

## Clean European Rail-Diesel

### D6.1.1 State of the Art Study Report of Low Emission Diesel Engines and After-Treatment Technologies in Rail Applications

Due date of deliverable: 30/11/2009

Actual submission date: 07/07/2010

**Leader of this Deliverable:** Dr. Georgios Patrianakos,  
Centre for Research & Technology Hellas (CERTH) /  
Chemical Process & Energy Resources Institute /  
Aerosol & Particle Technology Laboratory (APTL)

**Reviewed:** Y

Document status		
Revision	Date	Description
0.1	05/11/2009	1 <sup>st</sup> draft issue for comments (WP members only)
0.2	02.12.2009	2 <sup>nd</sup> draft issue incorporating previous comments (WP members only)
1	18.12.2009	3 <sup>rd</sup> draft issue to Quality Manager
2	05.01.2010	4 <sup>th</sup> draft issue to Quality Manager (CLD-D-APT-004-02)
3	08.01.2010	5 <sup>th</sup> draft issue to Quality Manager (CLD-D-APT-004-03)
4	18.01.2010	6 <sup>th</sup> draft issue to Quality Manager (CLD-D-APT-004-04)
5	07.07.2010	Final review before submission
6	28.08.2013	Submission with updated references

Project co-funded by the European Commission within the Seven Framework Programme (2007-2013)		
Dissemination Level		
<b>PU</b>	Public	X
<b>PP</b>	Restricted to other programme participants (including the Commission Services)	
<b>RE</b>	Restricted to a group specified by the consortium (including the Commission Services)	
<b>CO</b>	Confidential, only for members of the consortium (including the Commission Services)	

Start date of project: 01/06/2009

Duration: 48 months

Instrument: Large-scale Integrated Project

Thematic priority: Sustainable Surface Transport

## EXECUTIVE SUMMARY

---

The aim of this report is to review the state of the art in Diesel emission control technologies in the application areas where it has been pioneered so far, mainly road going vehicle Diesel engines, considering the potential for transfer of these technologies to rail applications. The review covers all the technology areas in which developments have led to emissions reductions for Diesel engines, including Diesel combustion, air management, Diesel fuel injection, exhaust gas recirculation (EGR), and exhaust gas after-treatment technologies. Also included is a review of clean Diesel engine technologies currently being used in rail vehicles. Past EU funded collaborative research that is relative to the topic of this report and in which the contributing partners have participated is also reviewed.

Recent advances in combustion technologies for light and heavy duty road vehicle engines have focused on improving the NO<sub>x</sub> / particulate matter (PM) tradeoff through the use of advanced combustion concepts such as homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI). The potential exists for transferring these technologies to rail engines in order to reduce raw engine exhaust emissions, particularly in the case of rail engines with outputs smaller than 560 kW that have similar design to heavy duty road vehicle engines.

Increased intake air pressure ratios can be used in rail engines to further reduce emissions however this will have an impact on the design of the after-treatment system due to the low exhaust gas temperatures downstream of the turbocharger, and will require extensive EGR cooling.

Injector technologies with directly driven needles and internal pressure transmission are transferable from heavy duty road vehicle engines to rail engines because of the same required profile and the similar engine speeds. To meet future emission limits, injection strategies with several injections per cycle become important.

Exhaust after-treatment technologies can be used to reduce tailpipe emissions levels to below those achievable with engine-based emission reduction technologies alone. There are three main after-treatment technologies that can be utilised in rail applications: Diesel oxidation catalysts (DOC) for the reduction of tailpipe CO and hydrocarbon (HC) emissions, Diesel particulate filters (DPF) for the reduction of tailpipe PM emissions, and selective catalytic reduction (SCR) technologies for the reduction of tailpipe NO<sub>x</sub> emissions. Careful integration of these technologies with each other and with the engine is required to ensure proper emissions reduction performance and good durability of the after-treatment system. In general, the use of after-treatment technologies can compliment engine based technologies particularly if the target emission limits do not require that both engine and after-treatment technologies be fully exploited in order to meet the limits. In this regard, the feasibility and effectiveness of various after-treatment systems should be examined within the context of an overall LCC optimization.

With the use of an after-treatment system it is important to define standard fuels in order to ensure that the target emissions and durability of the system are met. Alternative fuels offer new possibilities for emissions reductions however they must be tuned exactly to the engine. The compliance with future emission limits only by the use of alternative fuels cannot be expected. However, it is possible for alternative fuels to contribute to other measures for reduced emissions.

Compliance with Stage IIIA emission limits has been achieved solely with engine based emission reduction measures. However, to meet Stage IIIB limits, these measures alone are not sufficient and exhaust gas after-treatment is required. The use of after-treatment technologies in the railway sector is very limited to date and more knowledge is needed to fully understand the impact of these technologies in rail applications.

---

## TABLE OF CONTENTS

---

EXECUTIVE SUMMARY .....	2
LIST OF FIGURES .....	6
LIST OF TABLES.....	9
1. INTRODUCTION .....	10
1.1 Objectives .....	10
1.2 Inputs .....	10
1.3 Summary of Results .....	11
1.3.1 Diesel Combustion.....	11
1.3.2 Air Management .....	11
1.3.3 Diesel Fuel Injection.....	11
1.3.4 Exhaust Gas Recirculation.....	12
1.3.5 Diesel Exhaust After-Treatment .....	12
1.3.6 Diesel Fuel and Exhaust After-Treatment .....	13
1.3.7 Clean Diesel Engines in Railway Vehicles .....	13
1.4 Links .....	13
2. DIESEL COMBUSTION .....	14
2.1 Past Research .....	14
2.1.1 Combustion System Design.....	17
2.1.2 Fuel Injection Management.....	20
2.1.3 Advanced Combustions .....	23
2.2 Conclusions .....	24
2.3 References.....	24
3. AIR MANAGEMENT .....	26
3.1 Past Research .....	26
3.1.1 Current Technologies for Diesel Engine Charging .....	26
3.1.2 Increased Boost Pressure.....	27
3.1.3 Enhanced Intercooling .....	29
3.2 Conclusions .....	30
3.3 References.....	31
4. DIESEL FUEL INJECTION .....	32
4.1 Past Research .....	32

4.1.1	Unit Pump and Unit Injector .....	32
4.1.2	Common Rail.....	32
4.1.3	Injection Pressure Development .....	33
4.1.4	Injection Timing.....	34
4.1.5	Strategies for Multiple Injection .....	35
4.1.6	Injection Rate Shaping.....	36
4.2	Conclusions .....	37
4.3	References.....	37
5.	EXHAUST GAS RECIRCULATION.....	39
5.1	Introduction .....	39
5.2	Components.....	42
5.2.1	EGR Valves .....	42
5.2.2	EGR Coolers .....	43
5.3	Emissions Results.....	44
5.4	Influence from Fuels.....	46
5.5	Influence of Charge Temperature.....	47
5.6	EGR Control.....	48
5.7	References.....	48
6.	DIESEL EXHAUST AFTER-TREATMENT .....	50
6.1	Introduction .....	50
6.2	Diesel Oxidation Catalysts .....	50
6.3	Diesel Particulate Filters.....	53
6.3.1	Introduction.....	53
6.3.2	The Filtration Process.....	54
6.3.3	The Regeneration Process .....	54
6.3.4	Substrate Materials .....	56
6.3.5	Ceramic Wall-Flow Monolith Filters.....	58
6.3.6	Passive Regeneration Systems .....	60
6.3.7	Active Regeneration Systems.....	63
6.3.8	Regeneration Strategies .....	66
6.4	Selective Catalytic Reduction .....	68
6.4.1	Introduction.....	68
6.4.2	Operation Principle .....	68
6.4.3	SCR Catalysts .....	69

6.4.4	SCR Systems .....	70
6.4.5	NOx Reduction Performance .....	71
6.4.6	SCR with DPF.....	71
6.5	Past Research .....	72
6.6	Conclusions .....	81
6.7	References.....	81
7.	DIESEL FUEL AND EXHAUST AFTER-TREATMENT.....	89
7.1	Past Research .....	89
7.1.1	Standards for Diesel Fuel .....	89
7.1.2	Diesel Fuel Components and their Impact on After-treatment Systems .....	89
7.1.3	Alternative Sources for Diesel Fuel .....	92
7.1.4	Alternative Diesel Fuels and their Impact on After-treatment Systems.....	94
7.2	Conclusions .....	98
7.3	References.....	98
8.	CLEAN DIESEL ENGINES IN RAILWAY VEHICLES.....	100
8.1	Past Research .....	100
8.2	References.....	104

## LIST OF FIGURES

Figure 1: NOx-PM Trade-offs at Successive Emissions Levels Euro 6 scenarios will require additional technology [Nicol, 2007].	14
Figure 2: Relationship between Specific NOx and “Effective EGR”, including different operating points and different engines [Ruggiero et al., 2008].	15
Figure 3: Effect of EGR Rate and O <sub>2</sub> concentration in the intake air on NOx Reduction [Gänter, 2007].	15
Figure 4: EGR level targets in the whole engine operative area for US 2007 HD engines [Nicol, 2007].	16
Figure 5: Impact of Specific Power on peak firing pressure [Dreisbach, 2005].	16
Figure 6: Overview of the NADI™ combustion system concept [Colliou et al., 2006].	18
Figure 7: Smoke emission reduction at low air-fuel ratio (with high EGR) by means of combustion process improvement [Nicol, 2007].	18
Figure 8: Average compression ratio value for the European passenger car engines versus years and versus emission legislation.	19
Figure 9: Fuel consumption increase with respect to Euro 4 standards and smoke emissions versus engine speed for three compression ratio values employing a PCCI engine calibration. [Beatrice et al., 2009].	19
Figure 10: HCCI range with different compression ratio for an HD engine [Colliou et al., 2006].	20
Figure 11: Requirements for advanced fuel injection system. [Shinohara and Toyao, 2002].	21
Figure 12: HD engine requirements on future injection strategy (at left) and optimal rate shape (at right). [Ziegler, 2004].	21
Figure 13: Effects of injection pressure (Pinj) on Soot-NOx trade-off performed by EGR sweep [Moser et al., 2004], at left, and Effects of injection pressure in combination with EGR on Soot-NOx trade-off optimization for an HD engine at full load [Dreisbach, 2005], at right.	22
Figure 14: Effects of different injection strategy and nozzle design on soot emissions for an HD engine [GREEN project final report, 2008].	23
Figure 15: Advanced combustion concepts as HCCI, LTC and PCCI based on the in-cylinder $\phi - T$ map history.	23
Figure 16: Engine map with operating range of register charging [MTU-1].	26
Figure 17: Variants of high pressure turbo-charging [CODAN].	27
Figure 18: Engine results in comparison with the simulations [CODAN].	28
Figure 19: Impact of EGR to NOx and PM emission [FIF-1].	29
Figure 20: Differences in thermodynamic analysis for intake temperature of 0°C and 50°C at full load [FIF-2].	30
Figure 21: Differences between servo controlled and direct acting [DELPHI].	32
Figure 22: Development of injection pressure [BOSCH].	34

Figure 23: Influences of injection pressure and start of injection on fuel consumption and emissions [HDT].....	34
Figure 24: Emissions map for soot and NO <sub>x</sub> as a function of Equivalence ratio [-] and Temperature [K]. .....	39
Figure 25: Illustrative Equivalence ratio-temperature maps for “classical” Diesel combustion and several alternative modes .....	40
Figure 26: CO emissions map as function of Equivalence ratio [-] and Temperature [K]. .....	41
Figure 27: Schematic diagram of a 2-stage turbo charging system with long route (low pressure) and short route (high pressure) EGR.....	42
Figure 28: Delphi Dual Poppet Rotary EGR Valve with Torque Motor.....	43
Figure 29: Pierburg EGR Cooler and EGR valve .....	43
Figure 30: Scania 2-stage EGR cooling [Scania, 2007].....	44
Figure 31: Effect of increasing EGR on soot emissions at constant charge air pressures @ 50% load and 1500 rpm .....	45
Figure 32: Effect of increasing EGR on NO <sub>x</sub> emissions at constant charge air pressures @ 50% load and 1500 rpm. ....	45
Figure 33: CO (left panel) and HC (right panel) emissions for different EGR levels at 50 % load and 1500 rpm.....	46
Figure 34: Normalized brake specific fuel consumption (bsfc) for different EGR levels at 50 % load and 1500 rpm .....	46
Figure 35: Soot versus NO <sub>x</sub> for Diesel, Fischer-Tropsch and RME fuel @ 50 % load and 1500 rpm [Fredriksson, 2006] .....	47
Figure 36: The effect of inlet temperature on soot emissions with a post injection with a dwell time of 2 CAD at 50 % load and 1500 rpm (injection pressure 1750 bar) .....	47
Figure 37: Oxygen (Lambda) Sensor-Based Control system (Bosch) .....	48
Figure 38: Flow pattern through a ceramic wall-flow monolith DPF. ....	58
Figure 39: Optimum active regeneration interval for constant vehicle operating condition.....	67
Figure 40: Open loop urea SCR system.....	70
Figure 41: The MULTISENS sensor.....	73
Figure 42: The DEXA cluster vehicle demonstrators. ....	75
Figure 43: Integration of the MEP device. ....	77
Figure 44: The IMITEC sensor platform. ....	78
Figure 45: The concept of the Multifunctional Filter Reactor (MFR).....	79
Figure 46: Kinds of fuel for Diesel applications.....	89
Figure 47: Dependence of NO-oxidation from temperature and sulphur-concentration for a platinum catalyst [WALK].....	90
Figure 48: Influence of sulphur concentration on PM emission of a CRT-filter [ACEA].....	91
Figure 49: Converting paths from fossil and regenerative energy source to fuel [HARN] .....	93

Figure 50: Basics of NExBTL-process [HONK] .....	94
Figure 51: Course of emissions for C1-Test ISO 8178 [FIF].....	95
Figure 52: Course of particle size distribution for Bio-Diesel blends at $n = 2300 \text{ min}^{-1}$ ; $M_D=282 \text{ Nm}$ [FIF] .....	95
Figure 53: Raw emission from Diesel fuel, rapeseed oil and GTL [HARN] .....	96
Figure 54: NO <sub>x</sub> -emission and FSN by using micro emulsified fuels with different water fraction for speed = $1500 \text{ min}^{-1}$ (left) and speed = $1800 \text{ min}^{-1}$ (right) [BEM].....	97
Figure 55: Power Pack including exhaust gas post-treatment system (Source:Bombardier) .....	101

## LIST OF TABLES

---

Table 1: Partner participation in the present Deliverable .....	10
Table 2: Different injection strategies in Diesel combustion.....	35
Table 3: Ceramic wall-flow monolith materials .....	59
Table 4: Sources and influences on ash accumulation in DPF [GAERT].....	92
Table 5 Clean rail Diesel technologies .....	102

## 1. INTRODUCTION

---

### 1.1 OBJECTIVES

---

The objective of D6.1.1 is to review the state of the art in emission control technologies for Diesel engines, primarily as this has been pioneered in light and heavy duty road vehicles, while considering the potential for transfer of these technologies to rail Diesel engines.

Both engine based and exhaust gas after-treatment based technologies are covered:

- Diesel combustion
- Air management
- Diesel fuel injection
- Exhaust gas recirculation
- Diesel exhaust after-treatment

In addition, the effect of Diesel fuels on the performance of exhaust after-treatment systems is considered and technologies for emissions reduction already being applied in railway vehicles are reviewed.

The review also covers relevant past EU funded collaborative research in which the contributing partners have participated.

### 1.2 INPUTS

---

The inputs to D6.1.1 of the participating partners are shown in Table 1.

Partner	Contribution
CERTH/APTL	Diesel exhaust after-treatment
CHA	Exhaust gas recirculation
CNR-IM	Diesel combustion
HTW/FiF	Air management Diesel fuel injection Diesel fuel and exhaust after-treatment
MTU	Review of D6.1.1
UNEW	Clean Diesel engines in railway applications

**Table 1: Partner participation in the present Deliverable**

Section 1.4 describes how the present Deliverable inputs to and uses output from the rest of the CleanER-D project.

## 1.3 SUMMARY OF RESULTS

---

### 1.3.1 Diesel Combustion

In the road sector, the integration of cooled exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) technologies is considered to be necessary to meet the future Euro VI emissions limits. As such, recent developments in in-cylinder emission control technologies have sought to reduce particulate matter (PM) formation under high EGR rates through the adoption of advanced combustion concepts such as homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI). In this regard, new technologies for the control of the in-cylinder air / fuel mixing process, such as new piston bowl designs and new engine head architectures including variable valve actuation (VVA) systems show great potential for improving the NO<sub>x</sub> / PM trade-off by promoting HCCI / PCCI combustion over as much of the engine operating envelope as possible.

The use of very low NO<sub>x</sub> and PM combustion concepts appears in principle to be very useful in order to meet future emissions limits for rail Diesel engines. Nevertheless, the usefulness of advanced combustion concepts in rail engines has to be carefully evaluated in relationship to the different operating conditions between heavy duty road engines and rail engines. Rail Diesel engines with output less than 560 kW are usually derived from heavy duty road vehicle engines and therefore the transfer of combustion technologies is relatively easy to realise in this case. However, in the case of engines with larger outputs, the transfer of combustion technology is likely to be more difficult due to the different design of these engines.

### 1.3.2 Air Management

In principle, reaching future emissions limits for heavy duty vehicles and rail engines requires an increase of the intake air pressure ratio. However, for heavy duty vehicles a pressure ratio of 4 is required to meet EURO V/VI, whereas pressure ratios greater than 4 are already the state-of-the-art in rail engines today. For rail engines, the aimed pressure ratio is between 6 and 8. In this case a technology transfer from heavy duty vehicle engines to rail engines cannot be expected. The use of very large intake air pressure ratios will require very high EGR cooling rates and the development of after-treatment systems that can work reliably at the very low exhaust gas temperatures encountered downstream of the turbocharger.

### 1.3.3 Diesel Fuel Injection

The development and mass production of injectors with directly driven nozzle needles as well as injectors with internal pressure transmission indicates the trends in current injection technology. These injectors are transferable to rail engines because of the same required profile and similar speed ranges of heavy duty vehicles and rail engines. In order to meet future emission limits in rail engines, injection strategies with several injections per cycle become important. The precision in the reproducibility and repeatability of the injection quantity plays a determining role. For this purpose, injectors with directly driven needles are superior to injectors with a servo hydraulic driving mechanism. Also, the increase of the injection pressure is important for in-cylinder emissions reduction. This applies for heavy duty engines as well as for rail engines. With an increase of the injection pressure, the demands for the whole injection system become higher. By the pressure transmission in the injector, only adjacent components are in contact with the high pressure. A lower system pressure decreases the demands for the pressure resistance of lines, screw connections and high-pressure pumps.

### 1.3.4 Exhaust Gas Recirculation

Cooled EGR has generally been used in heavy duty road vehicles since the introduction of the US2004 emissions regulations in 2002. EGR allows a significant reduction in NO<sub>x</sub> but is followed by increased PM, CO and HC emissions and also increased fuel consumption. These increases are however quite small and can easily be handled if the EGR rate is kept below 30% - 40%. Due to the increase in PM emissions, an EGR strategy for NO<sub>x</sub> reduction is often combined with a DPF. EGR rates between 20% and 40% can reduce NO<sub>x</sub> emissions by more than 50%, where higher loads require higher EGR rates. It is important that cooled EGR is used since otherwise PM emissions increase too much.

### 1.3.5 Diesel Exhaust After-Treatment

Exhaust after-treatment technologies can be used to reduce tailpipe emissions levels to below those achievable with engine-based emission reduction technologies alone. There are three main after-treatment technologies that can be used in rail applications: Diesel oxidation catalysts (DOC) for the reduction of tailpipe CO and hydrocarbon (HC) emissions, Diesel particulate filters (DPF) for the reduction of tailpipe PM emissions, and selective catalytic reduction (SCR) technologies for the reduction of tailpipe NO<sub>x</sub> emissions.

Careful integration of these technologies with each other and with the engine is required in order to ensure good emissions reduction performance and good durability of the after-treatment system. There are consequences between the DOC, DPF and SCR functionalities that need to be considered for good performance and durability. In this respect, much of the recent progress in the state-of-the-art in after-treatment technologies for light and heavy duty road vehicles engines has arisen from the partial integration of the various emission reduction functionalities of previously separate after-treatment devices into single devices, e.g. DOC with PM reduction capability and catalyzed DPF with CO and HC reduction capability.

