engines up and until the Euro 3 certification level was based on a steady-state test. Back in 1994, the FIGE institute developed the European Transient Cycle (ETC), as a dynamic test cycle which would more reflect the varying engine load conditions encountered during normal operation. The 1999/96/EC directive incorporated this ETC test in the type approval procedure, to become effective as of the Euro 4 certification level (2005/2006). In the questionnaire, Euro 4 technology was used as a baseline, and consequently all scenarios for Euro 6 are based on this test cycle.

Towards the end of the nineties the need for global harmonisation of emission legislation was recognised. This led to the development of a world-wide ‘average’ driving cycle by TNO and RWTÜV: the World Harmonised Transient Cycle (WHTC) [a]. Together with the WHSC steady-state test, these cycles are proposed to be introduced in the regulatory framework for the Euro 6 certification level.

The basic difference between the ETC and WHTC lies in the development of these test cycles. While the ETC was based on a limited amount of (European) real world driving data, the WHTC approach started off by collecting all available data across the globe. Also the statistic procedure used to develop a representative driving cycle from a large database was more robust. In general, the WHTC can be seen as the cycle which better represents real-world driving behaviour, albeit a world-wide average, not a European average. In comparison, the average engine speed and power of the ETC are higher. At the same time, the engine load points are more well-spread in the WHTC, while they are rather concentrated at one engine speed for the ETC (near the ‘B’ speed of the ESC).

The emission values measured over a test cycle strongly depend on the characteristics of this cycle. As a result of the engine design and the manufacturer’s calibration, each point of the engine map has its own specific emission value. The cycle test result will therefore be determined by the engine map points covered over the cycle, the frequency in which they occur, and the speed of moving from the one to the other point. In effect, a limit value in the emission legislation can not be seen separately from the type approval test cycle. Due to the different characteristics of the WHTC and the ETC, the emission limit values for Euro 6 based on the WHTC would have to be reconsidered. This could be done by a validation programme of sufficient scale, with engines that have been recalibrated by the manufacturer.

It also has to be stressed here that a test cycle which focuses strongly on a limited area of the engine map or is not representative for real-life driving conditions poses the threat of a possible mismatch between the limit value and the real-life emissions. The manufacturer mainly has to optimise his calibration for the limited area, and has no incentive to bring down emissions in the less frequently operated areas. This may be illustrated by the fact that the downward trend in limit values over the consecutive certification levels have not always been followed by the emissions on the road. From Euro 1 to 2, the trend for real-life NO_x emissions was even opposite to the drop in limit

value. The issue mentioned here can be largely prevented by a solid NTE procedure for off-cycle emissions (see paragraph 5.2.1).
The potential introduction of the WHDC could influence the selection of technology combinations. The World Harmonised Transient Test Cycle (WHTC) starts from a cold engine (unlike the ETC) and has a lower load factor than the current European test cycles. This means that the engine's exhaust temperature during the first part of the WHTC are considerably lower than in the ETC. As a result, the reductant (urea) in the SCR system can not be injected in this early part of the cycle, until the exhaust temperature has risen above 180°C at the entry of the SCR catalyst, otherwise there will be a risk of ammonia slippage through the SCR catalyst. The effect of this is mitigated to some extent by the calculation of cycle emissions which is based largely on the hot cycle and to a lesser extent on the cold cycle. However the introduction of cold test cycles may lead to new technologies such as exhaust temperature management, which could have a detrimental effect on fuel economy. The technology of managing exhaust temperatures throughout the exhaust system is at an early stage of development. On-Board Diagnostics (OBD) system calibration will have to be adjusted in line with this system optimisation (see 5.2.3).

5.2.3 OBD

The On-Board Diagnostics (OBD) system was introduced to provide a tool to reduce air pollution, by monitoring the performance of all emissions related components, and notifying the user, when a malfunction is present, which may cause pollutant emissions to increase above specific levels, referred to as OBD thresholds. The current requirements for heavy duty diesel engines include monitoring of the following components, where applicable: catalytic converter, DeNOx system, particulate trap, fuel-injection system, combined DeNOx-particulate filter system, and any other components, the failure of which may result in emissions exceeding the thresholds. The California Air Resources Board (CARB) standards explicitly also include misfire, EGR system and fuel system monitoring. A comprehensive description of the technology of OBD systems for heavy duty engines can be found in an earlier report by the University of Graz [2]. Updates on the recent developments and future requirements of heavy-duty OBD in California were presented in a recent workshop by CARB [3].
The OBD thresholds are determined on the basis of the legislated test cycle. This means, that the OBD system should monitor the above mentioned components, and detect a malfunction, which corresponds to a particular emission level at the legislated test cycle. This poses several challenges for the calibration of the OBD system. In order to clarify these challenges, the failures, which should be detected by the OBD system, should be divided in two categories:

- Failures not related to OBD system calibration. This category mainly includes electrical failures, such as disconnection or breaking of wires, short circuits to ground or to other wires. These failures generate a clear monitoring result, and will be detected by any properly functioning OBD system, despite the fact that some of them may not cause emissions to increase above the OBD thresholds.

- Failures related to OBD system calibration. This category mainly includes failures that cause the emissions to increase steadily. For most of these failures, the OBD system relies on indirect assessments of the performance of the monitored components. For example, there is no primary physical effect to assess the emissions increase caused by a destroyed particulate filter. Instead, the OBD system determines the performance of the filter by measuring a secondary physical effect, the pressure drop along the filter. In order for the OBD system to identify a failure, the system must recognise a deviation of such secondary sensed parameters. This will cause the OBD system to compare this deviation with its stored information and generate a response that can be correlated to an increase of the emissions during the legislated test cycle. The OBD system is calibrated to turn the Malfunction Indicator (MI) on, when the deviation of the secondary monitored parameters reaches a predefined level, called calibration point. However, the correlation between sensed parameters and emissions in the test cycle may be weak, due to restrictions of the monitoring technology, as well as due to the variability of the ambient and operating conditions, under which the OBD system is required to perform diagnosis. Therefore, the calibration point does not correspond to a well defined emission level, but rather to a band of emission levels, as shown in fig 4.