Rail DPF applications are likely to require an active regeneration system since exhaust gas temperatures may be too low to facilitate a fully passive system and since the extended idle times of rail engines may lead to uncontrolled regeneration of the DPF. The use of an active regeneration system will incur a certain increase in system complexity and a fuel economy penalty. The use of SCR technologies will also incur an increase in system complexity and an increase in the operating cost of the engine due to the consumption of an on-board reductant such as urea to facilitate NO<sub>x</sub> reduction.

A significant consideration for the correct design and operation of after-treatment devices for rail applications is likely to be the minimization of the effect of spatial non uniformities on their operation due to the large size of these devices. In particular, the DPF must be able to regenerate safely in the presence of significant spatial non uniformities in the soot load distribution, and the SCR reductant must be uniformly delivered to the face of the SCR catalyst.

In general, the use of after-treatment technologies can complement engine based technologies particularly if the target emission limits do not require that both engine and after-treatment technologies be fully exploited in order to meet the limits. This may permit a certain degree of freedom in the design of the engine and the after-treatment system that enables a lower life cycle cost (LCC) to be achieved compared to the LCC that could be achieved if engine or after-treatment technologies were used alone. In particular, the use of SCR could allow a reduction of the EGR rate to the extent that a DPF is not required, increasing at the same time fuel economy and engine durability. In order to correctly assess the feasibility and effectiveness of such scenarios, it is necessary to consider the design of the after-treatment system within the context of an overall LCC optimization.

### 1.3.6 Diesel Fuel and Exhaust After-Treatment

In order to ensure the correct operation of the exhaust after-treatment system, the Diesel fuel has to comply with the standard EN 590 for sulphur, phosphor and ash content limit values. This applies also for Diesel fuel blends. Ash accumulation can have a significant impact on the durability of a DPF. The usage of low ash content engine oils (lowSAPS-oil) can reduce ash accumulation. Nevertheless, experience from heavy duty road vehicle engines shows that several ash cleanings are necessary during the life cycle of a DPF.

Investigations with alternative fuels, such as biogenic fuels of the 1st generation (biodiesel) and 2nd generation (xTL, HVO) as well as their Diesel blends, in heavy duty engines shows reduced emissions for PM, HC and CO as well as increased or same level emissions for NO<sub>x</sub> in comparison to Diesel fuel. Therefore, the requirement for less severe exhaust gas after-treatment can be expected with the use of these fuels. However, compliance with future emission limits only by the use of such fuels and without the use of exhaust after-treatment technologies cannot be expected. The use of micro-emulsified fuels is a promising approach, however this needs further investigation.

### 1.3.7 Clean Diesel Engines in Railway Vehicles

Compliance with EU Stage IIIA emission limits has been achieved using engine development and in-cylinder emission reduction technologies. However, to meet the far more restrictive Stage IIIB limits, these developments alone are not sufficient. Exhaust after-treatment is required to bring the levels of exhaust gas emissions to within the legislated limits. The use of such technologies in the railway environment is very limited to date. A significant amount of work led by the industry has been done in recent years to understand the implications and to develop solutions, using the knowledge gained in other industries (automotive in particular) to this extent. As a result, prototypes for a new generation of Diesel engines using EGR in combination with DPF or SCR after-treatment technologies are being developed and tested. However, more knowledge is needed to fully understand the true impact of these technologies.

## 1.4 LINKS

---

Deliverable D6.1.1 feeds in directly to SP5 “Sustainability and Integration”, and in particular to:

- WP5.2 “Identification of Emission Reduction Technologies for Further Assessment”
- WP5.3 “Sustainability Impact Assessment and Cost/Benefits Analysis of Project Results”

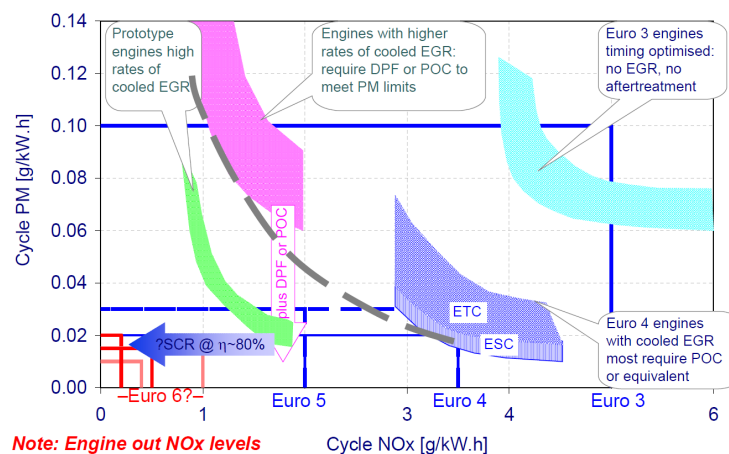
## 2. DIESEL COMBUSTION

### 2.1 PAST RESEARCH

A first evaluation of the transferability of the on-road combustion technology to rail engine was already carried out within the GREEN project (2008). It was concluded that for railcar application with power output up to 560 kW several technologies could be transfer from on-road HD engines in order to meet the IIIB target. For higher power application (typically from 1000 kW to 3000 kW) the combustion system characteristics and the operative conditions are much more different and the employment of the modern on-road technologies becomes more and more difficult and expensive. However, for rail engines up to 560kW, some synergies regarding the combustion system can be evidenced [Dreisbach, 2005].

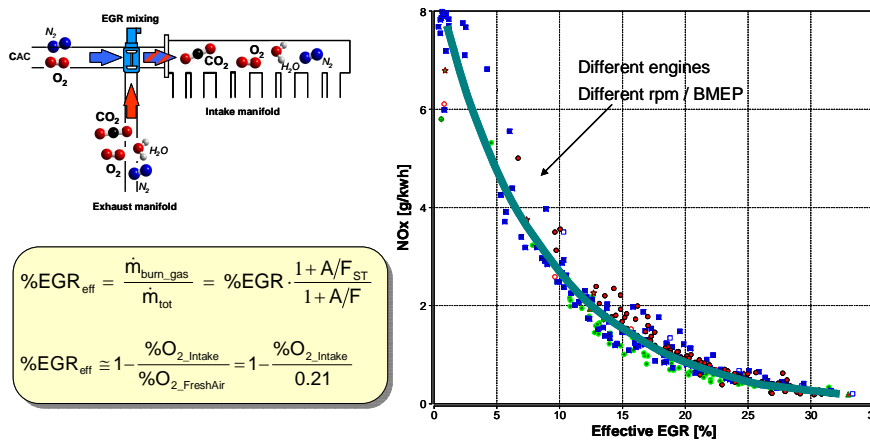
In particular, looking at the combustion technologies developed for on-road application on both LD and HD engines in the last decade, they were always addressed mainly to the in-cylinder control of both NO<sub>x</sub> and PM, whereas the unburned gaseous emissions as HCs and CO were mainly controlled by the DOC employment.

Starting from Euro 4 and Euro 6 emission levels for HD and LD engines respectively, the SCR technology was taken under consideration for NO<sub>x</sub> abatement in the engine exhaust flow. In both case, as also explained by Dreisbach (2005) and Nicol (2007), for Euro 6 scenario in all on-road diesel application the integration of in-cylinder NO<sub>x</sub>/PM control methodologies with exhaust after-treatment will be mandatory in order to meet the future legislations and the power performance requirements. In fact, the below diagram in Figure 1 [Nicol, 2007] indicates clearly that for future SCR systems with about 80% of efficiency, in order to meet the NO<sub>x</sub>-PM Euro 6 emission levels the combined use of cooled EGR and SCR systems will be mandatory.

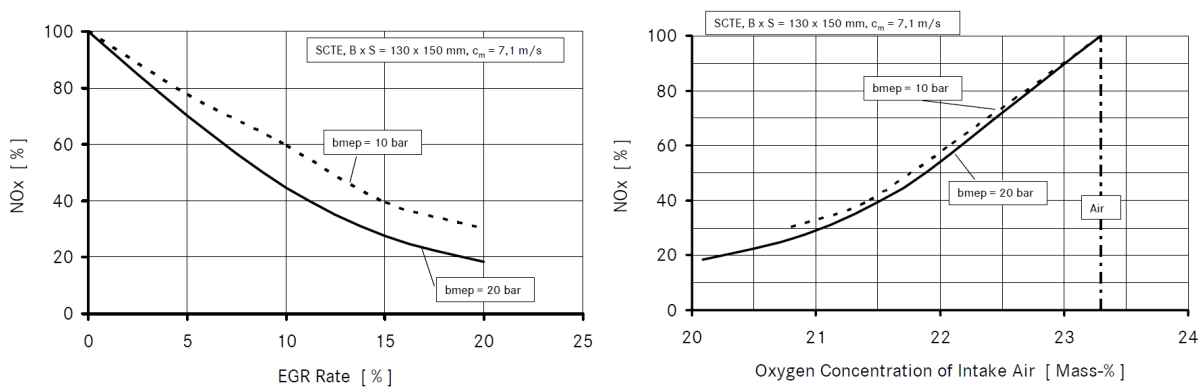


**Figure 1: NO<sub>x</sub>-PM Trade-offs at Successive Emissions Levels Euro 6 scenarios will require additional technology [Nicol, 2007].**

The EGR technique remains the most powerful methodology for a drastic reduction of the engine exhaust NOx emissions. This can be observed from the analysis of Ruggiero et al. (2008) and Ganter (2007). In fact, as reported by Ruggiero et al. (2008), the Figure 2 shows as for different engines and different operating conditions the NOx emissions are essentially controlled by the “effective” EGR rate. The definition of the “effective” EGR rate is reported in the same Figure 2. With respect to the conventional definition of the EGR, the “effective” EGR take into account the air fraction recirculated in the EGR line when the engine operate with lean air/fuel mixture. At the same time, in Figure 3, the effect of the EGR on NOx emission for an HD engine operating at two different engine loads is plotted [Ganter, 2007]. It can be noted that the percentage of reduction in NOx versus EGR is the same varying the engine load. All other engine parameters are less effective on NOx production with respect to the EGR.



**Figure 2: Relationship between Specific NOx and “Effective EGR”, including different operating points and different engines [Ruggiero et al., 2008].**



**Figure 3: Effect of EGR Rate and O<sub>2</sub> concentration in the intake air on NOx Reduction [Ganter, 2007].**

Therefore, the NOx in-cylinder control is mainly based on the increase of the engine EGR tolerability, considering EGR as main driver to reduce NOx. Therefore, the improvement of the NOx and PM emissions will be mainly based on the adoption of different methodologies to control PM formation under high EGR rate, as advanced combustions (HCCI/PCCI, etc.), complex fuel injection strategies, optimized combustion system designs etc. The future requirements in terms of EGR rate for HD engines able to meet the Euro 6 emission targets were indicated by Nicol (2007) and reported in Figure 4.

The increase of the EGR rate in the whole engine operating map will require the consideration of some important aspects regarding the combustion efficiency and the EGR use as reported by Dreisbach (2005). In particular, the peak cylinder pressures are a linear function of specific power, with EGR being an additional parameter, as reported in Figure 5. So the high EGR rate at high loads will require an increase of maximum permissible peak pressure. To this aim a further work in the piston design improvement will be necessary.

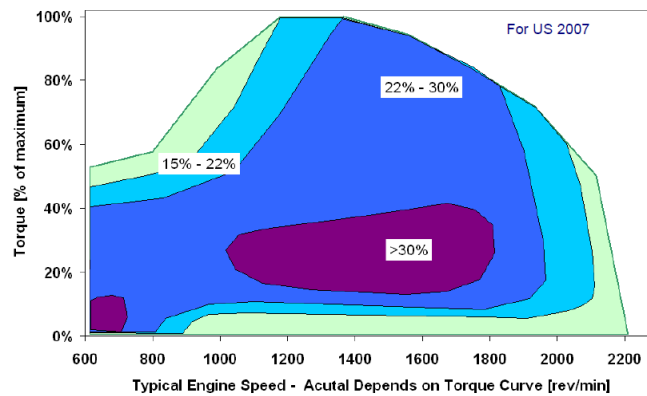


Figure 4: EGR level targets in the whole engine operative area for US 2007 HD engines [Nicol, 2007].

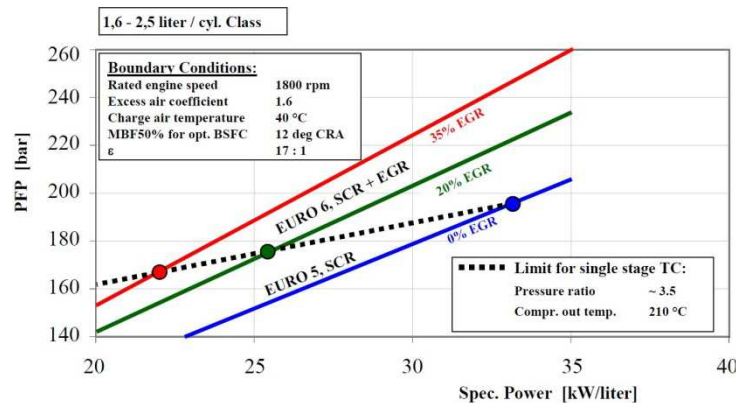


Figure 5: Impact of Specific Power on peak firing pressure [Dreisbach, 2005].

Assessed the necessity of high EGR rate to drop down the NO<sub>x</sub> formation, in most possible larger area of engine operating map, the in-cylinder PM control will be mainly based on the development and application of different methodologies affecting the in-cylinder soot formation as:

- The combustion system design and the in-cylinder air flow management;
- The fuel injection management;
- The advanced combustions.

These last technologies developed in the road sector for both LD and HD engines and liable for application on rail engines will be briefly discussed in the following.

### 2.1.1 Combustion System Design

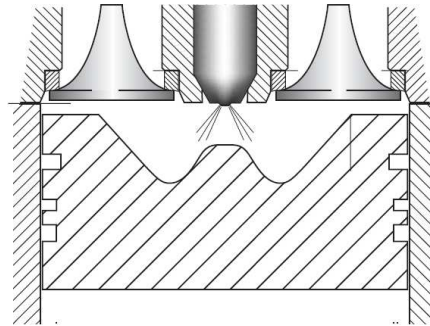
As known, the combustion system design in terms of compression ratio, piston bowl shape and engine head architecture is one of the main engine features which the LD engine differs from the HD one. Of course, the design of the most modern on-road HD engine is more susceptible for the transfer to rail engines.

Larger heavy-duty engines have typically used larger diameter and open-type bowls. These systems rely more on the fuel spray than the air motion to provide the mixing energy required. The HD engines generally operate at lower speeds, where the mixing rate required for complete combustion is lower. The orientation of the fuel spray varies from engine to engine. Some aim the fuel spray along the bottom surface of the bowl, others direct the fuel towards the squish region.

As followed for the LD engines, in the recent years the combustion system design development for HD engines has been mainly addressed to the exploitation of high EGR diluted and premixed charge (named as HCCI or PCCI) in order to drop the NO<sub>x</sub> and PM formation during combustion. These trends can be found in the analysis of the last EU research project implemented within FP6 and FP7 framework.

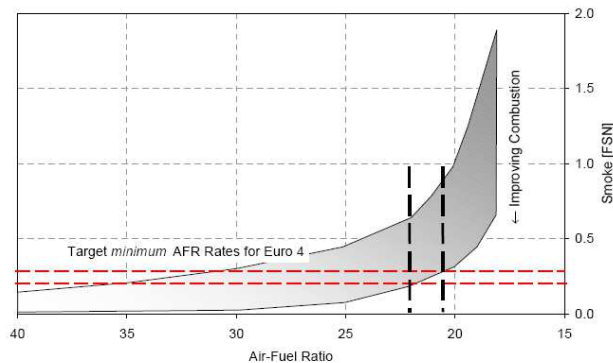
In the “Hy-SPACE” project (“Heavy duty Diesel whole space combustion”- Hy-SPACE), the concept of HCCI combustion, already development for LD application in the FP6 “D-ULEV” project, was transferred to the HD application (Colliou et al., 2006). The early homogenization required by the HCCI concept is unfeasible in a conventional direct injection combustion chamber, so the HCCI combustion system concept (developed by the Institute Francaise du Petrole and named “NADI”) required the re-design of the piston bowl. To avoid excessive wall impingement using early injection, the NADI concept required deepen and narrow bowl types with adapted fuel injection systems, as notable from the Figure 6. The research activities on NADI system development for HD engines lead to a homogeneous operation with high EGR-rates up to approximately 10 bar BMEP. This was considered not sufficient for a HD Diesel engine which in real road missions often operates in a BMEP-range up to 25 bars. At the same time a dual mode operation using homogeneous combustion at low BMEP’s and heterogeneous combustion at high BMEP’s was considered technically and economically a not good compromise.

If the HCCI combustion mode is considered not feasible today for series application, recent trends indicate a possible improvement in PM control with high EGR rate increasing both the maximum injection pressure and premixed fraction of the Diesel combustion (in order to increase the engine EGR tolerance). This will require a correspondent improvement in the fuel spray and bowl wall interaction. On this way, as reported by Nicol (2007), to meet Heavy Duty engine Euro 6 emission targets, the inlet swirl ratio has to be matched better to fuel system and nozzle



**Figure 6: Overview of the NADI™ combustion system concept [Colliou et al., 2006].**

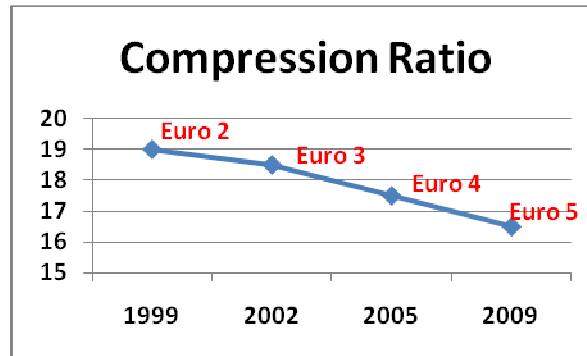
geometry, and at the same time, the piston bowl with re-entrant geometries has to be optimized in order to improve the mixing at retarded injection timings. So also the squish flow will have importance in the future for the premixed combustion optimization. The employment of flexible engine head (multivalve with swirl ration control), optimized nozzle geometry and piston bowl have a great potential in the improvement of NO<sub>x</sub>-PM trade-off as shown in Figure 7. These key-technologies addressed to the in-cylinder air-fuel mixing process have a great potential in the transferability to the rail sector.



**Figure 7: Smoke emission reduction at low air-fuel ratio (with high EGR) by means of combustion process improvement [Nicol, 2007].**

In the GREEN project (2008), a special research work was dedicated in the piston bowl optimization when innovative injection strategies are employed (multiple injections). In the final report the bowl modification criteria was not reported, but was claimed that significant improvement were reached coupling multiple injection with a new piston bowl design.

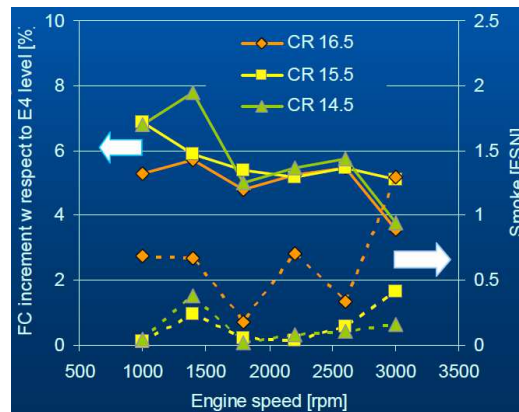
Another key parameter of the combustion system design affecting strongly the combustion process is the compression ratio. Theoretically, it is well known that the thermodynamic efficiency is proportional with the compression ratio. Nevertheless, in the real Diesel engine cycle the compression ratio has to be limited to avoid excessive peak pressure during combustion and so too high mechanical stress for the engine components. Looking at the compression ratio variation versus years for both LD and HD, a trend in its reduction can be observed. As an example, the Figure 8 shows the average compression ratio value for the European LD engines versus years and versus European emission legislation.



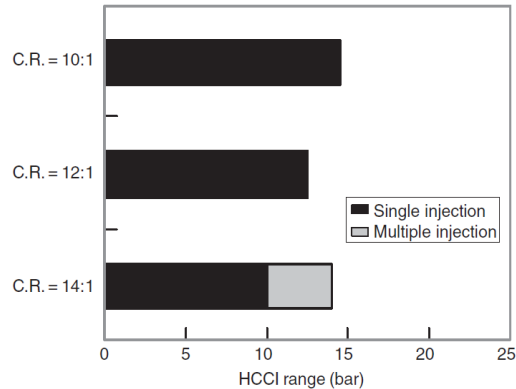
**Figure 8: Average compression ratio value for the European passenger car engines versus years and versus emission legislation.**

Different factors have driven the compression ratio reduction in the last decade, as for example the improvement of the glow plug performance, the improvement of the fluid-dynamic inside the cylinder, the employment of advanced injection system (common rail) able to use pilot injection and high injection pressure etc.