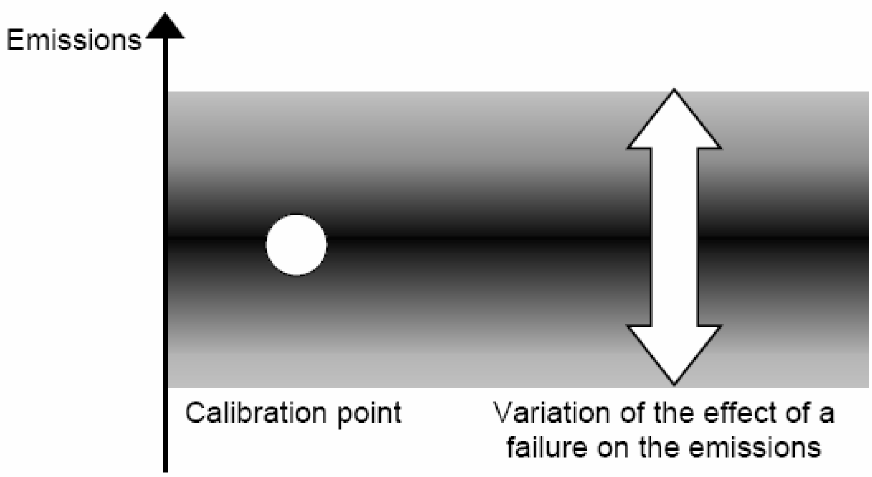


Fig.4. Correlation between OBD failure indication and the effect of a failure on the emissions

5.2.4 *Implication of an NTE limits approach on OBD system performance and calibration*

From the above discussion of OBD system calibration, we may deduce that for the first type of failures, the adoption of the NTE limits approach in the legislation has no effect on the OBD system, since these failures will be detected by any properly functioning system. As a result, the possible implications of an NTE limits approach on OBD, will involve the detection of second category of failures only.

The investigation of these implications, needs to account for two alternative approaches for the establishment of future OBD thresholds. These are discussed below.

In the first approach, the OBD thresholds continue to be expressed as emission limits referring to the legislated test cycle. This is the current approach adopted both in the European, federal US and California legislation, which assumes that the OBD system will still be required to detect malfunctions that will cause the test cycle emissions to increase over a specific threshold. In this approach, the requirements for OBD calibration are the ones described in the previous section. The adoption of NTE procedure as a supplementary procedure for type approval does not affect the calibration and operation of the OBD system. The main weakness of this approach is that the manufacturer is only required to demonstrate that the OBD system is efficiently monitoring the status of the various components on-cycle. The OBD system therefore monitors the performance of the various components under defined operating and ambient conditions. This is necessary, in order to achieve a sufficient correlation

between the secondary parameters monitored by the OBD system, and the emissions during the test cycle. However, this may result in infrequent monitoring, when the engine operates under real-world operating conditions, thus limiting the environmental benefit of the OBD system. In order to address this issue, CARB recently required from the manufacturers to include and store an index of how frequently each OBD monitor runs in the ECU, although a minimum value of this index will not be added as a requirement in the legislation soon.
In the second possible approach, the OBD thresholds are expressed as NTE limits themselves. According to this approach, the OBD system would be required to identify a malfunction when the pollutant emissions increased over a defined threshold under any operating condition inside the NTE zone. Under this approach, both the on- and off-cycle performance of the emission related components is monitored, which may result in an increased environmental benefit. However, such an approach is not feasible with the current monitoring technology, which relies on indirect assessment of the performance of the monitored components and systems. The correlation of the monitored parameters with the actual performance of each system is in many cases too weak to allow monitoring under a wide range of operating and ambient conditions. In order to monitor the performance of the emissions related components both on- and off-cycle, accurate and reliable On-Board Measurement (OBM) technologies will need to be developed. This would enable the OBD system to monitor directly the real-world emissions of the engine, rather than monitoring secondary physical parameters, and correlating them with emission levels at the test cycle. Regarding the current status of the required OBM technology, NO_x sensors are currently in the early stages of commercialization, and will probably be used for heavy duty OBD applications in the near future anyway. Soot sensors are only available as laboratory devices though, and little or no knowledge exists over their possible future application for OBD. Moreover, the technical feasibility and cost-effectiveness of such an approach are two issues that will need to be further studied in depth.

5.2.5 *New Metric PM measurements*

Because of the insight that particles are increasingly health threatening with decreasing size, lately much attention is paid to regulating particle size and number (in addition to mass only). The problem with regulating the size and number count of particulate emissions has been the availability of an adequate measurement procedure. This problem seems to be solvable as is proven during the execution of the Particulate Measurement Programme (PMP) conducted under the auspices of the UN-ECE. Being almost completely finished, (the final phase of the project, related to the HDE Round-robin is starting at the time this report is being completed), PMP provides a solid basis for introducing particulate size and number count to European mass emission regulations. This could lead to the introduction of such regulation in combination with Euro VI.

If a particulate number count limitation would become part of the Euro VI legislation procedure, this could have severe consequences for the technology combinations that would be able to live up to the Euro VI legislation. It is currently unclear what the possible limit values for solid particle number emissions might be, but they could be set in order to rule out open flow filters or to enforce efficient wall-flow DPFs. In the latter case, the technology combinations mentioned previously will be restricted to those with appropriate wall-flow filters.

5.3 Direct NO_2 emissions

Although emission of total oxides of nitrogen (NO_X) will drop considerably under pressure of Euro legislation, they remain problematic in relation to road transport, with ambient concentrations of nitrogen dioxide (NO_2) near many main roads being close to or even exceeding the limit values set for the European Union for 2010. The level of NO2 present in the exhaust gas of vehicles is an important issue in relation to road side NO2 levels (NOx not being regulated in the ambient air)

Some exhaust gas aftertreatment technologies appear to increase the relative amount of NO_2 in the total of NOx emissions. Particular suspicion was drawn to the relatively high primary NO_2 emissions associated with oxidation catalysts fitted to diesel passenger cars and certain types of regenerative particulate traps, fitted to HGVs and buses.