Both for LD and HD engines the main results of the compression ratio reduction was the abatement of soot formation for combustion regimes characterized by premixed and diffusive phase (improving the engine EGR tolerance) and the reduction of the cylinder peak firing pressure. Just to have a look on these effects, Figure 9 and Figure 10 report the results of the change of compression ratio on two different engines as regard the soot emission and the extension of HCCI application area linked with the maximum tolerable peak pressure respectively. The biggest drawback in the compression ratio reduction is the increase of HCs and CO emissions that under certain conditions can become critical also with the use of exhaust DOC systems.



**Figure 9: Fuel consumption increase with respect to Euro 4 standards and smoke emissions versus engine speed for three compression ratio values employing a PCCI engine calibration. [Beatrice et al., 2009].**



**Figure 10: HCCI range with different compression ratio for an HD engine [Colliou et al., 2006].**

Other experiences in compression ratio variation in HD engines were carried out within the GREEN project (2008). In particular the variable compression ratio (VCR) technology was explored in order to improve the fuel consumption at high load coupling the VCR system with an advanced two-stage turbocharger. An improvement of 5% with respect to the Euro 3 standards was reached.

Therefore, the recent trends in combustion system development for both LD and HD engines seem addressed to a reduction of the compression ratio, essentially in order to apply the HCCI or PCCI combustion at low/partial loads. However, as regard this critical parameter of the combustion system design, particular attention have to pay in the possible reduction of compression ratio for rail engines, essentially dependent on the their current status of technology, the cost of the re-design of the combustion system and finally in the concrete possibility to apply HCCI/PCCI combustion concepts in the future.

### 2.1.2 Fuel Injection Management

The choice of the fuel injection mode affects heavily the processes of mixture formation and combustion as well as the emission formation. It is well known that the fuel injection management, both as geometrical and flow rate characteristics, is the main responsible of the improvement of the Diesel combustion process observed in the last years. The main physical parameters of injection process that affect combustion process are injection pressure, velocity, injection timing, flow rate shape, number and timing of multiple injection as well as the main geometrical parameters of the nozzle design (hole numbers, diameters, length, conicity etc.). It is known that NO<sub>x</sub> is produced mainly due to the high local temperatures found in Diesel engines which are highly dependent on the initial rise of heat release. In addition, soot production and oxidation are both dependent on the mixing rate and local flame temperatures. The injection velocity and timing are the most influencing parameters on the previous factors, since their control both the mixing process and the rate of heat release.

With the employment of the electronic control in all injection systems installed on LD and HD on-road engines, the fuel injection strategy has been changed. Today, the basic injection strategy consists in a pilot plus a main injection. This permits the control of the peak of heat release (RoHR) and so of the noise emissions and the mechanical stress of the combustion system

components. The control of soot production during combustion is mainly demanded to an high injection pressure (possible with the use of the pilot injection) and the number, diameter and shape of the nozzle holes. In some more complex injection strategies, also an “after” injection later the main and a “pre” injection very close the main injection can be employed. Moreover a “post” injection can be employed for the DPF regeneration. The injection strategy based on the use of more than two injection per engine cycle is generally named “multiple injection”. A sketch of the overall effects of these injection strategies on the performance of the engine can be observed in Figure 11.

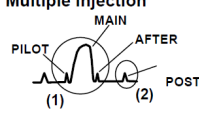
Items	Emission		Competitively		
	NOx	PM	Power	Noise	F/C
Higher Injection Pressure	-	++	+	-	Base
Multiple Injection 					
(1) Injection Duration Control	+	Base	Base	+	Base
(1) Combustion Rate	Base	+	+	Base	Base
(1) Soot Reoxidation	+	Base	Base	Base	-
(2) NOx Cat Conversion	Base	+	Base	Base	-
(2) DPT Regeneration					
Lower Leakage	Base	Base	Base	+	+
Lower Pump Drive Torque	Base	Base	Base	+	+

Figure 11: Requirements for advanced fuel injection system. [Shinohara and Toyao, 2002].

As in the past, also the recent trends on the advanced fuel injection management development indicate a further improvement in the fuel injection flexibility, both in terms of number and timing (multiple injection) and in flow rate control (high pressure and flow rate shaping). This will be very important in order to reach an accurate control of the air/fuel mixing and the interaction with the piston bowl. An overview of the new requirements to the future fuel injection strategies can be noted looking at the next Figure 12.

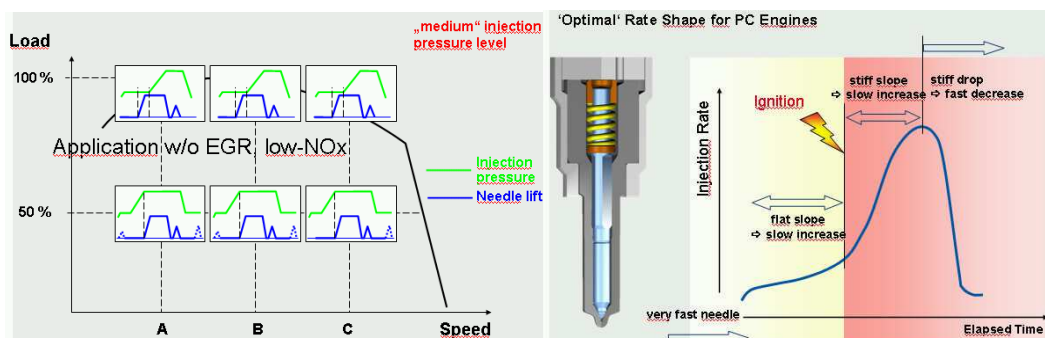
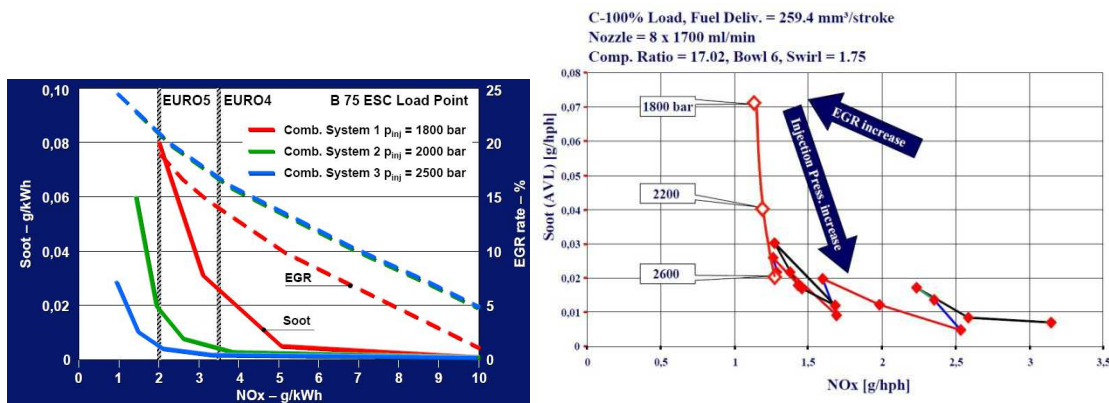


Figure 12: HD engine requirements on future injection strategy (at left) and optimal rate shape (at right). [Ziegler, 2004].

In particular, it is expected an increase of the control in number and timing of the multiple injection as well as to have the possibility to control the fuel injection rate.

As regard the injection pressure level, there is a continuous requirement in injection pressure increment in order to control the soot formation with high EGR rate. To this aim, injection pressure up to 2000 bar will be required in the next generation of LD engines.

The increase of the injection pressure is always a useful way to improve the HD engine performance at full load and the NO<sub>x</sub>-PM trade-off at part load as demonstrated by Moser et al. (2004) and Dreisbach (2005) in the left diagram of the Figure 13 and in the right plot of the same Figure respectively.



**Figure 13: Effects of injection pressure ( $P_{inj}$ ) on Soot-NO<sub>x</sub> trade-off performed by EGR sweep [Moser et al., 2004], at left, and Effects of injection pressure in combination with EGR on Soot-NO<sub>x</sub> trade-off optimization for an HD engine at full load [Dreisbach, 2005], at right.**

About the nozzle design effects on the HD engine performance improvement, a specific workpackage was dedicated in the GREEN project (2008). Results indicate the possibility to reduce soot up to 29% with advanced nozzle design and multiple injection in the steady state test point of 1880 rpm and 265 Nm with a NO<sub>x</sub> emission level of 2 g/kWh. The next Figure 14 shows the results. In the Figure, the third column refers to different injection strategies and different use of the nozzle hole (for detail see the GREEN final report).

The upgrade of the fuel injection management appears as a technological key for the improvement of the combustion control in all diesel engines. As an example, several technological solutions specifically developed to the increase the EGR rate (e.g. two stage turbocharger etc.) will depend on the possibility to increase the EGR tolerance and so the increase of the injection fuel management control. So, also for rail engines, the increase of the in-cylinder NO<sub>x</sub> and PM control will be directly linked with the increase of injection pressure and the adoption of flexible fuel injection strategies.

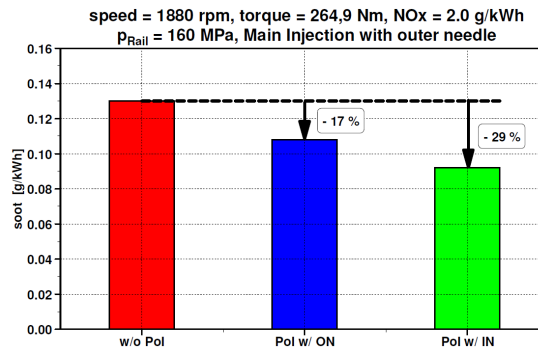


Figure 14: Effects of different injection strategy and nozzle design on soot emissions for an HD engine [GREEN project final report, 2008].

### 2.1.3 Advanced Combustions

As claimed before, the recent trends in the diesel combustion management are addressed to the employment of high EGR rate and stressed premixing level of the air-fuel charge in order to drop down NOx and PM simultaneously. An overview of the different advanced combustion concepts that are under development for LD and HD on-road engines with the relative acronyms are displayed in the Figure 15. All concepts are different in terms of the management of the injection rate, air charge, in-cylinder air motion etc., but all are based on the use of high EGR rate in order to control NOx and PM and reduce the combustion rate (and so the maximum pressure rise).

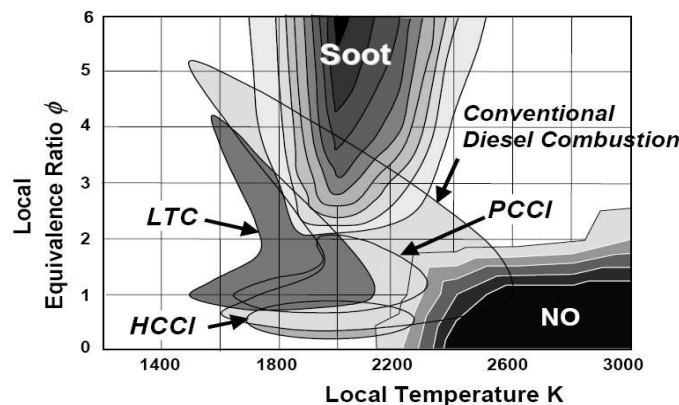


Figure 15: Advanced combustion concepts as HCCI, LTC and PCCI based on the in-cylinder  $\phi - T$  map history.

The choice of one or the other concept will depend from the complexity of the engine system and its management flexibility. As an example, in the Hy-SPACE project, the employment of the HCCI combustion system was considered not economically feasible for HD application. However, in the future, the possible increase of combustion control flexibility could permit the employment of advanced combustion (as example the PCCI or LTC concept) also to HD engines in a feasible

way. As reported by Nicol (2007) this will permit a drastic reduction of NO<sub>x</sub> and PM production in the medium load range.

The usefulness of the advanced combustion technologies in the rail sector will be carefully evaluated in relationships with the different operative conditions between on-road HD engines and rail engines. Taking into account that the rail engine load cycle consists of more idle time with difficulties in the DPF regeneration, the employment of very low NO<sub>x</sub>-PM combustion concepts appears in principle very useful in order to meet the emission requirement with acceptable fuel economy.

---

## 2.2 CONCLUSIONS

The combustion technology listed in Section 2.1 represents the most suitable solutions applicable to HD engines for the in-cylinder NO<sub>x</sub> and PM formation reduction. Of course, depending on the relative complexity they are susceptible of transferability to rail engines. As often reported, the common criteria will be the increase of EGR level in the most possible larger area of engine operating map with the adoption of different combustion technologies in order to improve the exhaust raw NO<sub>x</sub>-PM trade-off with acceptable fuel consumption.

---

## 2.3 REFERENCES

- European project GREEN (Green Heavy Duty Engine), 2008 – Contract N°. TIP4-CT-2005-516195/ Contract N° FP6-516195. Final technical report, Date 10/07/2008;
- Dreisbach R., 2005. Emission reduction technology – Synergies between On-road and Non-road engines. Proceedings of the 3rd AVL International Commercial Powertrain Conference. 20-21/04/2005, Graz, Austria.
- Nicol A., 2007. Heavy-Duty Diesel Engine Trends to Meet Future Emissions Standards (Euro VI). AECC Technical Seminar on Heavy-Duty Vehicle Emissions (Euro VI). Brussels, 25 October 2007. [www.aecc.be/content/HD%20Seminar/7\\_UK%20Ricardo\\_Nicol.pdf](http://www.aecc.be/content/HD%20Seminar/7_UK%20Ricardo_Nicol.pdf)
- Ruggiero A., Tonetti M., Gioannini A., Pelassa M., 2008. Combustion Technologies to meet Euro 6 Emissions Standards on a Diesel D-segment Passenger Car. Proceedings of the SIA International Conference : Le Moteur Diesel / Diesel Engine, Rouen - INSA Rouen (France), 28 & 29 May 2008.
- Gänter U., 2007. Boundaries of in-cylinder Nitric Oxide Reduction regarding Heavy Duty Diesel Engines. Proceedings of the Seminar on Combustion processes at Car Training Institute. 9-10/07/2007, Stuttgart, Germany. Websource: [www.car-training-institute.com](http://www.car-training-institute.com)
- Colliou T., Tilagone R., Martin B., 2006. Adapting the NADI™ Concept to Heavy Duty Engines. Oil & Gas Science and Technology – Rev. IFP, Vol. 61 (2006), No. 1, pp. 73-84.
- Beatrice C., Del Giacomo N., Guido C., 2009. Benefits and Drawbacks of Compression ratio reduction in PCCI Combustion application in an Advanced LD Diesel Engine. SAE paper 2009-01-1447.
- Shinohara Y., Toyao T., 2002. Japanese experience in the Common Rail fuel injection technology. ATA Paper 20A2015. Proceedings of the ATA International Symposium: "The

future of Diesel engine technology for passenger cars". October 12 - 13, 2000. Porto Cervo, Italy

Ziegler G., 2004. Euro 4 and Beyond –Role of Diesel Fuel Injection Systems. Symposium on int. automotive technology (SIAT 2005), Pune, India, January 19–22, 2005. websource: [www.walshcarlines.com/pdf/Impact of Diesel Fuel Injection SIAT 2005.pdf](http://www.walshcarlines.com/pdf/Impact%20of%20Diesel%20Fuel%20Injection%20SIAT%202005.pdf).

Moser F. X., Sams T., Dreisbach R., 2004. Lowest Engine-Out Emissions as the Key to the Future of the Heavy Duty Diesel Engine - New Development Results. Proceedings of the 10th Diesel Engine Emission Reduction Conference, Aug. 30 – Sept. 2, 2004, San Diego, CA, USA

### 3. AIR MANAGEMENT

“The objective of charging is to raise the charge density of the working media (air or air-fuel mixture) before entering the working cylinder by any way and with the help of a suitable system, i.e. to precompress it. Besides, the temperature of the working media should not be noticeable raised in order not to unfavourably affect the temperature profile of the high-pressure working process.” [HIERE]

#### 3.1 PAST RESEARCH

##### 3.1.1 Current Technologies for Diesel Engine Charging

Von Hoerner et al [MAN] justifies the exclusive use of superchargers within the commercial motor vehicle range with efficiency advantages towards mechanical loaders. Because of lower costs and higher long-term durability turbochargers with Waste gate are preferred to turbochargers with variable turbine geometry. For EURO V/VI pressure ratios of 4 are required for applications of commercial motor vehicles. Therefore a 2-stage exhaust gas turbocharger with intercooling is used. As a result of the rising pressure ratio the exhaust gas temperatures decrease after the turbocharger system. This results in higher requirements for the subsequent after-treatment system. For the regeneration of the DPF additional heating measures are necessary.

Wintruff et al [MTU-1] described the control concept for charging a MTU engine series 4000 for naval application. For this purpose the engine map was subdivided into 5 ranges as a function of engine speed and engine torque. According to the principle of the single-step register charging certain turbochargers are switched off with reduced load to adapt the throttle cross section of the turbines to the reduced air flow of the engine (Figure 16).

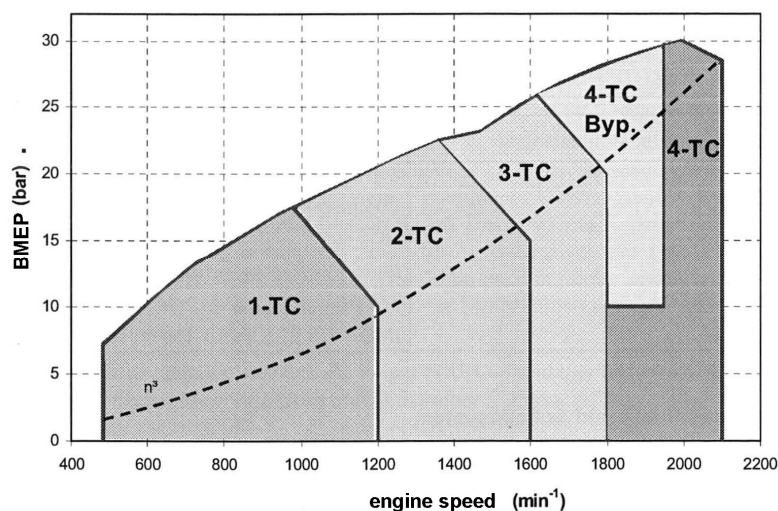


Figure 16: Engine map with operating range of register charging [MTU-1]

The demands with regard to long-term durability and efficiency are at least as high for rail applications as for heavy duty vehicles. In rail applications the transient operation is not in the foreground. For these both reasons fixed turbo-chargers are used in this field.

Edwards et al [BEHR] carried out fundamental investigations especially regarding the cooling technologies for heavy duty vehicles for meeting EURO VI. Three different concepts were examined:

- Concept SCR (SCR) with 1 stage charging.
- Concept EGR (EGR) with 2 stage charging and Diesel particle filter (DPF).
- Concept low temperature EGR (LT-EGR) with 2 stage charging and DPF.

For the concept SCR an air-to-air-charging cooler was used. For concept EGR and concept LT-EGR two charging coolers and an EGR water cooler were used. In addition, an additional low temperature cooler existed in the concept LT-EGR. Caused by the different concepts, a 37% higher heat quantity had to be dissipated for the EGR-concept than for SCR. Because the air temperature before engine intake could be lowered for the LT-EGR concept, savings effects arose in rejected heat and engine heat. All together the heat quantity to be dissipated was about 6% lower as in the concept EGR.

In rail engines with emission stage IIIa EGR is already used for the in-cylinder emission lowering. If this path is followed up to the emission stage IIIb, the EGR-rates are rising. Besides, the recirculated exhaust gas must be cooled and the released heat quantity be led away.

### 3.1.2 Increased Boost Pressure

Codan et al [CODAN] described different possibilities for increasing boost pressure. These are shown in Figure 17. Summarizing this work, it can be concluded that pressure ratios of 5 to 6 a 1-stage turbocharger is the best solution. For pressure ratios > 6, in particular > 8, the best choice is a 2-stage charging with 2 free running turbochargers.

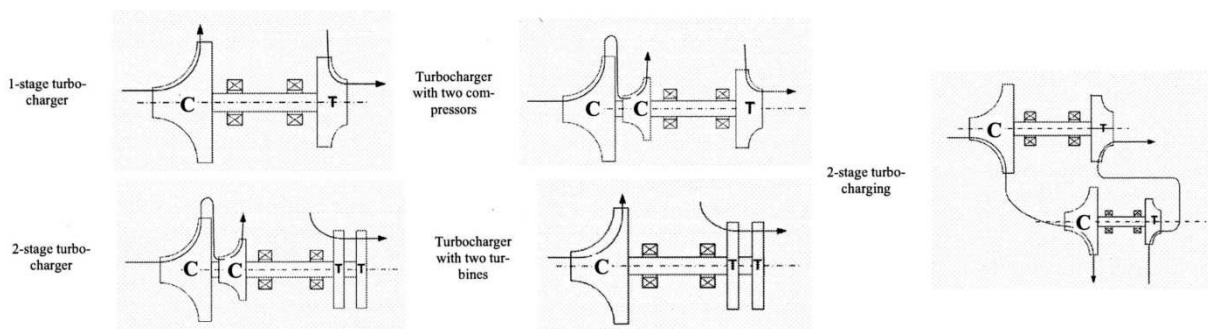


Figure 17: Variants of high pressure turbo-charging [CODAN]

The following advantages for the 2-stage charging with pressure ratio > 8 were mentioned in [CODAN]:

- I. Size of the turbochargers decreases because this is determined by turbine surface
- II. Efficiency of turbocharging can improved by intercooling
- III. Very good flexibility of the system
- IV. Better flexibility of the control
- V. Reliability and durability are in general better because of moderate compression ratios
- VI. Small turbochargers show better acceleration and vibration behaviour

With the combination of Miller-cycle and 2-stage high-level charging emission and consumption advantages can be achieved. Codan et al. [CODAN] carried out simulations regarding the combination which was confirmed by engine tests (Figure 18). The improvements of NOx result from the decrease of charge temperature by the Miller-Cycle. The reduction of fuel consumption is caused by the improvement of the thermodynamic efficiency during high-level charging.

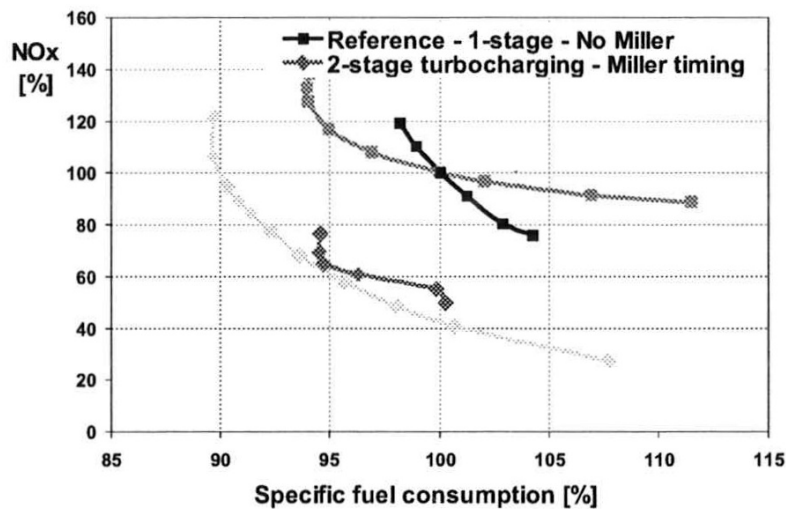


Figure 18: Engine results in comparison with the simulations [CODAN]

The high-level charging enables to add a certain portion of the exhaust gas as an inert gas to the fresh gas mass. For this purpose Sandig et al. [FIF-1] carried out investigations, where clear NOx reductions could be achieved with moderate increase of the filter smoke number by in-cylinder measures (Figure 19). These investigations were the basis for meeting stage IIIa for a MTU engine for rail application [MTU-2].

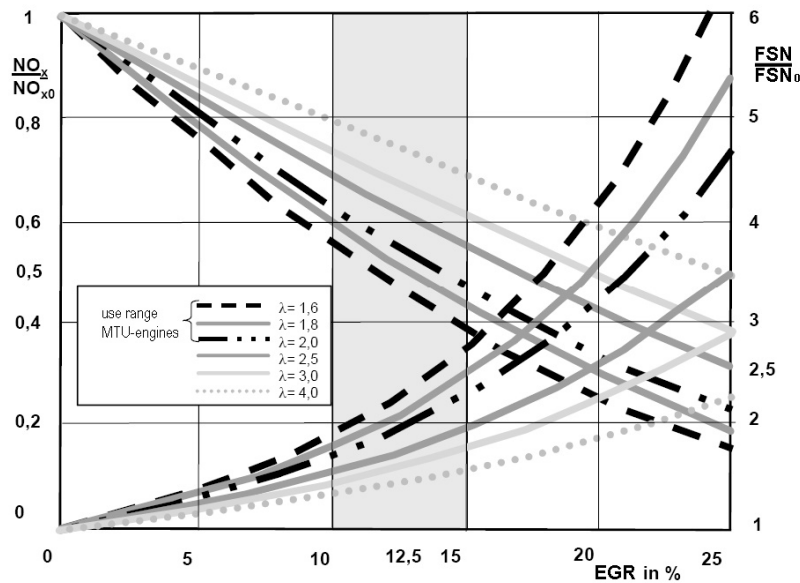
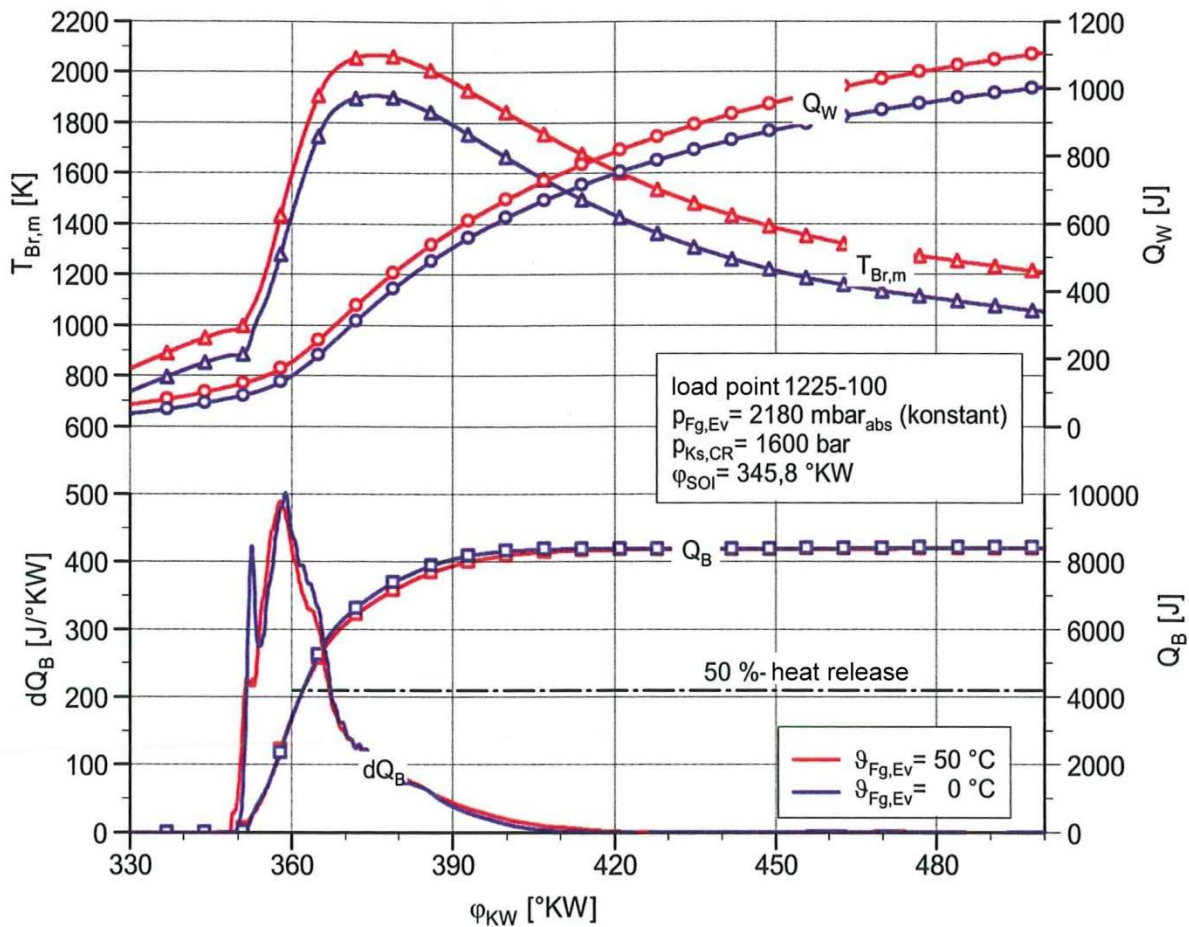


Figure 19: Impact of EGR to NOx and PM emission [FIF-1]

### 3.1.3 Enhanced Intercooling

In FVV project 'extreme air cooling for charging' [FIF-2] the influence of the charging air temperature on the course of the combustion and on the emissions (with priority to NOx and PM) was examined. Therefore the charging air temperatures were lowered up to 0°C. In Figure 20 the differences with regard to the calculated average temperature of the inertia  $T_{BR,m}$  between the charging air temperature of 0°C and 50°C at constant boost pressure is presented. As expected the filter smoke number decreased. A NOx reduction could be obtained in this operating point however only when the charge mass advantage was used by the cooling at the inlet of the EGR. A lowering of the specific fuel consumption of 10% could be proved. This could be explained by the lower wall heat losses  $Q_w$  due to the lower average temperature of inertia  $T_{BR,m}$ . Nevertheless, this was accompanied by an unfavourably increase in ignition pressure of up to 15%. By cooling the ignition delay is extended and therefore the premixed portion of the combustion changes. This is clearly shown by the peak at the beginning of the combustion in the heat release curve  $dQ_B$  in Figure 20. Nevertheless the sum heat release  $Q_B$  changes only slightly.

Practically such a high cooling of the intake mass is hardly representative in heavy duty vehicles as well as in rail engines. Nevertheless, basically the potential can be estimated what originates from the cooling of the intake mass.



**Figure 20: Differences in thermodynamic analysis for intake temperature of 0°C and 50°C at full load [FIF-2]**

### 3.2 CONCLUSIONS

In principle the way for reaching future emission limits for heavy duty vehicles and rail engines need an increase of the pressure ratios before engine intake. However, the status quo is different. For heavy duty vehicles a pressure ratio of 4 is required for EURO V/VI [MAN], whereas pressure ratios > 4 for rail engines are state-of-the-art today. For these engines the aimed pressure ratios is between 6 to 8 [CODAN]. In this case a technology transfer of the heavy duty vehicle to the rail application cannot be expected.

For future emission targets this encloses the following challenges:

- The choice of a suitable after-treatment system which works at very low temperatures downstream the turbocharger and with sufficient reliability and durability.
- The removal of the high heat flow from the charging air and EGR cooling.

The stationary test cycle after ISO 8178 T4 F can be seen as an advantage for the application of the charging as well as the after-treatment system, because this test consists only of 3 stationary test points. At the moment there are not transient test procedures for rail applications.

### 3.3 REFERENCES

---

- [BEHR] Edwards, S.; Eitel, J.; Pantow, E.; Lutz, R.; Dreisbach, R.; Glensvig, M.:  
Emissionskonzepte und Kühlsysteme für Euro 6 bei schweren Nutzfahrzeugen  
In: MTZ 69 (2008), Nr. 9, S. 690 ff
- [CODAN] Codan, E; Mathey, Ch.:  
Hochdruckaufladung bei Grossmotoren  
Dresden, 12. Aufladetechnische Konferenz, 2007
- [FIF-1] Schneemann, A.; Sandig, R.; Bach, E.; Emmrich, Th.; Hofmann, U. Bergmann, D.;  
Philipp, C.:  
Nutzung der Potenziale der Abgasrückführung zur Erfüllung zukünftiger strengster  
Abgasemissionswerte für Dieselmotoren schwerer Nutz- und Schienenfahrzeuge  
In: BMBF-Projekt FKZ 19 U 9921 2, 1999 - 2002
- [FIF-2] Lienig, U.; Zikoridse, G.:  
Tieftemperaturverbrennung durch extreme Ladeluftkühlung (Vorhaben 879  
Abschlußbericht)  
Frankfurt/M., FVV-Heft 861, 2008
- [HIERE] Hiereth, H.; Prenninger, P.:  
Aufladung der Arbeitskraftmaschine, Der Fahrzeugantrieb  
Wien/New York, Springer-Verlag, 2003
- [MAN] von Hoerner, R.; Lämmermann, R.; Reisch, S.; Weiß, J.:  
Abgasturboladerkonzepte für heute und zukünftige Nutzfahrzeugmotoren  
Dresden, 12. Aufladetechnische Konferenz, 2007
- [MTU-1] Wintruff, I.; Mänle, T.; Traub, R.; Oberste-Brandenburg, C.:  
Einstufige Hochaufladung für die leistungsgesteigerten Marinemotoren der MTU-  
Baureihe 4000  
Dresden, 12. Aufladetechnische Konferenz, 2007
- [MTU-2] Bergmann, D., Phillip, Ch., Rall, H.; Traub, R.:  
Erprobung der Abgasrückführung an schnelllaufenden Schiffs- und Lokmotiv-  
Dieselmotoren  
In: MTZ 68 (2006), Nr. 1 S. 20 ff

## 4. DIESEL FUEL INJECTION

The Diesel injection technology has developed during the last 20 years very strongly. Beside the charging technology and the after-treatment technologies it belongs to the key technologies for a highly efficient and environmentally friendly internal combustion engine.

Section 4.1 below discusses the state-of-the-art in fuel injection technologies for passenger cars and heavy duty vehicles and evaluates the potential for transferring these technologies to rail applications.

### 4.1 PAST RESEARCH

#### 4.1.1 Unit Pump and Unit Injector

At these systems no more developments were made or published recently. All current developments refer to Common Rail systems, because the largest technological development potential is seen herein.

#### 4.1.2 Common Rail

A direct acting nozzle needle was introduced by DELPHI [DELPHI] by means of a piezo stack (see Figure 21 right). For the adaptation of the low displacement a hydraulic transmission is used for the activation of the nozzle needle. The application is first intended only for passenger car. Basically this technology is applicable for heavy duty vehicles as well as for rail applications.

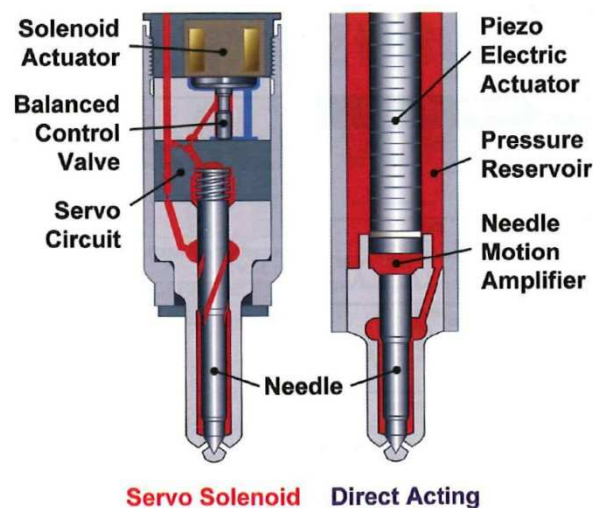


Figure 21: Differences between servo controlled and direct acting [DELPHI]

Comparing to servo-hydraulically control, regardless whether it is acted by solenoid or piezo stack (Figure 21 left), there are the following advantages:

- no leakage
- excellent repeatability of total injection quantity for multiple injection
- independency of needle lift on system pressure → quicker opening and fastenings
- Lower variations between injections → better reproducibility
- better performance for small injection quantities in comparison to the servo-hydraulic acting injector

A new pressure-translated injector of the 4th generation was introduced by BOSCH [BOSCH]. This is characterized by a separation of injection and pressure transmission module. Both are separately switchable with the help of single solenoid valves, so that with this system an injection rate shaping is also realizable.

The injector has the following features [BOSCH]:

- Flexible and hydraulically efficient injection rate shaping for the optimisation of the high load points
- pre-injection and post-injection with rail pressure  $\leq 900$  bar reduces the spray impulse and the wetting of the cylinder surface with fuel → lower / no dilution of lubricant
- minimization of high pressure loaded parts
- pump, rail and lines must be dimensioned only for 900 bar (in this example)

Mechanical as well as overall properties of this injector are relevant for rail applications. In particular all measures for the thermo management which can be realised with the help of this injection system can be realised with less construction effort.

An external solution for the injection of Diesel fuel in the exhaust gas pipe after the turbine was introduced by Renault [RENAUL]. This system avoids the wetting of the wall with fuel which can occur when using post-injection as a possible in-cylinder solution. For this system a gasoline injector has been modified and optimised. The pressure supply is realised at the low pressure side of the high-pressure pump. From other manufacturers (e.g., Daimler, EPA engines) similar systems are also known.

If an external solution is necessary for the thermo management in rail application, a HC-doser system is needed. For commercial vehicles such systems have been already established because no late post-injection is possible with the injection systems used here (UI,UP). For rail applications such a solution is scalable.

### 4.1.3 Injection Pressure Development

In the publication of Bosch [BOSCH] (Figure 22) a prospect on the development of the injection pressure is given. It is estimated that by high boost pressures and high EGR-rates a rise of the injection pressure will be necessary up to 2500 bar. With it the rising of particle emission as a result of the high EGR-rates can be counteracted by the improvement of the internal mixture formation.

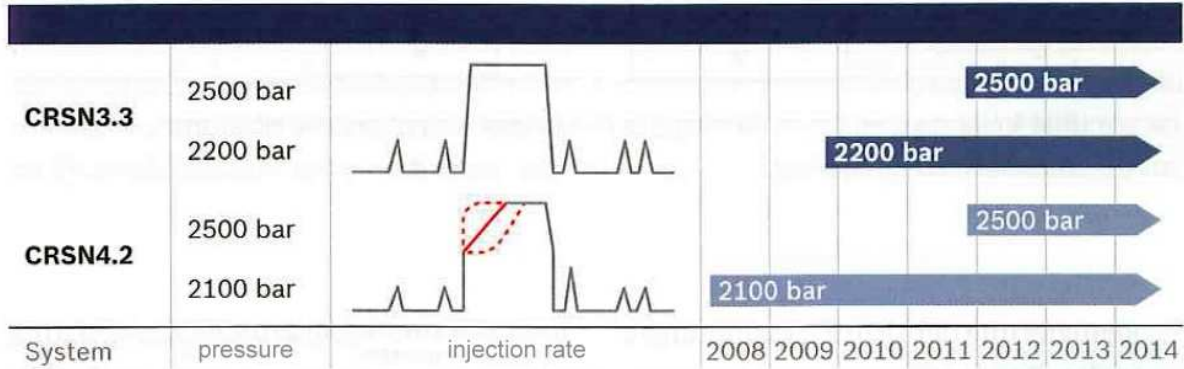


Figure 22: Development of injection pressure [BOSCH]

#### 4.1.4 Injection Timing

Kozuch et al [HDT] have been published investigations showing the dependency of start of injection and injection pressure on the emissions. Figure 23 (left side) show the already known relation that a misalignment of the start of injection towards late causes a late combustion and a late centre of heat release. The NOx emission decreases whereas the fuel consumption rises. Figure 23 on the left side shows that this does not depend on the injection pressure which was varied. Figure 23 on the right side shows the reduction of the particle emission with increasing injection pressure.

Rail applications meet the current emission limits (stage IIIa) with the help of in-cylinder measures [MTU]. For this purpose the exhaust gas recirculation (EGR) is used for the reduction of the NOx emission. To cope with future emission limits (e.g. stage IIIb) a rising of the injection pressure is favourable. This knowledge is the connection to the trends displayed in Figure 22 for the development of the injection pressures.