Several independent investigations during the last 3 years reported indications that the fraction of NO_2 in the direct tail-pipe emissions of current on-road vehicles was significantly higher than generally thought and accepted. Data on direct NO_2 emissions and their fraction in the NO_x emission was gathered from different emission measurement programs. This data was reviewed with respect to the accuracy, the reliability and the level of the data presented in these studies. This resulted in the following findings:

Available data show a substantial influence of the measurement method on the measured direct NO_2 emissions. The equilibrium of NO and NO_2 is very delicate and can easily be disturbed by several conditions in the measurement process.

Considering the above, new dedicated measuring procedures have been defined which should be suitable for the assessment of the current direct NO_2 exhaust gas situation (focusing on the severe impact of diesel vehicles). This procedure comprises the determination of the NO_2 mass emission by means of *simultaneous* analysis of the NO and NOx concentration (NO_2 is the result of subtraction of NO from NOx) from the *raw* (undiluted) exhaust gas, over direct, on-line sampling at the tailpipe exit. For the gas analysis an instrument using the *chemiluminescence* principle was proposed
For this principle of analysis, however, problems regarding ammonia interference should be considered as in the near future SCR-DeNOx systems will probably gain importance in emission inventories. When the suggested procedure is considered for future research into the NO_2 situation and maybe even for adaptation in a type approval system, further research should focus on possible effects of ammonia on the measured level of NO_2. For establishing the 2006 situation however the above mentioned measuring method can be seen as fully sufficient.

The main reason for the increased attention towards direct NO_2 emissions lies in the fact that active oxidation catalysts coated with platinum are a prominent source of elevated NO_2 emissions, as in this type of catalyst the conversion of NO to NO_2 is promoted by the strong oxidizing environment. An oxidation catalyst is used on most modern diesel passenger cars and on some trucks, for the latter only in combination with a continuously regenerating filter. In addition to the main reason for its application (oxidation of CO, HC and the volatile organic fraction of PM) the property of an oxidation catalyst to produce NO_2 is exploited in some exhaust gas aftertreatment systems such as diesel particle filters. In these systems the oxidation catalyst is placed before the actual PM trap in order to provide excess NO_2 and thus to enable the effective lower-temperature oxidation of the trapped particles. If not carefully designed, such an arrangement allows a major part of this NO_2 to exit the tail pipe as only a certain amount is used in the process.

The results from the emission measurement programmes executed recently underline the importance of the discussion above. It must be mentioned up front that the majority of the data comes from measurements on passenger cars, since these have been equipped with oxidation catalysts for many years and even PM trap applications are becoming more general. For HD vehicles (useful) data stem from some limited measurements on trucks and busses retrofitted with PM traps.
For diesel vehicles in general the mass fraction of NO_2 ranges from about 5% of NO_x (for Euro 3 trucks) to almost 80% for some DPF equipped vehicles. A large increase in direct NO_2 emissions can be observed for diesel passenger cars going from Euro 2 to Euro 3 (with which the introduction of highly active oxidation catalyst occurred). From Euro 0 to Euro 2 the average fraction does not vary much and is about 15 to 20%. For the Euro 3 diesel cars the measured NO_2 fraction is considerably higher and in the order of 50%. The absolute NO_2 emission increases sharply from Euro 2 to Euro 3 and continues at this level to Euro 4.
HD vehicles have not been equipped with oxidation catalysts before Euro IV. The introduction of PM traps on HD vehicles initiated the application of the oxidation catalysts in this segment. For HD it can therefore be stated that the introduction of exhaust gas aftertreatment (starting with Euro IV) significantly increases the direct NO_2 emissions of the vehicles (while for passenger cars the DOC was already on the vehicles before the PM traps were fitted). The industry is aware of the issue of increased direct NO_2 emissions and has stated that in principle there are technical solutions available for limiting the direct NO_2 emissions of vehicles with exhaust gas aftertreatment, but that in order to start this development the regulator (the EU) should put adequate legislation in place.

In view of the above, the topic of direct NO_2 emissions is high on the priorities list of several national European governments and they are sponsoring dedicated research programmes in order to further investigate:
-Which measurement method(s) to use in future
-The relation between DPF technology and direct NO_2 emissions
-Possible solutions to decrease direct NO_2 emissions
-The fleet statistical side of direct NO_2 emissions, especially looking at the effect of the introduction of DPF systems on vehicles.

5.4 Fuels

Although the issue of fuel quality in relation to Euro VI will be handled under the review of Directive 98/70/EC which is currently ongoing in a separate process some points should be made in this report.
Diesel (and Bio diesel) will be the major fuels within the scope of Euro VI. CNG/LNG will play increasing, but still minor role. Pure Hydrogen, and biomass-to-liquid fuels are beyond the scope of Euro VI, least for the vast majority of applications

One main issue as already mentioned in chapter 2 is the sulphur content of the fuels used. The engine and exhaust gas after treatment technologies that could be used in order to comply with Euro VI scenarios are in principle more sensitive to fuel quality than earlier technologies like the oxidation catalyst. The durable operation of technologies like DPF (especially wall flow) and DeNOx (especially LNT) are yet sensitive to sulphur and so produce increased CO_2 emissions (because of increased regenerations) and decreased durability to sulphur contents in the fuel of above 10 mg/kg. At this level of sulphur content in the fuel, the sulphur content of lubricant oil is starting to play an important role as well.

The effects of other fuel properties like fuel volatility, olefins content and aromatics content play a much less important role, especially since their ranges are already regulated by existing legislation.