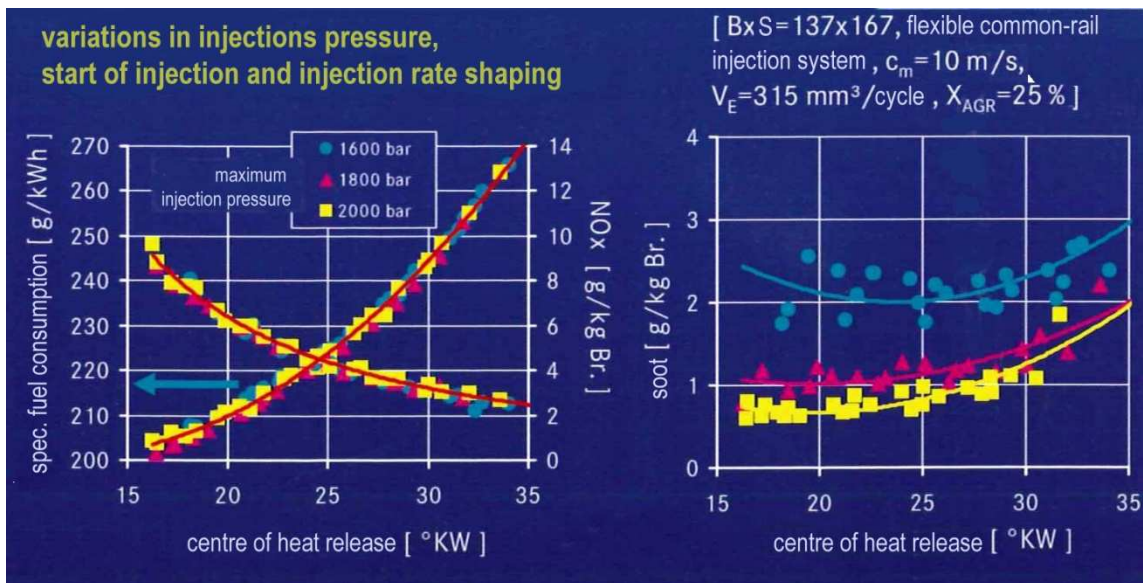


Figure 23: Influences of injection pressure and start of injection on fuel consumption and emissions [HDT]

#### 4.1.5 Strategies for Multiple Injection

Kozuch et al [HDT] also discussed different strategies with the multiple injection with / without EGR. Müller et al [FVV] examined combustion processes for homogeneous combustion for the heavy duty vehicle sector. Table 2 shows the strategies and specific features in tabular form.

Pos.	strategy	EGR	NOx	PM	Remarks
1	Pre-/main injection [HDT]	3%	↑	↓	Pre-injection quantity is converted in premixed combustion and leads to a temperature rise in the combustion chamber, approx. 25% NOx is thereby formed Main injection quantity burns diffusion controlled Pressure gradient and sound pressure level are lowered
2	Pre-/main-/ post-injection [HDT]	30,5%	↓	↑	Slow pre-combustion Main injection into the pre-combustion → high soot increase Post-injection causes insufficient soot oxidation => adaption of the strategy from pos. 1 not possible
3	late main injection [HDT]	30,5%	↓	↓	Injection to TDC + long ignition delay Combustion only after finishing injection HPLI- process → homogeneous combustion
4	Main-/ post-injection [HDT]	24-30%	↓	↓	Potential only usable with high EGR-rate Early start of the main injection because of high ignition delay Post-injection shortly after the main injection → premixed combustion
5	Early multiple injection [FVV]	>60%	↓	↓	Partitioning of the total injection quantity on several short injections → avoidance of wall wetting Start of injection approx. 90°CA before TDC, last injection at 40° CA before TDC Control of combustion with EGR-rate Homogeneous combustion → up to 8 bar imep
6	Early multiple injection + late main injection [FVV]	0%	↓	↓	Division of the combustion in homogeneous and heterogeneous combustion → division of the injection quantity For homogeneous combustion → several short injections → avoidance of wall wetting For heterogeneous combustion → injection after finishing homogeneous combustion

**Table 2: Different injection strategies in Diesel combustion**

The strategies listed before focus on in-cylinder emission reduction and could be adapted for rail applications. In particular the introduced strategy in pos. 3 of Table 2 is relevant for an internal solution because, NO<sub>x</sub> and particle emission can be simultaneously reduced.

#### 4.1.6 Injection Rate Shaping

Rate shaping by influencing the needle lift or needle speed is possible with directly driven, piezo-acting injectors [ITV-H]. Therefore the current control can be accordingly adapted for the piezo stack. Investigations by FEV [FEV] shows only low advantages for the noise and worse specific fuel consumption, CO and FSN was observed. Therefore the modulation of the needle lift for injection rate shaping is not the right way.

The modulation of the system-pressure is another proposal to the exposition of the injection rate shaping. This is the operating principle of a injections system developed by the FEV [FEV]. The configuration consists of a proportional pretransfer valve and a conventional spring-loaded injection nozzle. Both assemblies are combined in the injector housing. As an advantage the quick opening and fastenings of the spring-loaded needle is mentioned beside the freedoms with the modifications of the injection rate. With it the range of the seat throttling will fast left during opening and fastening. Remarks to the influence on the emission behaviour was not made.

In the FVV project, injection rate shaping II' [FIF] investigations were carried out with a pressure-modulated system of a MTU single cylinder research engine like series 4000 with pre-transfer valve (proportional valve) and CR-injector. By means of the steady throttle which is in the line between the proportional valve and the injector a decrease of the system pressure can induced during operation. This represents the injection pressure at the start of the injection. By switching the proportional valve before or during the injection the injection pressure is raised to the rail pressure.

This investigation especially focused on:

- heterogeneous combustion process with different combustion chamber bowls
- Influence of the injection system on the emissions

Results of the investigation:

- Pressure modulation has no significant improvement on the trade off's (NO<sub>x</sub>, FSN, BSFC) compared with the conventional Common Rail-injection system
- The huge equipment needed is not justified.

Application examples of such systems are not known in practice. Kozuch et. al. [HDT] observed no important influence of injection rate shaping on soot emission at high load and 25% EGR rate. In fact the position of the combustion centre of heat release and the injection pressure is more important.

Based on the investigations listed before the injection rate shaping is not useful for significant emission reduction for rail applications.

---

## 4.2 CONCLUSIONS

The development and the mass production of injectors with directly driven nozzle needle [DELPHI] as well as injectors with internal pressure transmission [BOSCH] indicate the trends in the injection technology. These injectors are transferable because of the same requirement profile and similar speed ranges of heavy duty vehicles and rail engines.

For future emission limits injection strategies with several injections per cycle become more important. The precision in reproducibility and repeatability of injection quantity plays a determining roll. For this purpose, injectors with directly driven needle are superior to injectors with servo hydraulic driving mechanism.

The increase of the injection pressure has a determining impact in the in-cylinder emission reduction. This applies on for heavy duty engines as well as for rail engines.

With the increase of the injection pressure the demands for the whole injection system become higher. By the pressure transmission in the injector only adjacent components are in contact with the high pressure. A lower system pressure decreases the demands for the pressure resistance of lines, screw connections and high-pressure pumps.

---

## 4.3 REFERENCES

- [BOSCH] Leonhardt, R.; Parche, M.; Alvares-Avila, C.; Krauß, J.; Rosenau, B.:  
Druckübersetztes Common-Rail System für Nutzfahrzeuge  
In: MTZ 70 (2009), Nr.5, S. 368 ff
- [DELPHI] Schöppe, D.; Zülch, S.; Hardy, M.; Geurts, D.; Jorach, R.; Baker, N.:  
Common-Rail-Einspritzung mit Direkt-Acting-Injektor von DELPHI  
In: MTZ 69 (2008), Nr. 10, S. 842 ff
- [FEV] Schmücker, J.; Pischinger, S.; Laumen, H.; Krüger, M.:  
Possibilities of injection rate shaping on heavy duty engines.  
München, Haus der Technik, 2005
- [FIF] Sandig, R.; Zikoridse, G.:  
Einspritzverlaufsformung II – Potenzial der Einspritzverlaufsformung bei  
luftverteilenden Brennverfahren in GroßDieselmotoren (Vorhaben 849  
Abschlußbericht).  
Fankfurt/M., FVV-Heft 861, 2008
- [FVV] Müller, E.; Weiskirch, Ch.; Bach, E.; Emmrich, Th.; Schneemann, A.:  
Homogene Dieselverbrennung – Verfahren zur Emissionsreduzierung, Teil 2:  
Untersuchungen am Nfz-Dieselmotor  
In: MTZ 67 (2006), Nr. 11 S. 906 ff
- [HDT] Kozuch, P.; Gärtner, U.:  
Besonderheiten der Abgasrückführung bei Nutzfahrzeugen  
In: Motorische Verbrennung, Heft 5.1, Haus der Technik e.V., 2005

- [ITV-H] Meyer, S.; Krause, A.; Krome, D.; Merker, G.:  
Ein flexibles Piezo-Common-Rail-System  
Im: MTZ 63 (2002), Nr. 2, S. 86 ff
- [MTU] Bergmann, D., Phillip, Ch., Rall, H.; Traub, R.:  
Erprobung der Abgasrückführung an schnelllaufenden Schiffs- und Lokomotiv-  
Dieselmotoren  
In: MTZ 68 (2006), Nr. 1 S. 20 ff
- [RENAUL] Fasolo, B.; Hardy, J.; Leroy, K.:  
Abgaskraftstoffsystem für effiziente DPF-Regeneration  
In: MTZ 70(2009), Nr. 8, S. 554 ff

## 5. EXHAUST GAS RECIRCULATION

### 5.1 INTRODUCTION

Cooled Exhaust Gas Recirculation (EGR) has generally been used in Heavy Duty trucks since the introduction of US2004 in 2002. EGR allows a significant reduction in  $\text{NO}_x$  but is followed by increased PM, CO and HC emissions and also increased fuel consumption, these increases are however quite small and can easily be handled if EGR is kept below 30-40 %. Due to the increase in PM emissions an EGR strategy for  $\text{NO}_x$  reduction is often combined with a DPF (Diesel Particulate Filter). EGR between 20 and 40 % can reduce  $\text{NO}_x$  emissions by more than 50 % where higher loads require higher EGR-levels. It is important that cooled EGR is used since otherwise PM emissions will increase too much.

The emissions formation in a Diesel engine can be visualized using a so-called equivalence ratio-temperature map, see Figure 24. This type of map was first used by Kamimoto et al (Kamimoto T. and Bae M, 1988)

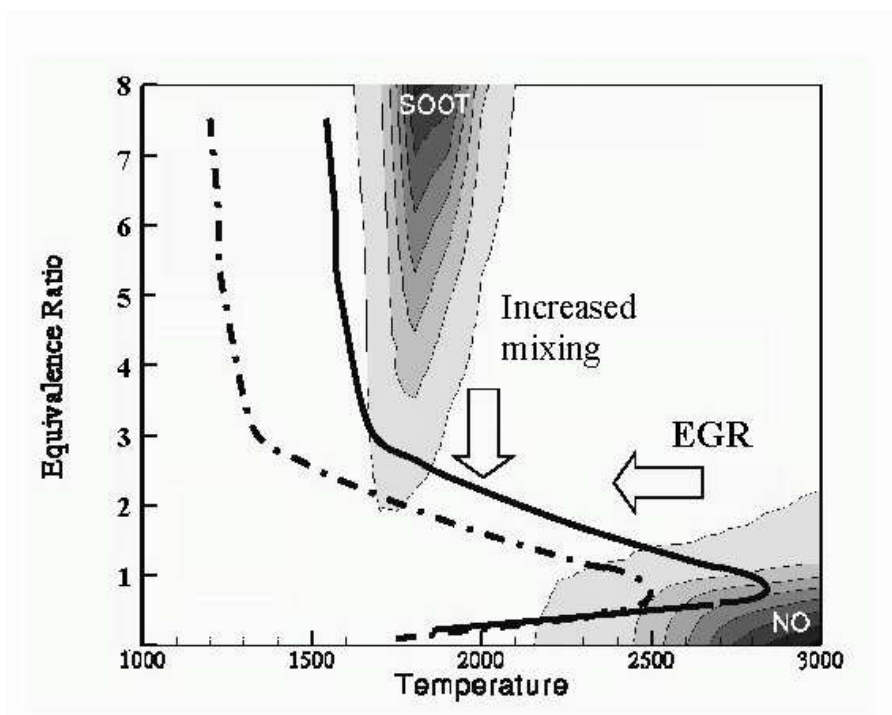


Figure 24: Emissions map for soot and  $\text{NO}_x$  as a function of Equivalence ratio [-] and Temperature [K].

From Figure 24 it can be seen that soot is formed in rich conditions, with equivalence ratios  $> 2$ , and at intermediate temperatures. At high temperatures the Polycyclic Aromatic Hydrocarbons (PAH, which are soot precursors) are oxidized instead of forming soot, while at low temperatures the temperature is too low to transform PAH into soot (Akihama K. Takatori Y. Inagaki K. Sasaki

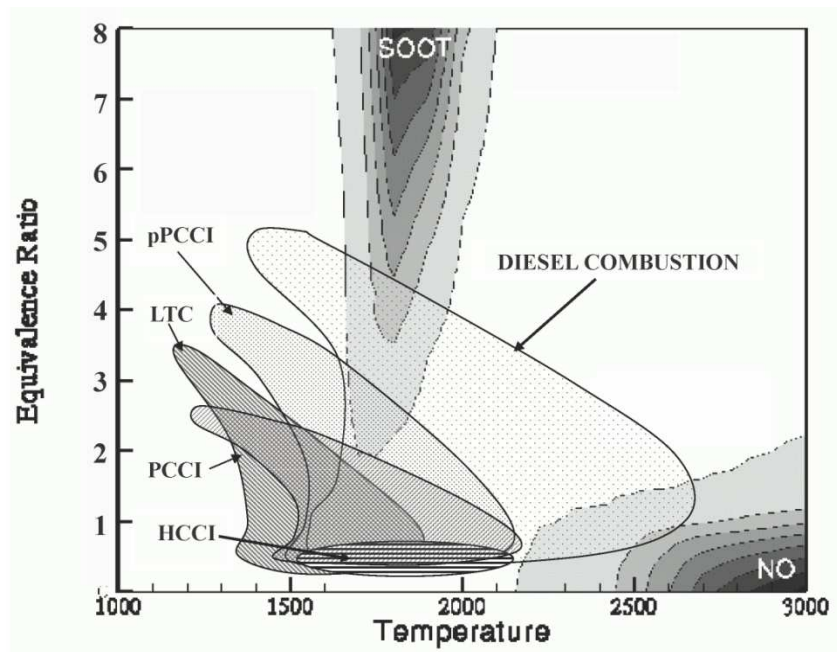
S. and Dean A. 2001). NO is formed at high temperatures in lean conditions due to the high activation energy of the  $O + N_2 \rightarrow NO + N$  reaction of the Zeldovich mechanism (Zeldovich 1947) and its dependence on the  $O_2$  concentration. Soot oxidation takes place at high temperatures and in lean conditions, so the soot oxidation zone to a large extent overlaps the NO formation area.

Figure 24 also shows lines indicating the adiabatic flame temperature (at constant volume); the highest temperature that can be obtained if all chemical energy is converted to thermal energy in an adiabatic system. The figure indicates that the local combustion temperature should be kept below approximately 2200 K to avoid high NO formation at low equivalence ratios. At high equivalence ratios (>2) it becomes necessary to further decrease the maximum allowable temperature to completely avoid soot formation. If the local flame temperature is kept below approximately 1650 K, both the NO and soot formation areas are completely avoided regardless of the equivalence ratio. Also, rapidly mixing fuel and air to local equivalence ratios > 2 prevents soot formation. As indicated by Figure 24 there are essentially two kinds of measures for reducing soot and NO emissions formation:

- Measures that lower the local flame temperature such as EGR and reductions in the initial temperature or compression ratio.
- Measures that increase the mixing velocity, such as raising the injection pressure, reducing the orifice size and increasing swirl.

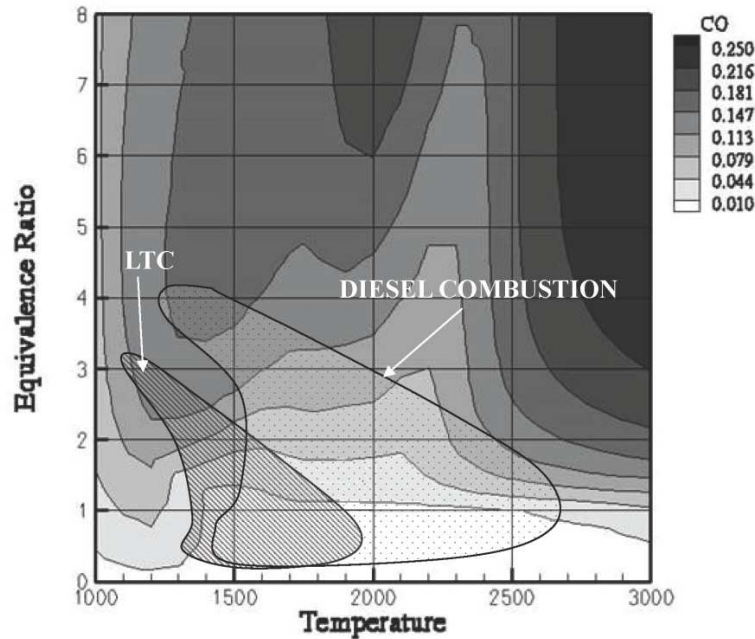
In most cases a combination of increasing the mixing and reducing the temperature is used.

Several different combustion regimes can be defined depending on the local in-cylinder conditions during combustion, see Figure 25.



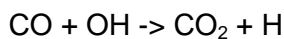
**Figure 25: Illustrative Equivalence ratio-temperature maps for “classical” Diesel combustion and several alternative modes**

Other factors must also be taken into consideration when selecting a combustion system. Figure 26 shows a map of CO emissions as functions of equivalence ratio and temperature.



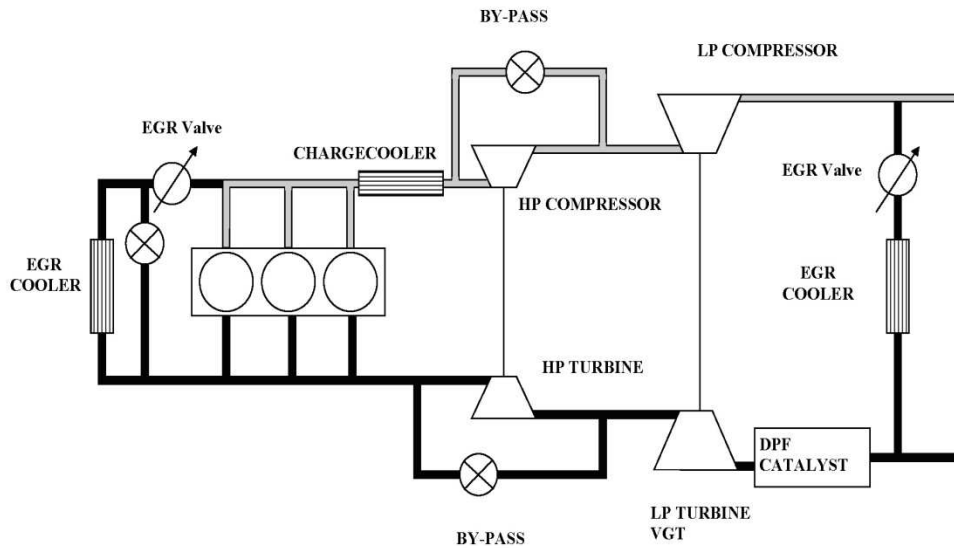
**Figure 26: CO emissions map as function of Equivalence ratio [-] and Temperature [K].**

CO conversion occurs via the reaction:



This reaction is slow and at low temperatures it can deviate substantially from equilibrium. From Figure 26 it can be seen that CO emissions increase substantially at temperatures <1400 K. This is due to a rapid decrease in OH radical production at these temperatures. High EGR combustion systems therefore often suffer from elevated CO emissions which reduce the combustion efficiency and thus reduce engine efficiency.

Future Diesel engines will have to meet increasing demands for reductions in exhaust emissions and fuel consumption. To ensure emissions are sufficiently low, large amounts of EGR will have to be used to control NO<sub>x</sub> formation and ignition delays (to allow premixed or partially premixed combustion) at higher than currently possible loads. The charge temperature must also be low to ensure NO<sub>x</sub> and soot emissions are low. These adjustments will increase the demands for high charging pressure, and for further enhancement of the transient behaviour of the charging system. A conventional charging system cannot be used since it will not allow high amounts of EGR to be used during transient changes, and the maximum load with high EGR will too low. To significantly increase the charging pressure a 2-stage charging system could be used, the main advantage of which is that two differently sized compressors can be connected in series so that two optimized maps can be used, one for high flow and one for low flow conditions, thereby greatly expanding the useable compressor map and allowing higher charging pressures.



**Figure 27: Schematic diagram of a 2-stage turbo charging system with long route (low pressure) and short route (high pressure) EGR**

At the low exhaust flows associated with low engine speeds the exhaust bypass is closed and the whole flow passes through the high pressure turbine. When the exhaust flow increases at higher engine speeds the bypass starts to open and increasingly large proportions of the exhaust gasses are expanded solely in the low pressure turbine.

In Figure 27 two EGR systems are schematically shown: a so-called long route, and a short route system. To maintain sufficiently high EGR flows at low engine speeds, when the backpressure from the silencer is low, long route EGR also often requires an exhaust throttle. Long route EGR offers better mixing with the fresh air and better EGR distribution between cylinders than short route EGR. At low engine loads short route EGR is often used, and at very light loads the EGR cooler is also sometimes by-passed to increase the intake temperature and reduce cyclic variations, especially when using Low Temperature Combustion. At medium and high load conditions low pressure EGR is mainly used but the control strategy depends on the specific system architecture. The EGR route that provides the lowest backpressure at a given EGR level should be chosen.

## 5.2 COMPONENTS

### 5.2.1 EGR Valves

EGR valves can be of different designs; examples are butterfly valves or poppet valves. Most EGR valves for heavy duty engines are today electrically actuated where stepper motors or linear solenoids are used for controlling the valve motion.



**Figure 28: Delphi Dual Poppet Rotary EGR Valve with Torque Motor**

An EGR valve must have design that prevents carbon contamination, which can adversely affect the valve operation. An EGR valve must also have a fast opening and closing response time to cope with transients (less than 50 ms, [Flaig, 2000]).

### 5.2.2 EGR Coolers

To be able to reach low  $\text{NO}_x$  high efficiency EGR coolers adopted for a wide range and high rate of EGR must be used [Adachi, 2009]. The EGR cooler should reduce the recirculated exhaust temperature from a maximum 650 C down to a maximum of about 130 C if the engine coolant is used as a cooling medium. Since the thermal conductivity is a key factor cooler material is important, the material must also be highly corrosion resistant and resist deposit build-up. The cooler tubes can have fins or be corrugated on the gas side in order to increase heat transfer but also to counteract fouling. EGR coolers usually have a counter flow arrangement.



**Figure 29: Pierburg EGR Cooler and EGR valve**

A cooler by-pass as shown in Figure 27 can also be integrated in the cooler design as been shown by Tokyo Radiator Mfg Co [green car congress].

For lower EGR temperatures a 2-stage cooling strategy is needed where a second cooler that uses ambient air as a cooling medium can be used, see Figure 30.

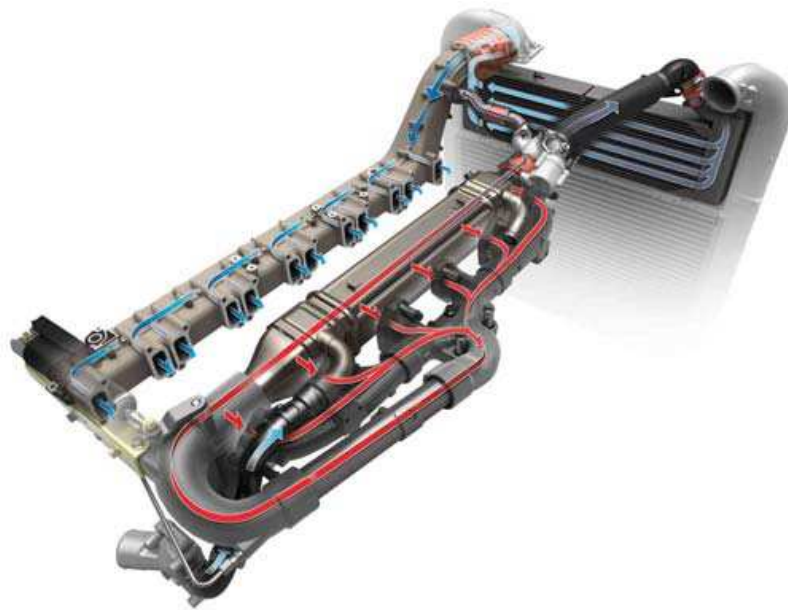


Figure 30: Scania 2-stage EGR cooling [Scania, 2007]

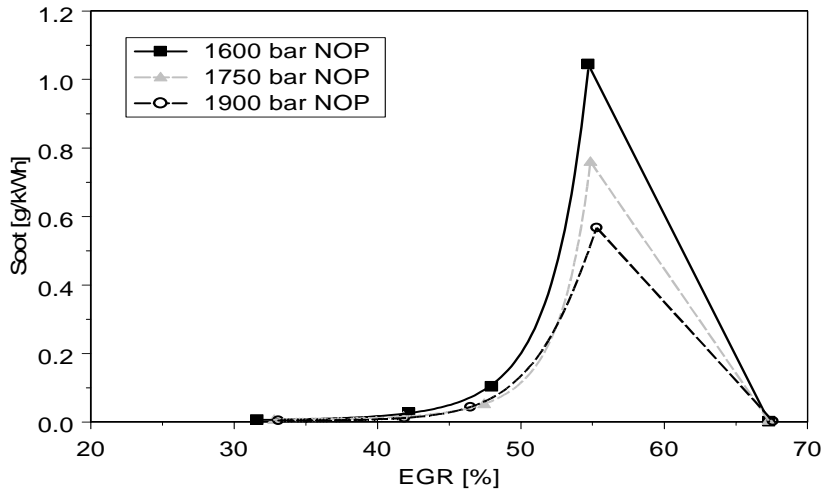
### 5.3 EMISSIONS RESULTS

If EGR is gradually increased from zero to a high level in an operating engine, the soot and NO<sub>x</sub> responses are generally as illustrated in Figure 31 and Figure 32, which shows emissions obtained from a single-cylinder heavy-duty engine in tests with injection pressures of 1600, 1750 and 1900 bar [Alriksson *et al*, 2007]. In Figure 31 soot levels are very low at zero or low EGR rates, since temperatures are high enough to oxidize most of the soot formed. As EGR rates increase the temperature decreases, and despite associated reductions in soot formation, engine-out soot emissions increase since the soot oxidation rates decline even more sharply. At about 55% EGR engine-out soot emissions are maximal in these operating conditions, and if EGR levels are further increased soot emissions rapidly fall and finally approach zero at about 65% EGR. At this operational point the local in-cylinder conditions do not cross the soot formation peninsula shown in Figure 25 and the engine is operating in low temperature combustion (LTC) mode at almost stoichiometric conditions. Low temperature combustion was first presented by Toyota in 2000 (Sasaki *et al*. 2000).

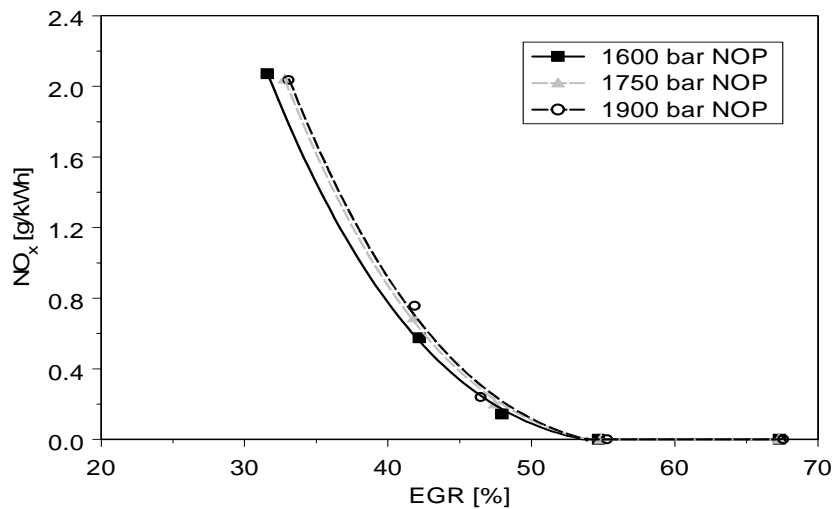
At the higher injection pressure of 1900 bar the mixing velocity is increased and the injection duration is reduced. The mixing is improved so locally rich areas with equivalence ratios >2 are avoided, thus less soot is formed.

As can be seen in Figure 32, NO<sub>x</sub> emissions decrease with increasing EGR and approach virtually zero for EGR values higher than about 55%, at which the maximum combustion

temperature has shifted away from the NO formation area shown in Figure 25. Increased injection pressure (increased injection rate) leads to higher NO<sub>x</sub> emissions due to more rapid combustion, especially at low EGR levels.

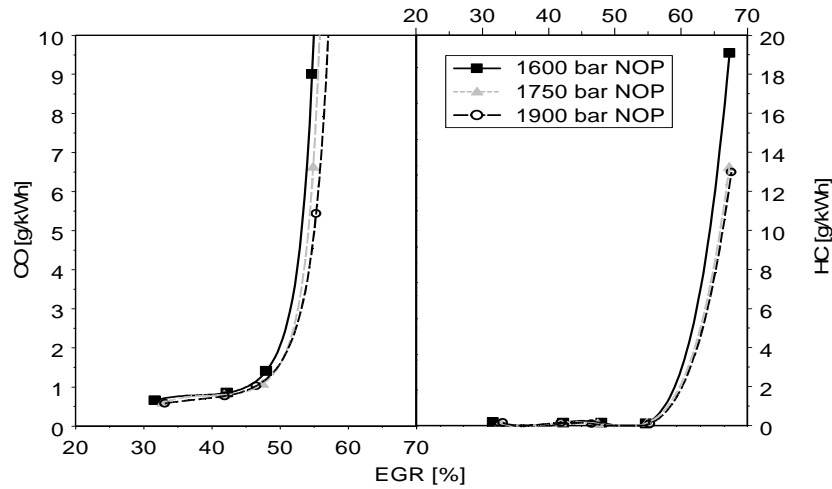


**Figure 31: Effect of increasing EGR on soot emissions at constant charge air pressures @ 50% load and 1500 rpm**



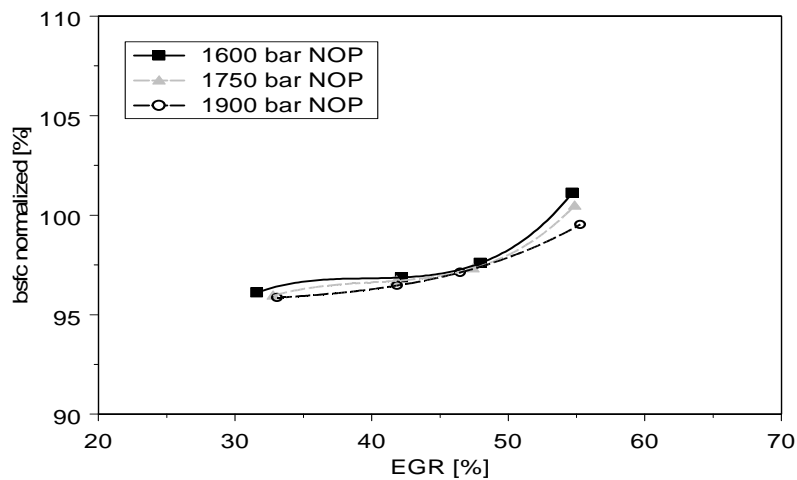
**Figure 32: Effect of increasing EGR on NO<sub>x</sub> emissions at constant charge air pressures @ 50% load and 1500 rpm.**

A problem with high EGR levels is the increase in emissions of unburned hydrocarbons and especially carbon monoxide, see Figure 33.



**Figure 33: CO (left panel) and HC (right panel) emissions for different EGR levels at 50 % load and 1500 rpm**

A problem with high EGR levels is increased fuel consumption due to the lower combustion efficiency caused by the increase in emissions of unburned hydrocarbons and monoxide (see Figure 26), due to the reduced reaction rates, see Figure 34.



**Figure 34: Normalized brake specific fuel consumption (bsfc) for different EGR levels at 50 % load and 1500 rpm**

## 5.4 INFLUENCE FROM FUELS

Figure 35 shows the emissions results for three different fuels, Diesel, Fischer-Tropsch and RME using a single injection and varying amounts of EGR. For the alternative fuels, very low soot

emissions were obtained, but at the expense of high NO<sub>x</sub> emissions. However, by increasing EGR rates both low NO<sub>x</sub> and low soot could be achieved.

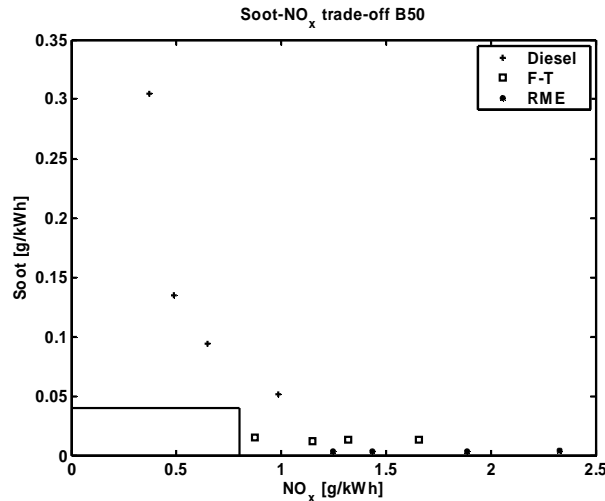


Figure 35: Soot versus NO<sub>x</sub> for Diesel, Fischer-Tropsch and RME fuel @ 50 % load and 1500 rpm [Fredriksson, 2007]

## 5.5 INFLUENCE OF CHARGE TEMPERATURE

Increased EGR cooling and thus reduced charge air temperature results in decreased soot emissions, see Figure 36. This is mainly a result of lower soot formation leading to lower engine-out soot emissions despite the lower soot oxidation rates at low temperatures. The reduced temperature also results (as expected) in a reduction in NO<sub>x</sub> emissions

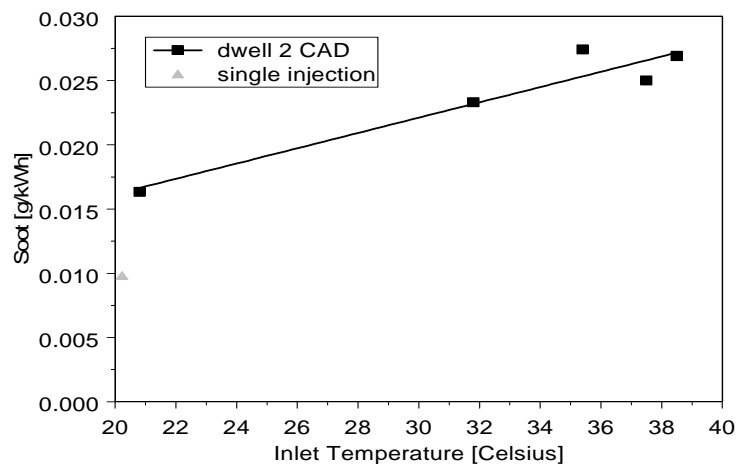


Figure 36: The effect of inlet temperature on soot emissions with a post injection with a dwell time of 2 CAD at 50 % load and 1500 rpm (injection pressure 1750 bar)

## 5.6 EGR CONTROL

When higher EGR rate is applied to a turbocharged and intercooled Diesel engine, it is essential to develop control methods for EGR to avoid transient particulate increases (it is necessary to properly control the transient excess air). Close loop control is preferred [Yokomura, 2004].

There are basically two different ways:

- Using existing sensors and using model based control (air-mass, imap and temperature)
- Using a wide range oxygen sensor and measure air excess in the exhaust.

A principal sketch of a closed loop control system using an oxygen sensor is shown below.

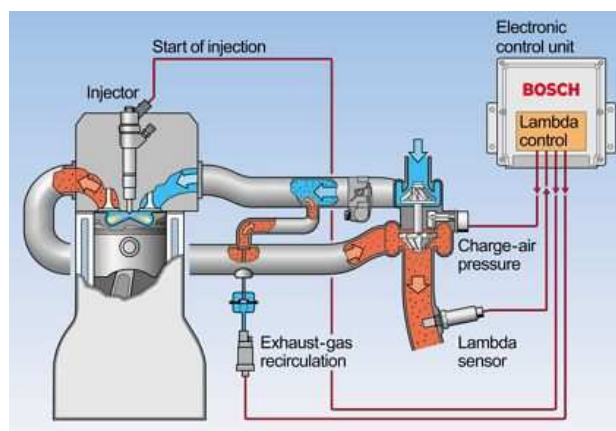


Figure 37: Oxygen (Lambda) Sensor-Based Control system (Bosch)

## 5.7 REFERENCES

- Kamimoto T. and Bae M. (1988). High combustion temperature for the reduction of particulate in Diesel engines. SAE paper 880423.
- Akihama K. Takatori Y. Inagaki K. Sasaki S. and Dean A. (2001). Mechanism of the Smokeless Rich Diesel Combustion by Reducing Temperature. SAE Paper 2001-01-0655.
- Zeldovich, Y. A. (1947). Oxidation of Nitrogen in Combustion. A. o. S. o. USSR. Moscow-Leningrad, Institute of Chemical Physics.
- Flaig, B., F. Zimmermann, 2000. "Electric exhaust gas return valve", MTZ Motortechnische Zeitschrift, 61 (2000) 9.
- Scania, press release P07X02SE / Per-Erik Nordström, 2007 (in swedish).
- [www.greencarcongress.com/2006/08/new\\_egr\\_cooler\\_.html](http://www.greencarcongress.com/2006/08/new_egr_cooler_.html)
- Adachi T, Aoyagi Y, Kobayashi M, Murayama T, Goto Y and Suzuki H, "Effective NOx Reduction in High Boost, Wide Range and High EGR Rate in a Heavy Duty Diesel Engine", SAE paper 2009-01-1438.

Yokomura H, Kouketsu S, Kotooka S and Akao Y, "Transient EGR Control for a Turbocharged Heavy Duty Diesel Engine", SAE paper 2004-01-0120.

Alriksson M, Girja S and Denbratt I, "The Effect of Charge Air and Fuel Injection Parameters on Combustion with High Levels of EGR in a HDDI Single Cylinder Diesel Engine" SAE paper 2007-01-0914.

Sasaki S, Ito T and Igushi S, "Smokeless rich combustion by low temperature oxidation in Diesel engines". 9th Aachen Colloquium, 2000.

Fredriksson J, "Interim Report, Work Package A2.6 Green", 2007.

## 6. DIESEL EXHAUST AFTER-TREATMENT

---

### 6.1 INTRODUCTION

---

The aim of Diesel exhaust gas after-treatment systems is to reduce engine emissions beyond the level that is possible using engine based emission reduction technologies alone.

Diesel exhaust after-treatment systems can be used to control the majority of engine emissions and may include the following functionalities:

- Diesel oxidation catalysts (DOC) to convert unburned hydrocarbons (HC) and carbon monoxide (CO) to carbon dioxide (CO<sub>2</sub>) and water vapor.
- Diesel particulate filters (DPF) to capture the particulate matter (PM) emitted by the engine and oxidize it to carbon dioxide and water vapor.
- Selective catalytic reduction (SCR) to convert nitrogen oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) to nitrogen (N<sub>2</sub>).

The above processes are usually performed by so-called after-treatment devices placed at various positions along the exhaust system. Essentially, these devices are chemical reactors in which the necessary after-treatment reactions are performed.

A primary consideration in the use of exhaust gas after-treatment systems is the type of engine measures that are used in conjunction with these for reducing emissions. In this respect the use of exhaust gas recirculation (EGR) to reduce NO<sub>x</sub> is of particular importance since it is usually accompanied by an increase in PM emissions. Therefore, depending on the type of engine measures that are used, a complimentary after-treatment system is required. For example, if a high EGR rate is used to decrease NO<sub>x</sub> to acceptable levels but which increases PM above acceptable levels, then a DPF may be used to reduce the PM. On the other hand, if a reduced EGR rate is used, then SCR may be necessary. Therefore it is necessary for the design of the after-treatment system to be fully integrated with the design of the engine.

In Sections 6.2, 6.3 and 6.4 below, the state of the art in the three main exhaust after-treatment technologies that have been developed for light duty and heavy duty vehicle applications in the road sector (DOC, DPF and SCR) are reviewed and issues regarding the transfer of these technologies to the rail sector are discussed.