The oil industry have reacted to the legal requirement of introduction low sulphur fuels as laid down in Directive 98/70/EC, amended by Directive 2003/17/EC, including the introduction of almost sulphur free grades (< 10 mg/kg max. S) on a balanced geographical basis from 2005, heading for full area coverage in 2009.

The introduction of biofuels (or blends of regular and biofuels) poses additional problems to future engine and exhaust gas afterteatment technology. Limited blending (up to 10%) seems to be no problem for the technologies under discussion for Euro VI. Higher blends however need to meet the specification from the European fuels quality directive, with special attention for density, lubricity, and viscosity.

5.5 Durability

One of the issues that was addressed in the questionnaire was the durability of technology to be applied to facilitate the step from Euro IV to Euro VI. Information was requested on the current durability intervals (100.000, 200.000 and 500.000 km).
On this issue only very little input with limited detail and non-specific input was received. The input ranged from “no information available” (especially on extended durability) up to “no difference to Euro IV”.

One of the major points on the durability issue is the durability of DeNOx technology. SCR-DeNOx in principle should be very durable, but large scale practical evidence is yet lacking. The main problem with durability lies with LNT. Although this technology could give good possibilities to reach low NOx emissions at relatively low costs, the durability of these systems in 2006 is far from proven. This is the main reason why the panel did not take this technology into account in their final (cost) assessment (although it is acknowledged as a feasible Euro VI DeNOx technology).

6 Costs

6.1 General

The main issue of the Euro VI panels' assessment work was to establish the costs related to technology options that meet the EC's scenarios.
These costs however are highly confidential information only available at single manufacturers level and is one of the main competition issues between the different systems proposed. This confidentiality issue was clearly revealed in the responses to the EC questionnaire, in which cost data provided were very limited and highly aggregated.

For the assessment to be made by the panel, detailed cost data should be available in order to be able to clearly distinguish between the detailed scenarios. Taking into account public information on this point was not seen as being a solution, because the public information available (market prices of vehicles with certain technologies under Euro IV) a) gives little additional information on typical technologies, b) gives market prices instead of costs and c) almost only relates to concepts with PM traps (and not yet much DeNOx technology). More detailed commercial (and confidential) studies available to the European Commission are mainly based on US data, legislation and market development and are therefore of little relevance for the EU situation.

In order to be able to satisfy the desire for detailed additional cost information for several technology applications for Euro VI, the panel decided to build a detailed cost/technology model that could be linked directly to the technology applications specified in chapter 4. The model structure was based on the expert panel's know-how on technical measures that can be applied to minimise emissions. The model input was initially retrieved from the stakeholders input. But in order to retrieve more detailed cost data to fill the detailed model, confidential meetings were arranged with stakeholders (see paragraph 1.2). Because of the high level of confidential input in the model, the model itself will not be made available.

A model was built for both CI and CNG engines. The model for CNG engines however was much less detailed than the one for CI, because for CNG engines only very limited information was available. The result of this lack of detail in the CNG evaluation is that only one type of engine (9 litre, 6 cylinder bus engine) could be addressed in some detail.

The set up of the cost model and the assumptions made to populate the model are presented in the following.

6.2 Technical aspects

- The model is consistent with the set up described in chapter 4 "General approach". This means that costs for technologies are linked to a) emission limit values per component, and b) swept volume of the engine .
- In order to be able to calculate the additional costs for Euro VI, the base case (Euro IV) technology applications (as described in chapter 3) for each engine type (CI, CNG) and swept volume class is part of the model as well.

- Costs for each of the emission reduction technologies are basically linked to the effective size (litre) of the technology on the vehicle. This size is directly linked to the swept volume of the engine. For NGVs only one swept volume class (9 litre) was assessed. Next to the effective reduction devices, necessary sensors and control equipment are added as well.
- For aftertreatment devices the swept volume is linked to the volume of the substrate/filter material and PGM loading (see chapter 5).
- The actual PGM loading of the catalyst to achieve certain reduction efficiencies is subject to change over time. Optimised processes for producing catalysts lead to the possibility of "thrifting", which means less PGM mass on the catalyst with similar overall efficiency. This thrifting has been an ongoing process for many years and leads to catalyst technology becoming less expensive over time for a given set of emission limit values. This effect on costs to a certain extent compensates the increased PGM loading that is needed due to more stringent emission limit values. Having in mind this effect, the PGM loading of Euro VI catalyst technology has been corrected for thrifting that would have occurred without tightening the emission standards. This correction of -30% has been applied based on data over the last years (supplied by AECC members).
- No additional technical or cost information has been added for N1 class 2 vehicles because these vehicles are in fact not HDV but large passenger cars, with passenger cars technology. This incompatibility of technology with HDV showed clearly in the very poor responses from the questionnaires on this class. The additional costs for this category have been established in the Euro 5 passenger cars part of this contact. In this report the "M1 > 2 l large" class is used, for passenger cars with an average swept volume of 4.8 litres and a reference mass > 2.5 tonnes, which is rather similar to N1 class 2. Using the passenger car data for HDV purposes creates the need from a translation from g/km to g/kWh. This translation must be executed using information from the TREMOVE categorisation in order fit the TREMOVE modelling set up afterwards. After this translation it will however become clear that the limit value settings of the Euro 5 and Euro VI scenarios are not completely compatible. A solution for this incompatibility will have to be found.
- The costs for engine measures are also based on swept volume proportionality.
- Some of these engine measures (2-stage turbo and HPI) are seen to serve more purposes than reducing regulated emissions only. They can (and will) also be used to improve the fuel consumption. In the case of very low NOx limit values this means that they will be used to compensate for the fuel consumption increase caused by the inevitable lowered engine-out NOx (and therefore implicit decrease of combustion efficiency).