### 6.2 DIESEL OXIDATION CATALYSTS

---

The Diesel Oxidation Catalyst (DOC), ubiquitous in automotive Diesel applications since the mid-1990s, is expected to form an integral part of the rail Diesel powertrain for the traditional functions of carbon monoxide (CO) and hydrocarbon (HC) emissions abatement and, depending on the application, particulate emissions reduction by the oxidation of soluble organic fraction SOF of Diesel particulates. The DOC may also find complementary roles on rail powertrains in combination with DPF and SCR NO<sub>x</sub> reduction systems. Overall, the DOC technology pertinent to Diesel locomotives is nearer to the state of the art of applications satisfying the Euro2 or Euro3 emission regulations. While more recent developments in DOC technology are outlined here, not all of these are expected to be a significant part of DOC adoption into rail Diesel emission control

concepts since these developments address technical challenges arising out of the highly transient nature of automotive powertrain operation and from recent developments in pre-mixed combustion concepts.

The DOC is to a large extent an evolution from the Three-Way Catalytic (TWC) converter introduced in the 1980s and widely used for spark ignition engines. The TWC generally operates in conditions of zero or small oxygen concentrations with simultaneous presence of CO and unburned or partially burned fuel hydrocarbons and can therefore reduce NO<sub>x</sub> while oxidising the CO and hydrocarbons. Conversely, the DOC generally operates in exhaust gas conditions of excess oxygen (typ. 8%-10%, potentially as low as 2% for premixed combustion modes) and therefore cannot provide substantial reduction of NO<sub>x</sub>. However, the DOC has been one of the most robust, application-proven and effective emission control technologies for both particulate matter (PM) and gaseous emissions reduction. PM reduction is through the cracking and/or oxidation of heavy organic fractions of unburned fuel (SOF) that may form part of the engine-out emitted particulates. The potential for this PM reduction by the DOC is application dependent since the SOF varies greatly with combustion process conditions and especially with exhaust temperature. Gaseous emissions functions of the DOC involve oxidation of CO and unburned gaseous hydrocarbons which are converted into CO<sub>2</sub> and water vapour. At the same time, the DOC converts nitrogen monoxide (NO) into NO<sub>2</sub> to an extent governed by thermodynamic equilibrium. Although, without additional after-treatment, this conversion can result in increased NO<sub>2</sub> emissions (higher toxicity than NO emissions), this DOC function is recently being exploited for the intensification of the urea SCR function due to the fact that NO<sub>2</sub> is reduced by a reaction pathway that exhibits a higher rate than that for NO.

Application conditions (fuel sulphur levels, average exhaust temperature) also determine the degree to which SO<sub>2</sub> oxidation must be countered. For the very prevalent alumina-supported platinum (Pt/Al<sub>2</sub>O<sub>3</sub>) catalysts, higher exhaust temperatures and higher fuel sulphur levels promote the emission of SO<sub>3</sub> derived particulates from the DOC. This challenge has occupied technology development especially before the regulation of very low sulphur (below 50 ppm) Diesel fuel and the tradeoff between high activity for HC/CO oxidation and selectivity for suppression of SO<sub>3</sub> formation is relatively well understood. In particular, for many past automotive applications, selectivity for HC/CO oxidation was modulated by either the addition of sulphate suppressors or by use of sulphation-resistant wash coat support materials. In more recent applications, the reduction of fuel sulphur content down to levels of around 10 ppm has permitted the gradual shift of technology development towards higher HC/CO oxidation activity, precious metal reduction and overall durability improvement. Factors such as phosphorus poisoning from lube-oil components [Bunting et al. 2005] [Eaton et al. 2006] have been studied to the point where some DOC improvement can be suggested for mitigation of these problems.

The past decade has also seen improvement and new developments in DOC substrates. The more traditional ceramic honeycomb substrates have evolved to higher cell densities and thinner honeycomb walls (as far as 900 cells/inch<sup>2</sup> / 2.5 mil walls) while many novel metallic substrates, incorporating mixing structures and higher surface areas, have also been demonstrated and/or commercialized, e.g. [Presti et al. 2005]. The overall state of the art in DOC substrates seems to be that ceramic honeycombs with around 600 cells/inch<sup>2</sup> and below 4 mils (100 micron) wall thickness seem to perform best with numerous other ceramic honeycomb (e.g. 400 cpsi / hexagonal cell) and metallic substrates offering very similar performance [Makino et al. 2006]. The more extreme cell densities and the mixing-enhanced metallic substrates seem to not provide significant benefit and have been seen to suffer from higher pressure drop and/or slightly inferior thermal characteristics for certain certification cycles [Floerchinger et al. 2004].

Optimization of the coating (at a macroscopic scale) has received less attention in the open literature compared to substrate, wash coat and catalyst formulation improvement. However, there is potential that concepts such as zonal coating (e.g. as investigated by Cordiner et al. (2007)) will be significant for cost reduction (by reduction of total precious metals loading) given the relatively large DOC volumes that may be applied to locomotive emission control. Of course, developments in catalyst formulation that increase durability and reduce dependence on platinum in particular (e.g. [Verdier et al. 2006]) by combining base metals / rare earths in this catalyst can have similar significance for the rail application of DOC.

Another set of recent DOC-related developments that seem very pertinent to rail transport emission control, include the concept of using an open-cell foam or other non-honeycomb substrate to host DOC catalysts and the possibility to incorporate the DOC function in the DPF. Using a non-honeycomb substrate such as a metallic foam can offer the advantage of improved flow distribution even for very close-coupled and/or space-constrained applications [Dimopoulos et al. 2009] and can reduce the soot challenge to the downstream DPF by increasing the residence time of some deposited soot in the vicinity of the DOC catalyst where oxidation by  $\text{NO}_2$  can take place [Hossfeld et al. 2006] [EMCON Technologies GmbH 2009]. This concept has been taken further with the advent of “open” particulate traps, i.e. essentially a catalytic converter flow-through substrate modified such as to enhance partial particulate matter capture and continuous oxidation (e.g. as shown by Lylykangas et al. (2002), Vakkilainen et al. (2004) and Jacobs et al. (2006)), and has been driven by the need for a blockage-immune PM emissions reduction device especially for retrofit applications although it is a concept attracting a certain amount of controversy with respect to its use for certification of particle emissions in new applications.

A further step in the direction of combining soot particulate reduction and DOC function, made possible by the improvement of DOC wash coat techniques and in higher porosity DPF substrates, is the incorporation of DOC catalysts in the DPF itself [Pfeifer et al. 2005]. This has been shown at a fundamental level to have very high potential for soot oxidation by the  $\text{NO} - \text{NO}_2$  turnover mechanism [Vlachos et al. 2008] while at the same time providing the traditional DOC functions, engine cabin space saving and reduced system cost due to having one less substrate. The weak point of DOC-DPF systems such as the above and for any standalone DOC system in the absence of downstream  $\text{NO}_x$  control, is the high level of  $\text{NO}_2$  emissions. However, there is a recent development, shown by Johansen et al. (2007), that indicates a possible solution to this  $\text{NO}_2$  emissions problem by new formulations of soot oxidation catalysts for the DPF that work synergistically with a preceding DOC.

Therefore, overall, DOC functionality can be seen as one of the most mature technologies expected to form an integral part of the Diesel locomotive exhaust after-treatment system, especially for the traditional function of oxidizing CO and hydrocarbons / volatile organic compounds and as a complementary device coupled to a Diesel Particulate Filter for particulate reduction and/or a Selective Catalytic Reduction (SCR) converter for  $\text{NO}_x$  emissions abatement.

Finally, it should be noted that many of the currently used DOC technologies depend on the use of low sulphur fuel. While it is not expected that the rail transport applications will adopt the more sulphur-sensitive DOC variants early on, sulphur aging of the catalyst can be a problem if ultra-low sulphur fuel is not possible for a certain application or very demanding requirements for DOC durability / service life are specified. A recent development which is pertinent to this problem is the sulphur trap shown by Yoshida et al. (2007) which has been demonstrated to provide an essentially sulphur free downstream exhaust up to a capacity of about 20 g sulphur per litre of trap volume.

There are numerous other recent developments in automotive DOC technology that may find only very niche application relevance in the rail transport sector. These include developments driven

by the need to optimize the DOC for the so-called cold start emissions and, more recently, by the challenge presented by recent concepts of pre-mixed or Homogeneous Charge Compression Ignition (HCCI) combustion, situations which exhibit lower exhaust temperatures and often higher concentrations of both CO and hydrocarbons sometimes reaching up to 5000 ppm for CO and/or HC [Johnson 2008] [Zinola et al. 2008]. The lower exhaust temperatures by themselves pose a significant challenge since the conversion rates are highly temperature dependent. However, the combination of lower temperatures and significantly higher concentrations effects a non-linear reduction of DOC conversion efficiency due to the emergence of so-called inhibition phenomena, i.e. above certain concentrations a portion of the pollutants that need to be oxidised progressively lose access to the catalytic sites. This problem currently forms perhaps the most primary front of current DOC research [PAGODE 2006] [Rappé et al. 2007] [Sumiya et al. 2009] where the solutions sought involve hot-spot or layered coating wash coat synthesis, the use of supports such as ceria or ceria-zirconia that can store and/or transport oxygen for the catalyst, and hydrocarbon storage materials for buffering spikes in hydrocarbon and/or CO emissions. The relevance of such DOC improvement modalities will depend on the adoption of pre-mixed / low temperature combustion concepts by the rail sector and (perhaps niche) applications that exhibit significantly transient engine operation.

## 6.3 DIESEL PARTICULATE FILTERS

---

### 6.3.1 Introduction

The particulate matter (PM) emitted by Diesel engines can be controlled using Diesel particulate filters (DPF).

Diesel PM consists mainly of [Kittelson 1998]:

- Solid particles: carbonaceous soot particles and inorganic ash particles.
- The soluble organic fraction (SOF): volatile soluble organic compounds, originating from unburned fuel and lubrication oil, nucleated as particles or adsorbed on solid particles.
- Sulphuric acid and sulphate particles originating from  $\text{SO}_3$ .

The DPF can effectively control the solid particle component of Diesel PM [Mayer et al. 2002] such as soot and ash particles. However, it may not also be effective at controlling the SOF or sulphuric acid / sulphate component, which may need to be controlled using other means, for example a Diesel oxidation catalyst (DOC) and low sulphur fuel.

A DPF consists of a porous filter substrate which physically captures the PM as the exhaust gas passes through the substrate. A significant volume of soot quickly accumulates in the filter during its operation which must therefore be removed in order to regenerate the filter and avoid an excessively high backpressure in the exhaust system. Usually, the filter is regenerated chemically by oxidizing the soot particulates to mostly carbon dioxide. DPF regeneration can be distinguished into passive and active regeneration. The aim of passive regeneration is to oxidize the soot on a continuous basis at the exhaust gas temperatures encountered under typical engine operating conditions whereas active regeneration aims to oxidize the soot periodically by raising the exhaust gas temperature to above the soot ignition temperature.

In the following sections a review is made of the filtration and regeneration processes in a DPF, of DPF substrate materials and in particular ceramic monolith substrates, of passive and active DPF regeneration technologies, and of regeneration strategies and related aspects.

### 6.3.2 The Filtration Process

DPFs function by physically capturing and withholding the PM suspended in the exhaust gas as this passes through the porous filter substrate [Konstandopoulos et al. 1989] [Konstandopoulos et al. 2000]. Filtration can be divided into deep bed filtration where the PM is captured and withheld throughout the depth of the substrate material, and surface filtration where the PM is captured on the surface of the substrate material and leads to the formation of a filtration cake.

The performance of a DPF is measured in terms of its filtration efficiency which is the ratio of the rate at which particulate mass is collected by the filter to the rate at which particulate mass enters the filter. It is also important to consider the pressure drop that arises in a DPF due to the resistance that the porous material of the filter substrate and the particle deposits in the filter present to the exhaust gas passing through the filter. The pressure drop gives rise to a backpressure of equal magnitude in the exhaust system which results in a fuel economy penalty for the engine. The pressure drop depends on the permeability of the filter substrate material and the permeability of the soot deposits.

Usually, filter substrates with an open pore structure / large pore size have low filtration efficiency and low pressure drop whereas filter substrates with a closed pore structure / small pore size have high filtration efficiency and high pressure drop. The efficiency of surface or cake filtration may reach very high values since the particulate deposits themselves are filtering the PM. Also, it is possible for particulate deposits within the substrate to be re-entrained by the gas during operation of the filter (known as blow off) thus reducing the apparent filtration efficiency.

The contribution of SOF and sulphate particles to the total PM number and mass depends on the temperature of the exhaust gas and the presence of precursors such as  $\text{SO}_3$ . A DPF can effectively capture solid particles such as soot particles [Mayer et al. 2002]. However, a DPF may not be effective at controlling SOF and sulphate particles because these are formed by nucleation and condensation downstream of the DPF where the temperature is lower [Andersson et al. 2001] [Mayer et al. 1999]. In particular, the sulphate particle precursor  $\text{SO}_3$  is formed from  $\text{SO}_2$  at high temperatures or through catalytic action and is gaseous at the temperature of the exhaust gas flowing through the DPF. Sulphuric acid and sulphates are then formed from the reaction of  $\text{SO}_3$  with water downstream of the DPF where the temperature is lower. The formation of sulphate particles may result in apparent negative filtration efficiencies [Mayer et al. 1999]. Therefore, low sulphur fuel may be necessary when using a DPF with a catalytic functionality that also promotes  $\text{SO}_2$  oxidation, in order to avoid the formation of sulphate particles.

The use of a catalyzed filter in rail applications may also require the use of low sulphur fuel in order to avoid the formation of sulphate PM downstream of the filter.

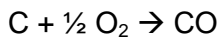
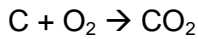
### 6.3.3 The Regeneration Process

The regeneration process is of critical consequence to the durability of the DPF because during this process the DPF can be exposed to high temperatures that damage the substrate material and result in failure of the DPF. Therefore, although the primary function of a DPF is to filter the PM in the exhaust gas, DPF regeneration is the most important issue in DPF research and development.

During the regeneration process, the accumulated carbonaceous soot particle deposits in the filter are oxidized to gaseous products in order to prevent further build up of these deposits and an excessive backpressure in the exhaust system. The soot can be oxidized by oxygen ( $\text{O}_2$ )

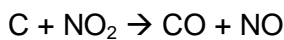
thermally or catalytically using a soot oxidation catalyst and can also be oxidized by nitrogen dioxide (NO<sub>2</sub>) if this is present in sufficient quantities.

The oxidation of soot by oxygen can proceed via two reaction paths:

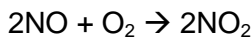


Thermal oxidation of soot by oxygen occurs at temperatures above the soot ignition temperature of approximately 600 °C whereas catalytic oxidation of soot by oxygen using a soot oxidation catalyst can occur at lower temperatures [van Setten et al. 2001].

Oxidation of soot by NO<sub>2</sub> occurs primarily via one reaction path:



Oxidation of soot by NO<sub>2</sub> can occur at significantly lower temperatures compared to oxygen [Cooper et al. 1989]. Engine out NO<sub>x</sub> emissions usually consist mostly of NO and little NO<sub>2</sub>. However, the NO<sub>2</sub> fraction can be increased according to the reaction:



The conversion of NO to NO<sub>2</sub> is kinetically controlled at low temperatures and therefore initially increases with temperature. However, above a certain temperature NO conversion decreases progressively due to thermodynamic limitations. The platinum catalysts used to promote NO to NO<sub>2</sub> oxidation also exhibit comparable activity for SO<sub>2</sub> to SO<sub>3</sub> oxidation and are prone to inhibition by SO<sub>2</sub> and can result in the formation of sulphate particles. Therefore, they have to be used with very low sulphur fuel [Cooper et al. 1989].

The regeneration process can be viewed as a dynamic process in which the difference between the rate of soot accumulation due to filtration and the rate of soot removal due to oxidation determines whether the mass of soot in the filter (the soot mass load) is increasing or decreasing. The rate of soot accumulation due to filtration depends on the soot emission rate of the engine and the filtration efficiency of the filter. The rate of soot removal due to oxidation depends on the oxidation reaction rate which in turn depends strongly on the temperature of the filter. In general, the oxidation reaction rate increases with increasing temperature and therefore at high exhaust gas temperatures the rate of soot removal due to oxidation tends to be higher than at low exhaust gas temperatures. Therefore, depending also on the rate of soot accumulation due to filtration, and all else being equal, at low exhaust gas temperatures the soot mass load tends to be increasing whereas at sufficiently high exhaust gas temperatures the soot mass load tends to be decreasing.

The exhaust gas temperature of Diesel engines is usually below the soot ignition temperature of approximately 600 °C. Therefore, to regenerate the DPF it is necessary to facilitate soot oxidation catalytically at the exhaust gas temperatures encountered under typical engine operating conditions or to facilitate soot oxidation thermally by increasing the temperature of the soot to above its ignition temperature.

The soot can be oxidized at temperatures below the ignition temperature using a soot oxidation catalyst and using catalytically generated NO<sub>2</sub>. In principle this can enable the filter to regenerate passively at lower temperatures. However, the degree to which this is possible also depends greatly on the exhaust temperature dynamics under typical engine operating conditions [Mayer et al. 2001].

Alternatively, the filter can be regenerated by actively increasing the temperature of the soot to above its ignition temperature. This may involve the use of engine management methods to

increase the temperature of the exhaust gas and/or other methods to increase the temperature of the exhaust gas or the filter.

It is noted that if a passively regenerating filter is operated at low exhaust gas temperatures for prolonged time or if the time between regenerations of an actively regenerated filter is too long then the soot mass load may increase sufficiently to enable uncontrolled regeneration. In this event, because of the large soot mass load, the heat release from the soot oxidation reactions is sufficient to raise the temperature of the filter to above the soot ignition temperature and therefore to sustain the thermal oxidation of the soot until all of the soot is oxidized. The heat release may be so large that the temperature of the filter exceeds the melting temperature of the substrate material or the substrate cracks because of exceedingly high thermal stresses.

Low exhaust gas temperatures encountered in rail applications may render the use of passively regenerating filters difficult due to the risk of uncontrolled regeneration and in this respect actively regenerated filters may be necessary.

Theoretical models for describing and understanding the filtration and regeneration processes in ceramic wall-flow monolith filters are reported in [Konstandopoulos et al. 2000] [Konstandopoulos et al. 2001] [Konstandopoulos et al. 2003] [Kladopoulou et al. 2003] [Konstandopoulos et al. 2005a].

### 6.3.4 Substrate Materials

The purpose of the DPF substrate is to filter the PM and to facilitate the oxidation of the accumulated carbonaceous soot particles to gaseous products in order to regenerate the DPF. In this respect, several design parameters related to the substrate material are important [Hashimoto et al. 2002] [Konstandopoulos et al. 2004b] [Cutler et al. 2000]:

- Filtration efficiency, affected by the porosity and pore size distribution of the material. The material must be able to physically capture a large percentage of particles in terms of both particle mass and particle number.
- Pressure drop, also affected by the porosity and pore size distribution of the material. The flow of exhaust gas through the material must not excessively increase the exhaust backpressure.
- Filtration area: the material / substrate must allow the filter to store a large volume of particulate matter for a given filter volume.
- Melting point: the material must not melt at the temperatures encountered during controlled or uncontrolled regeneration (potentially higher than 1000 °C).
- Heat capacity, which affects the amount of heat required to increase the temperature of the substrate.
- Thermal conductivity, which determines how quickly heat is conducted from high temperature regions to low temperature regions.
- Thermal shock resistance: the material must not easily crack in the presence of high temperature gradients.
- Strength: the substrate must be able to withstand high thermal stresses, high static forces (e.g. canning forces) and high levels of vibration.
- Chemical durability: the material must have low reactivity with various oxidizing and reducing species and with ash.

- Compatibility with regeneration methods: the material should ideally be compatible with at least one regeneration method, e.g. it can be coated with catalysts, it is compatible with catalytic fuel additives, it is electrically conductive (electrical regeneration), etc.
- Secondary emissions: during operation the material should not result in additional particulate or gaseous emissions.
- Weight
- Cost
- Availability

A brief overview of some substrate materials that have been developed for DPF applications is given below.

### **Ceramic Wall-Flow Monoliths**

Ceramic wall-flow monoliths are the most developed type of DPF substrate material. Ceramic monoliths facilitate mainly surface filtration and usually have high filtration efficiencies particularly when loaded with soot [Konstandopoulos et al. 2007]. Also, due to their honeycomb structure they are able to store a large volume of soot. Ceramic monoliths are usually made of silicon carbide (SiC) or cordierite (a synthetic ceramic). SiC has a high heat capacity and high melting point and therefore under conditions of uncontrolled regeneration is slow to heat up and does not melt. Cordierite has lower heat capacity and high thermal shock resistance and therefore can be heated efficiently during controlled regeneration and can withstand high temperature gradients during uncontrolled regeneration. Compared to other substrate materials, ceramic monoliths are more prone to cracking. Ceramic monoliths can be coated with catalysts and can be used with catalytic fuel additives for passive regeneration. Ceramic wall-flow monoliths are discussed in greater detail in Section 6.3.5.