  Some responses to the questionnaire included statements on the expected changes in fuel consumption compared to Euro IV due to the introduction of Euro VI emission limits. Responses reached from possible slight fuel consumption decrease for the CI scenarios 1, 2 and 3 and increases in fuel consumption for the low NOx scenarios up to 4% (AECC) to fuel consumption neutrality for scenarios with NOx limit values higher than 0.5 g/kWh and fuel consumption increases of typical 3 to 5% (up to 9.5%!) for the most stringent NOx scenarios (ACEA).

  In this context, a decision has to be taken on how to count the costs of these "dual-use" technologies. Some argue that the running costs are so important for the truck operators that irrespective of whatever limit value setting is applied, the truck manufacturers will have to do everything technically possible to achieve fuel neutrality compared to the baseline. In this opinion, the cost for 2-stage turbo charging and HPI should be fully counted as being part of the emission reduction

costs (in order to achieve fuel consumption neutrality as much as possible). On the other hand, it was argued that a difference should be made between the use of these technologies (a) for the purpose of compliance with the emissions legislation, and (b) for the purpose of gaining a competitive advantage by means of fuel efficiency improvements. In this view, (b) is a matter of competition in the truck market unrelated to the emissions legislation and therefore only (a) should be considered in connection with Euro VI, i.e. only a part of the cost of these technologies should be counted towards the compliance cost of the emissions legislation. This would imply, in analogy with the passenger cars part of the project (Euro 5)[1], that 50% of the cost for HPI and 2-stage turbo charging would be allocated to the introduction of the Euro VI standards.
The panel was not in the position to make this choice (given the nature of their contract). Instead it has decided to specify the costs for both approaches in parallel.
- As is the case for CI, also for SI HDV engines running costs (and therefore fuel consumption) are a major issue for their market ability. As stated earlier, significant developments efforts have to be made for SI CNG engines in order to meet Euro VI limit values, but especially the more fuel economic lean burn engines (compared to stoichiometric) will need much more expensive developments i.e. aftertreatment than under the current EEV legislative framework, depending on the chosen scenario. In the context of the CI discussion on allocation of costs to emission reduction or fuel consumption reduction, a similar discussion occurs for the allocation of the additional costs for lean burn CNG engines compared to stoichiometric engines. The separate presentation of the costs for lambda 1 and for lean burn engines enables a separate treatment of these two alternatives in the modelling. Because of the market sensitivity of the fuel consumption issue, market shares of stoichiometric and lean burn engines are very difficult to predict and highly sensitive to the emission limit values in the Euro VI scenarios (and other incentives on CO_2 emission reduction).

6.3 Economic parameters

- All costs used in the model are based on costs and prices being specified for the year 2012 in the questionnaires responses, expressed in 2012 Euros.
- The model takes into account: catalyst *price*, *price* of some additional components (sensors), costs for engine internal measures and costs for packaging, redesign and validation. The reason for eventually using *price* instead of *costs* is due to the fact that the market for those components is so competitive that no cost information became available (even under highest confidentiality).
- The costs for basic development of technologies are *not* taken into account, since it is found that (for the manufacturers) these costs are impossible to be allocated to certain typical developments.
- An important factor in the costs for exhaust gas after treatment is the price of PGM. It is therefore important for the assessment to predict the price of PGM in 2012. This prediction however proves to be extremely difficult. The PGM price is market (supply and demand) based and has been unstable during the time automotive catalysts have been used. Next to the automotive use, precious metal is also used for industrial catalysis, constructions and for jewellery. With an increasing demand for PGM from the automotive industry over the last decade (especially Pt) and mining capacity staying behind, a shortage of Pt has occurred. Because of this, the price of Pt

[1] Where ¼ of the cost was taken into account for technologies that were seen to serve four different purposes

has reached an all time high in 2006, being significantly higher then at the moment at which the stakeholders made up their minds about the costs to be linked to the EC questionnaire.

After detailed discussions with relevant experts on the topic of PGM demand and supply, in 2005 (part 1 on the project) it was reasonable to assume that the 2004 PGM price was really an all time high. This assumption proved to be wrong although developments like large increasing mining capacity between 2004 and 2010 and a shift towards more and much cheaper Pd (instead of Pt) in future catalyst could lead to gradual stabilisation of the market. Due to the proven total unpredictability of the PGM price for the typical automotive PGM combination the panel has decided not to use any price indexation on PGM towards 2012. The price level used was therefore taken to be constant at the level of summer 2004 (the moment the questionnaire was sent out).

- As far as the panel is informed the cost data supplied are based on uncertain production volumes of certain typical components in 2012. This leads to the panel's conclusion that cost figures for especially DeNOx and DPF in 2012 and later, could be lower than expressed by the stakeholders now, if large volumes of the total new sold vehicles would be equipped with these components (in case of scenarios 4,5 or 6). Because of this aspect costs data should be seen as worst case.
- The applicability of LNT DeNOx technology is unsure yet and prices/cost for this technology are impossible to predict at this moment (the technology being in a prototype phase). Therefore, cost estimates for LNT technology are not part of the panel's assessment.

The results of the panel's evaluations are presented in the following. For CI two types of tables are presented showing in table 5 the full cost allocated to emission reduction and in table 6 only 50% of "2-stage turbo charging" and "HPI" allocated to emission reduction. The presented "low" and "high" options reflect the cost of the two most feasible options to meet the emission limit values, with the "low" option achieving this at lower cost than the "high" option. In one case (scenario 6) there is only one technology set up that is foreseen to meet the limit values.

Table 5. Additional costs for HD CI from Euro IV to Euro VI in 2012 (full cost allocated to emission reduction)

	limits g/kWh ETC*	Engine swept volume (L)	cost (€)		
			low	high	avg
scenario 1	PM: 0,030	6	297	533	415
	NOx:2,00	9	346	935	640
	THC: 0,55	13	428	1287	857
scenario 2	PM: 0,015	6	1131	1753	1442
	NOx:1,00	9	1632	2315	1973
	THC: 0,55	13	2116	3080	2598
scenario 3	PM: 0,015	6	1631	1853	1742
	NOx: 0,50	9	2332	2415	2373
	THC: 0,55	13	2816	3180	2998
scenario 4	PM: 0,025	6	2559	3255	2907
	NOx: 0,40	9	3189	4218	3703
	THC: 0,20	13	3778	5251	4515
scenario 5	PM: 0,010	6	3355	3553	3454
	NOx: 0,40	9	4318	4615	4466
	THC: 0,16	13	5351	5780	5566
scenario 6	PM: 0,020	6	3753	3753	3753
	NOx: 0,20	9	4815	4815	4815
	THC: 0,55	13	5980	5980	5980
	* NH3 10 ppm CO 4,0 g/kWh				

Figure 5 : Example of CI 13 l swept volume additional to Euro IV costs (full cost allocated to emission reduction)

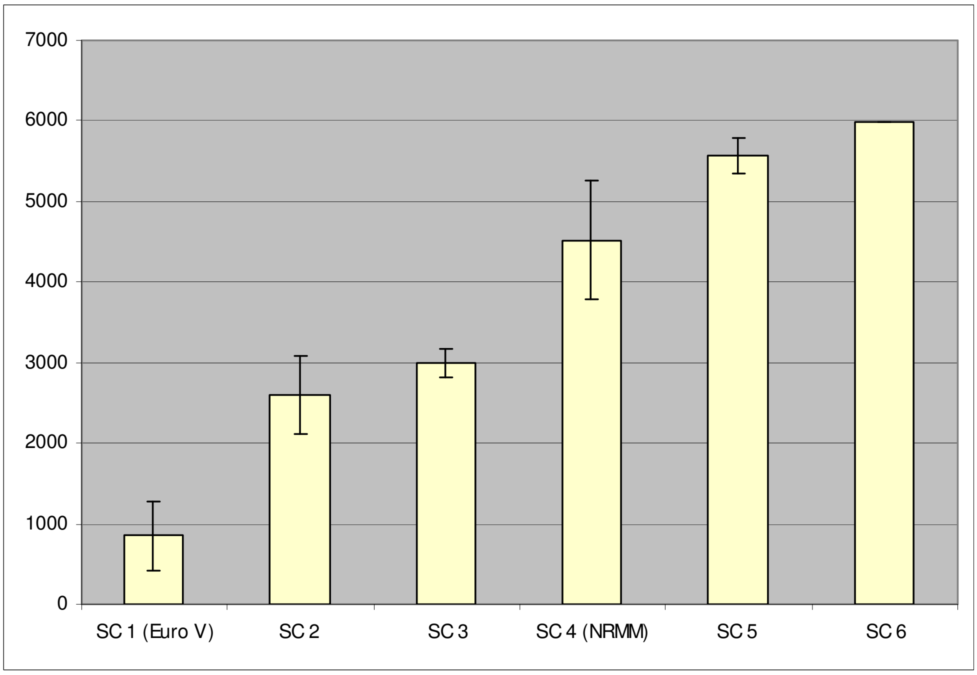


Table 6. Additional costs for HD CI from Euro IV to Euro VI in 2012 (50% 2-stage turbo and HPI cost)

	limits g/kWh ETC*	Engine swept volume (L)	cost (€)		
			low	high	avg
scenario 1	PM: 0,030	6	297	533	415
	NOx:2,00	9	346	935	640
	THC: 0,55	13	428	1287	857
scenario 2	PM: 0,015	6	1131	1753	1442
	NOx:1,00	9	1632	2315	1973
	THC: 0,55	13	2116	3080	2598
scenario 3	PM: 0,015	6	1431	1853	1642
	NOx: 0,50	9	2032	2415	2223
	THC: 0,55	13	2516	3180	2848
scenario 4	PM: 0,025	6	2059	2755	2407
	NOx: 0,40	9	2589	3618	3103
	THC: 0,20	13	3078	4551	3815
scenario 5	PM: 0,010	6	2855	3053	2954
	NOx: 0,40	9	3718	4015	3866
	THC: 0,16	13	4651	5080	4866
scenario 6	PM: 0,020	6	3253	3253	3253
	NOx: 0,20	9	4215	4215	4215
	THC: 0,55	13	5280	5280	5280
	* NH3 10 ppm CO 4,0 g/kWh				

Figure 6. Example of CI 13 l swept volume additional to Euro IV costs in 2012 (50% 2-stage turbo and HPI cost)

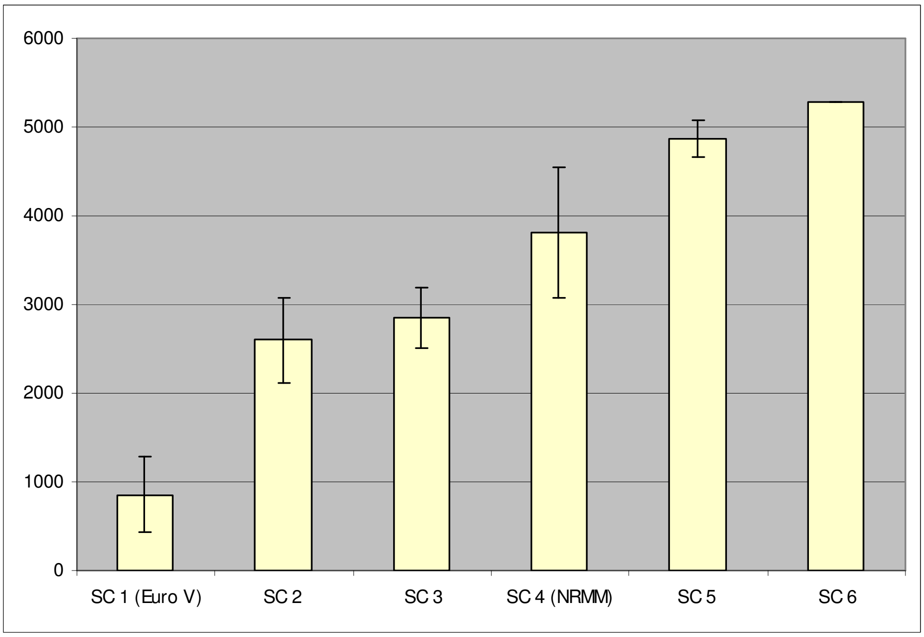
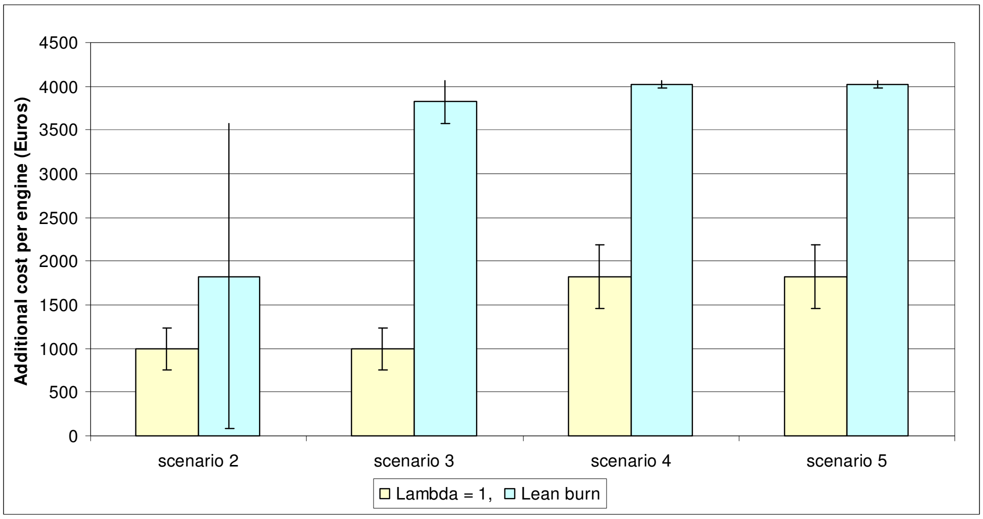


Table 7.Additional costs for Heavy Duty NGV SI Stoichiometric and Lean burn

		cost (€)					
6 cylinder, 9 litre NGV engine		Stoichiometric			lean burn		
	limits g/kWh ETC*	low	high	avg	low	high	avg
scenario 2	CO: 3,0 NMHC: 0,40 CH4: 0,65 NOx: 2,0 PM: 0,02	760	1240	1000	80	3570	1825
scenario 3	CO: 3,0 NMHC: 0,40 CH4: 0,65 NOx: 1,0 PM: 0,01	760	1240	1000	3580	4070	3825
scenario 4	CO: 4,0 NMHC: 0,20 CH4: 0,5 NOx: 0,4 PM: 0,01	1460	2190	1825	3980	4070	4025
scenario 5	CO: 4,0 NMHC: 0,16 CH4: 0,5 NOx: 0,4 PM: 0,01	1460	2190	1825	3980	4070	4025
* all NH3: 10 ppm							

Figure 7. S1 NGV low and high costs SI stoichiometric and lean burn



7 Conclusions

The Euro VI evaluation panel has assessed the information supplied to the Commission by stakeholders on technologies and costs to meet typical Euro VI emission limit value settings with regard to coherence and completeness.

Despite a certain paucity of data returned in response to the HDV questionnaire, the panel remains confident the technology and cost model developed to reach Euro VI when applied to the baseline technology assumptions (Euro IV) leads to a reliable estimate of the cost of future technologies and is reasonably consistent with the original data supplied to the Commission.

The model was used to predict the costs within a bandwidth of probable technology solutions to meet the EC specified Euro VI emission limit values scenarios. These solutions have been based on typical combinations of aftertreatment and engine measures. The combinations selected were based on the applicable limit values (for the scenarios) and technologies that were seen to be adequate to achieve these limits, based on the information supplied by the stakeholders to the panel.
Key issues and assumptions were:

- the use of cost assumptions for the year 2012 and beyond, based on 2004 costs and production volume data (with the exception of PGM price development and thrifting). This ignores the likely changes in costs due to technical progress and mass production;
- the assumption of a stable market price for automotive PGM compositions and a 30% reduction in PGM use (thrifting);
- the inability of the panel to effectively take into account LNT technology at the moment of the assessment;
- the inability of the panel to discriminate between cost for emission reduction and fuel consumption decrease;
- the fact that the costs and availability of urea (and distribution) for SCR technology on diesel vehicles have not been taken into account;
- not being able to take into account development costs.

Apart from these limitations, the output produced will also need some further processing before it can be used as input to simulations within the CAFE programme. In particular, assumptions will have to be made on:

- the correspondence of the engine swept volume (used in this report) to TREMOVE gross vehicle weight classes;
- the N1 class 2 vehicles within the HD limit values concept;
- market share distribution of stoichiometric and lean burn CNG (SI) engines
- the trade off between costs for Euro VI emission reduction and CO_2 emission reduction;

The panel cannot further elaborate on the assumptions to be made. It will be up to the Commission (and subsequent studies on scenario formulations for TREMOVE) to decide how to use the information presented here in the impact assessment of a proposal for a Euro VI standard. However in order to facilitate the choices of the Commission the cost for all CI Euro VI scenarios are presented in two ways (tables next): one with *all* cost allocated to Euro VI emission reduction and one with *only 50%* of the cost of “high pressure injection “ and “two stage turbo charging” allocated to Euro VI. The latter technologies being seen as possibly contributing to both to fuel consumption reduction as well as regulated emissions reduction.

In the following, the result of the Euro VI panel’s work is presented in 3 tables. The tables contain the technology scenarios and associated costs for respectively compression ignition (CI, *all* and *50%*), and NGVs (*stoichiometric* and *lean burn technology*).

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A Cost model overview

cost build up per technology

Component	Cost per comp.	weighting factor	cost per volume
Cooled EGR	a	1	A
DPF sensor suite	b	1	B
Ad-Blue dosing unit	c	1	C
DeNox sensor suite	d	1	D
HPI	e	1 or 0.5	E
2 stage turbo	f	1 or 0.5	F
Enhanced cooled EGR	g	1	G
active DPF regeneration	h	1	H

Component	Cost per litre €	Washcooat / litre	Monolith / litre	PGM 2012 (price*thrifting)	thrifting 2012	Canning / litre	index 2012 (price*thrifing)
DPF closed	l	price	price	price	value	price	value
DPF open	j	price	price	price	value	price	value
SCR	k	price	price	price	value	price	value
LNT	l	price	price	price	value	price	value
Oxicat	m	price	price	price	value	price	value
NH3 cat	n	price	price	price	value	price	value

CI Engine Volume	**V**						
scenario (example 2)	relative cat volume	technology	Catalyst Volume	component cost	price catalyst/filter	comp in low scen.	comp in high scen.
		Cooled EGR		a*V			
		DPF sensor suite		b*V			x
		Ad-Blue dosing unit		c*V		x	
		Nox sensor suite		d*V		x	
		HPI		e*V		x	
		2 stage turbo		f*V			
		Enhanced cooled EGR		g*V			x
		active DPF regeneration		h*V			
	rel. vol. fact.	DPF closed	calc. value		i*rel.vol.fact*V		
	rel. vol. fact.	DPF open	calc. value		j*rel.vol.fact*V		x
	rel. vol. fact.	SCR	calc. value		k*rel.vol.fact*V	x	
	rel. vol. fact.	LNT	calc. value		l*rel.vol.fact*V		
	rel. vol. fact.	Oxicat	calc. value		m*rel.vol.fact*V	x	x
	rel. vol. fact.	slip cat	calc. value		n*rel.vol.fact*V		x
	total cost					cost	cost

B Euro VI scenarios

Diesel HD engines:

Scenario 1 = Euro 5

Scenario 1		Diesel engines
ETC test cycle	CO	4.0 g/kWh
	THC	0.55 g/kWh
	NOx	2.0 g/kWh
	PM	0.03 g/kWh

Scenario 2:
Diesel: -50% NOx and -50% PM over Euro 5.

Scenario 2		Diesel engines
ETC test cycle	CO	4.0 g/kWh
	THC	0.55 g/kWh
	NOx	1.0 g/kWh
	NH_3 (1)	10 ppm
	PM	0.015 g/kWh
	PM new metric	review at later date

Scenario 3:
Diesel: -75% NOx and -50% PM over Euro 5.

Scenario 3		Diesel engines
ETC test cycle	CO	4.0 g/kWh
	THC	0.55 g/kWh
	NOx	0.5 g/kWh
	NH_3 (1)	10 ppm
	PM	0.015 g/kWh
	PM new metric	review at later date

Scenario 4 = equivalent to NRMM Stage IV (from
Diesel: -80% NOx, -17% PM, -64% THC over Euro 5.

Scenario 4		Diesel engines
ETC test cycle	CO	4.0 g/kWh
	THC	0.20 g/kWh
	NOx	0.4 g/kWh
	NH_3 (1)	10 ppm
	PM	0.025 g/kWh
	PM new metric	review at later date

Scenario 5 :
Diesel: -80% NOx, -66% PM and -70% THC over Euro

Scenario 5		Diesel engines
ETC test cycle	CO	4.0 g/kWh
	THC	0.16 g/kWh
	NOx	0.4 g/kWh
	NH_3 (1)	10 ppm
	PM	0.01 g/kWh
	PM new metric	review at later date

Scenario 6:
Diesel: - 90% NOx, -33% PM over Euro 5.

Scenario 6		Diesel engines
ETC test cycle	CO	4.0 g/kWh
	THC	0.55 g/kWh
	NOx	0.2 g/kWh
	NH_3 (1)	10 ppm
	PM	0.02 g/kWh
	PM new metric	review at later date

Gas HD engines:

Scenario 1 = Euro 5

Scenario 1		Gas engines
ETC test cycle	CO	4.0 g/kWh
	NMHC	0.55 g/kWh
	CH_4	1.1 g/kWh
	NOx	2.0 g/kWh
	PM	-

Scenario 2:
Gas: Present EEV values.

Scenario 2		Gas engines
ETC test cycle	CO	3.0 g/kWh
	NMHC	0.4 g/kWh
	CH_4	0.65 g/kWh
	NOx	2.0 g/kWh
	NH_3 (1)	10 ppm
	PM	0.02 g/kWh
	PM new metric	review at later date

Scenario 3:
Gas: -50% NOx, -50% PM over EEV. CO, NMHC and

Scenario 3		Gas engines
ETC test cycle	CO	3.0 g/kWh
	NMHC	0.4 g/kWh
	CH_4	0.65 g/kWh
	NOx	1.0 g/kWh
	NH_3 (1)	10 ppm
	PM	0.01 g/kWh
	PM new metric	review at later date

Scenario 4 = equivalent to NRMM Stage IV (from
Gas: -80% NOx, -64% NMHC & -55% CH_4 over Euro 5.

Scenario 4		Gas engines
ETC test cycle	CO	4.0 g/kWh
	NMHC	0.20 g/kWh
	CH_4	0.5 g/kWh
	NOx	0.4 g/kWh
	NH_3 (1)	10 ppm
	PM	0.02 g/kWh
	PM new metric	review at later date

Scenario 5 :
Gas: -80% NOx, -50% PM, -70% NMHC & -25% CH_4

Scenario 5		Gas engines
ETC test cycle	CO	4.0 g/kWh
	NMHC	0.16 g/kWh
	CH_4	0.5 g/kWh
	NOx	0.4 g/kWh
	NH_3 (1)	10 ppm
	PM	0.01 g/kWh
	PM new metric	review at later date

(1) In the case of a technical solution for diesel or gas engines utilising SCR and 'urea'.