### **Sintered Metal**

DPF substrates based on sintered metal have been developed [Biddinger 2005]. The filter substrate comprises a folded bellows stack of sintered metal filter plates. Sintered metal has high filtration efficiency and high thermal durability. Also, the use of plate material allows flexibility in the filter design to meet different packaging requirements. A catalyst coated sintered metal filter for heavy duty vehicles was recently developed in the COMET project discussed in Section 6.5.

### **Metal Fibers**

DPF substrates based on metal fibers have also been developed [Brillant et al. 2005]. The filter substrate is based on pleated panels made from sintered non-woven metal fibers. The metal fiber material can facilitate deep bed filtration. Also, the metal fiber material can be used with catalytic fuel additives for regeneration. Furthermore, it is electrically conductive and therefore regeneration via resistive heating of the substrate is possible. An electrically regenerated DPF system based on a pleated metal fleece substrate is reported in [Meinig et al. 1998].

### **Ceramic Fibers**

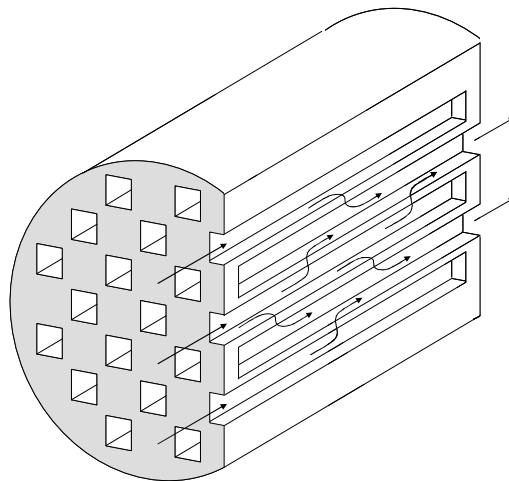
DPF substrates based on ceramic fibers have been developed using for example knitted fibers [Mayer et al. 1993], fiber wound cartridges [Shirk et al. 1995] and non-woven fiber fabric [Sakaguchi et al. 1999]. Ceramic fiber substrates can facilitate deep bed filtration. Ceramic fiber substrates can be used with catalytic fuel additive based regeneration methods (e.g. [Mayer et al. 1993]) and also with electric regeneration methods (e.g. [Shirk et al. 1995], [Sakaguchi et al. 1999]).

## Ceramic and Metal Foam

Ceramic foam DPF substrates have been researched in the past. Recently, the use of catalyst coated ceramic foam together with ceramic wall-flow monoliths has been researched to improve passive regeneration performance [Setiabadi et al. 2003]. Also, catalyst coated metal foam DPF substrates have recently been researched [Koltsakis et al. 2006]. Annular metal foam substrates can be configured for filtration in the radial direction. Ceramic and metal foam substrates can facilitate deep bed filtration and good soot – catalyst contact. Foam substrate materials were also researched in the STYFF-DEXA project discussed in Section 6.5.

### 6.3.5 Ceramic Wall-Flow Monolith Filters

Most Diesel particulate filters are based on ceramic wall-flow monoliths. Ceramic wall-flow monoliths were developed from the ceramic flow-through monoliths used in automotive catalytic converters. The monolith contains many small parallel channels forming a honeycomb structure. At each end of the monolith the channels are plugged in a checkerboard pattern thus forcing the exhaust gas to flow through the porous walls of the channels (hence the term “wall-flow” as opposed to “flow-through”). The flow pattern through a wall-flow monolith filter is illustrated in Figure 38 (note that the width of the channels is greatly exaggerated).



**Figure 38: Flow pattern through a ceramic wall-flow monolith DPF.**

Ceramic wall-flow monoliths are usually manufactured from silicon carbide (SiC) or cordierite. However, recently NZP and aluminum titanate materials have also been developed. These materials and related references are shown in Table 3. The monolith is formed by extruding the ceramic material in clay form, firing the extrusion and then plugging the channels at each end.

The microstructural properties of the monolith material and the channel geometry are important parameters for the filtration performance of the DPF.

The manufacturing process is carefully controlled in order to ensure that the material of the monolith has specific microstructural properties. The material microstructure is usually characterized in terms of the porosity and mean pore size. The porosity is the ratio of the voids volume to the bulk volume of the material and the mean pore size is the mean diameter of the

void spaces in the material. The porosity is typically in the range of 45 - 60% whereas the mean pore size is typically in the range of 10 – 20  $\mu\text{m}$ . SiC usually has a more uniform pore microstructure compared to cordierite.

Material	Chemical Composition	References
Silicon Carbide	SiC	[Itoh et al. 1993] [Ohno et al. 2000] [Hashimoto et al. 2002] [Stobbe et al.1993]
Cordierite	2MgO-2Al <sub>2</sub> O <sub>3</sub> -5SiO <sub>2</sub>	[Merkel et al. 2001b] [Hashimoto et al. 2002]
NZP	-	[Cutler et al. 2000]
Aluminum Titanate	Al <sub>2</sub> TiO <sub>5</sub>	[Ogunwumi et al. 2005]

**Table 3: Ceramic wall-flow monolith materials**

The monoliths must also be carefully designed with respect to channel geometry [Konstandopoulos et al. 2004b]. The most common geometrical parameters are the cell density (i.e. the number of channels per unit face area), the channel wall thickness, the length of the monolith, and the specific filtration area of the monolith (i.e. the filtration area per unit volume of monolith). Wall-flow monolith filters usually have 100 – 300 cells per square inch (cps) of face area and a specific filtration area in the range of 0.6 – 1  $\text{m}^2/\text{dm}^3$ .

The mechanical and thermal properties of the monolith material are very important for the regeneration performance and durability of the filter.

The melting point of the material must be higher than the normal use temperature of the filter and higher than any temperature spikes encountered during controlled or uncontrolled regeneration [Cutler et al. 2000]. However, the maximum allowable temperature can be limited by ash reactions which begin at about 1250 °C [Merkel et al. 2001a].

In the presence of temperature gradients, thermal stresses arise in the material. The thermal stresses increase with increasing coefficient of thermal expansion and increasing elastic modulus of the material. If the thermal stress exceeds the strength of the material, the material cracks. Therefore, for high thermal shock resistance, a low coefficient of thermal expansion, a low elastic modulus and high strength are required.

The bulk volumetric heat capacity of the monolith determines how much heat is required to increase its temperature during regeneration. A low heat capacity is desirable for controlled regeneration because it allows a rapid temperature increase and therefore minimizes the fuel penalty to start regeneration [Cutler et al. 2000]. However, a high heat capacity may be desirable to minimize the temperature increase during uncontrolled regeneration.

The thermal conductivity of the material determines how quickly heat is conducted from high temperature regions to low temperature regions. High conductivity promotes rapid heat conduction and a more uniform temperature distribution and therefore is preferable regarding thermal shock resistance (although rapid heat convection can still result in high temperature gradients). However, high conductivity can result in heat being conducted away from the regeneration front during controlled regeneration leading to extinction of the regeneration [Cutler et al. 2000].

SiC sublimates at around 2400 °C and therefore does not melt at high regeneration temperatures. However, SiC has a high coefficient of thermal expansion and therefore may be prone to cracking in the presence of high temperature gradients. In this respect SiC substrates are constructed from

smaller cement bonded monolith segments in order to relieve thermal stresses [Mizutani et al. 2006]. Also, SiC has a high heat capacity and high thermal conductivity, which can help to reduce temperature spikes during uncontrolled regeneration.

Cordierite has a low coefficient of thermal expansion and therefore good thermal shock resistance. Also, cordierite has a low heat capacity and low thermal conductivity and therefore can be heated quickly during controlled regeneration, which can help to reduce the regeneration fuel penalty. However, the melting point of cordierite is about 1460 °C and therefore during uncontrolled regeneration it can sometimes melt.

A very important consideration for filter durability is the very high temperatures that the monolith material may be exposed to during the regeneration process due to the heat release from the soot oxidation reactions. Furthermore, due to spatial non uniformities in the distribution of the accumulated soot throughout the substrate, the material may also be exposed to high temperature gradients and therefore to high thermal stresses. High temperatures and high thermal stresses during the regeneration process can result in melting or cracking of the monolith material.

In rail applications, significant spatial non uniformities might exist in the distribution of the accumulated soot due to the large size of the substrate, which during the regeneration process could result in locally high temperatures and/or high temperature gradients in the substrate. Therefore, ensuring that the monolith material does not fail due to melting or cracking during the regeneration process might be of significant importance.

The chemical resistance of the monolith material is also very important for the durability of the DPF. The material is exposed to high temperatures under both oxidizing and reducing atmospheres and therefore must be chemically resistant. The material must also be resistant to ash. Ash consists of metal oxides formed from the combustion of lubrication oil and catalytic fuel additives. As discussed in [Merkel et al. 2001a], ash can form eutectics with SiC and cordierite substrates at about 1250 °C, resulting in glazing of the surface of the channel walls that increases backpressure or pin holes in the channel walls that compromise filtration efficiency. Furthermore, the ash can sinter and adhere to the walls at lower temperatures making it difficult to remove from the filter.

In rail applications, it may be important to minimize ash accumulation in the DPF in order to attain the necessary durability and lifetime for the filter.

### 6.3.6 Passive Regeneration Systems

The aim of a passive regeneration system is to enable soot oxidation at the exhaust gas temperatures encountered under typical engine operating conditions i.e. at temperatures below the soot ignition temperature of approximately 600 °C. Passive regeneration systems aim to bring the soot into contact with an appropriate soot oxidation catalyst or to convert NO in the exhaust gas to NO<sub>2</sub> in order to enable oxidation of the soot by NO<sub>2</sub>. Passive regeneration systems may enable the entirely passive regeneration of the filter or they may promote a certain level of passive regeneration while also requiring periodic active regeneration of the filter. Based on the reviewed literature, the main technologies that have been developed for passive regeneration are discussed below as well as some additional points that may also be relevant for rail applications.

## Catalyzed DPF

In a catalyzed DPF (CDPF) the filter substrate is coated with catalysts to promote soot oxidation at the exhaust gas temperatures encountered under typical engine operating conditions. Catalyzed DPFs have been developed using several filter substrate materials however they are usually based on ceramic wall-flow monoliths.

Development of CDPF technology is reported in [Konstandopoulos et al. 2004a] and application of some CDPF technologies is reported in [LeTavec et al. 2002], [Kimura et al. 2004] and [Brown et al. 2004].

The filter substrate can be coated with a soot oxidation catalyst that promotes oxidation of soot by oxygen. The filter substrate can also be coated with a catalyst that oxidizes NO to NO<sub>2</sub> in order to promote the oxidation of soot by NO<sub>2</sub>.

In a wall-flow monolith CDPF, the catalyst coating and the soot cake on the walls of the channels are in very close proximity to each other and it has been suggested [Vlachos et al. 2008] that the catalyst produced NO<sub>2</sub> can diffuse upstream to the soot cake and the soot oxidation produced NO can diffuse downstream to the catalyst and therefore that a certain amount of NO/NO<sub>2</sub> recycling may occur in a CDPF that improves its regeneration performance. However, overall, a certain minimum NO<sub>x</sub>/PM ratio is likely to be required in the exhaust gas in order to facilitate adequate NO<sub>2</sub> oxidation of soot in a CDPF.

In general, various base metal oxides (e.g. cerium and iron oxides) are used as soot oxidation catalysts and noble metals (e.g. platinum and palladium) are used to catalyze the oxidation of NO to NO<sub>2</sub> in order to promote NO<sub>2</sub> oxidation of soot [van Setten et al. 2001] [Neeft et al. 1996] [Konstandopoulos et al. 2005b].

Base metal oxides are thought to catalyze soot oxidation via a spillover mechanism and a redox mechanism where the metal alternates between two valence states [van Setten et al. 2001]. Furthermore, base metal catalysts have been found not to increase NO<sub>2</sub> emissions [Brown et al. 2004].

Noble metal catalysts can also be used to promote CO and HC oxidation in the filter [Pfeifer et al. 2007]. However, the oxidation of NO to NO<sub>2</sub> can increase tailpipe NO<sub>2</sub> emissions. Furthermore, noble metal catalysts can oxidize SO<sub>2</sub> to SO<sub>3</sub> and therefore they are prone to sulphur poisoning and they can increase sulphate particle emissions. In this respect, very low sulphur fuel is usually necessary to control sulphate particle emissions. Also, the effect of sulphur poisoning may be temporary and it may be possible to desulphurize the catalyst by raising the exhaust gas temperature sufficiently [Pfeifer et al. 2007].

## Continuously Regenerating DPF

In [Allansson et al. 2000], experience of the durability of the continuously regenerating Diesel particulate filter technology patented by the company Johnson Matthey is reported for a variety of heavy duty Diesel vehicles and a Diesel Multiple Unit (DMU). This technology uses NO<sub>2</sub> produced catalytically from the NO in the exhaust gas to combust the soot trapped in the filter at significantly lower temperature than oxygen [Cooper et al. 1989] thus enabling continuous regeneration under standard heavy duty Diesel engine conditions where temperatures are favourable for NO<sub>2</sub> production [Allansson et al. 2000]. Systems having accrued high mileage were removed from their vehicles and subjected to engine bench testing over steady state and transient cycles. The conversions of PM, gaseous HC and CO were found to be very high with virtually no deterioration over time [Allansson et al. 2000].

In [Ball et al. 2004], experience from the application of this technology to city buses in Europe is reported, and the influence on regeneration of factors such as fuel sulphur content and exhaust gas NO<sub>x</sub>/PM ratio and temperature is discussed, as well as monitoring and maintenance topics.

In [Allansson et al. 2004], further improvements to this technology are reported. Improvement of catalyst NO oxidation activity following prolonged field ageing within low temperature duty cycles is reported. Also, the development of an optimized system that is more effective over very low temperature duty cycles is reported.

### **Catalytic Fuel Additives**

Catalytic fuel additives (also known as fuel borne catalysts) may be used to promote soot oxidation in a DPF [Neeft et al. 1996] [van Setten et al. 2001]. Catalytic fuel additives are organometallic compounds that can be dissolved in Diesel fuel. After combustion in the engine, metal oxide or metal sulphate particles remain [Neeft et al. 1996]. These catalyst particles are emitted either as independent particles or embedded in soot particles [Mayer et al. 1998] [Mayer et al. 2003]. The catalyst particles are then collected in the DPF where they are uniformly distributed in the soot deposits and can promote soot oxidation.

The catalyst is usually added to the fuel in the form of a fuel soluble organometallic compound. The nature of the organic part is not so important for catalytic activity since it is combusted in the engine. However, the physical properties of the organic part are important because they affect fuel miscibility and stability. Various metals and organometallic compounds have been used in the past [Neeft et al. 1996].

Recently, catalytic fuel additives have been applied serially in Diesel passenger cars [Blanchard et al. 2003]. The development of several types of catalytic fuel additive has been reported, e.g. cerium [Quigley et al. 2002], iron doped cerium [Blanchard et al. 2002] and iron [Harle et al. 2008]. An integrated system approach has been used in which the catalytic fuel additives are used together with active methods for DPF regeneration. The catalytic fuel additives promote soot oxidation in the DPF and reduce the energy and time required for active regeneration. A certain decrease in the balance point temperature of the filter is possible by increasing the catalyst dosing rate. However this would increase the rate at which the catalyst accumulates in the filter in ash form, which is not desirable from the point of view of backpressure / fuel economy and filter maintenance intervals. As such, this has motivated the development of new catalytic fuel additives with increased catalyst activity in order to reduce the dosing rate and limit ash accumulation in the filter [Blanchard et al. 2002] [Harle et al. 2008].

### **Additional Points**

In heavy duty vehicles the drop in exhaust gas temperature in the exhaust pipe between the engine and the muffler can be significant and therefore for retrofit DPF applications it can be important to efficiently insulate the exhaust pipe in order to ensure the best possible conditions for regeneration [Mayer et al. 2001].

In retrofit DPF applications the conditions available for passive regeneration are often examined using exhaust temperature frequency distributions from which the percentage of time for which the temperature is above a certain level can be determined. However, due to the thermal inertia of the DPF it is also necessary to consider the distribution of dwell time at particular temperatures as well as the temperature history [Mayer et al. 2001].

If the exhaust gas temperatures are sufficiently high then the rate of soot removal due to oxidation may on average be sufficient for passive regeneration. However, if the exhaust gas temperatures are too low then the DPF will tend on average to accumulate soot until the exhaust

gas temperatures increase sufficiently for the rate of soot removal due to oxidation to balance the rate of soot accumulation due to filtration. However, prolonged operation at low temperatures (for example due to long idle times) could lead to high soot mass loads and the risk of uncontrolled regeneration. Uncontrolled regeneration can result in very high filter temperatures and catastrophic failure (cracking and melting) of the filter substrate. Therefore, depending on the operating conditions and duty cycle of the engine, active regeneration of the filter can be necessary.

Ensuring the necessary conditions for passive regeneration is very important for the long term durability of the filter. For the retrofit application of passively regenerating systems in heavy duty vehicles, the exhaust temperature dynamics of the application vehicle under typical operating conditions have to be screened [Mayer et al. 2001]. However, certain vehicles may exhibit a diverse range of operating profiles and this could lead to the filter being deployed under conditions that are different from those analyzed. Therefore, where there is uncertainty active regeneration is advisable [Mayer et al. 2001].

The influence of EGR on the NO<sub>x</sub>/PM ratio may also be of importance in the case of passive regeneration systems that use NO<sub>2</sub> for soot oxidation.

The reliance on a catalytic functionality in passive regeneration systems also means that precautions may be necessary to prevent inadvertent catalyst deactivation so that good filter durability is achieved.

Ash accumulation may also impact filter durability. Usually it is necessary to remove ash periodically using various methods.

The following points may also be important in the case of catalytic fuel additives.

The catalyst is usually added to the fuel using an on-board dosing system that regulates the dosing rate. This increases system complexity compared to other passive systems.

Catalytic fuel additives have to be compatible with Diesel fuel (miscibility, stability) and with the materials used in the fuel system. They also have to be compatible with the Diesel injection system and must not increase engine wear. Furthermore, they have to be compatible with the DPF material.

The accumulation of catalyst ash in the DPF is additional to the accumulation of regular ash from lubrication oil and engine wear and therefore this increases the exhaust backpressure and associated fuel penalty of the filter and requires more frequent ash removal.

The use of catalytic fuel additives can result in the formation of nano sized catalyst particles in the exhaust gas that are much smaller than soot particles [Mayer et al. 1998] [Mayer et al. 2003]. Therefore it can be necessary to ensure that catalytic fuel additives are used together with a DPF that efficiently filters the catalyst particles over the entire size range [Mayer et al. 2003] [Mayer et al. 2002].

### 6.3.7 Active Regeneration Systems

The aim of an active regeneration system is to enable thermal oxidation of the soot in the DPF by periodically increasing the temperature of the soot to above its ignition temperature of approximately 600 °C. The energy required for this can be provided by the engine using various engine management methods to increase the temperature of the exhaust gas. Alternatively, other methods that are independent of the engine can be used to increase the temperature of the exhaust gas or the DPF.

Engine management based methods for increasing the exhaust gas temperature include [Lemaire et al. 1994] [Spurk et al. 2003]:

- Increase of intake air temperature
- Exhaust gas recirculation
- Retarded injection timing
- Increase of exhaust gas backpressure
- Decrease of boost pressure
- Increase of intake air vacuum
- In-cylinder post-injection

In general, the increase of exhaust gas temperature results in a deterioration of engine efficiency and therefore an increase in fuel consumption. The above methods can also lower the exhaust gas oxygen content and increase PM emissions [Lemaire et al. 1994]. Furthermore, the increase in exhaust gas temperature that can be realized with individual engine management methods is limited and therefore it may be necessary to use a combination of several engine management methods [Konstandopoulos et al. 2004a] possibly together with another method such as a DOC [Hiranuma et al. 2003].

Methods for actively increasing the temperature of the exhaust gas or the DPF that are independent of the engine rely on the use of Diesel fuel or electricity as on-board sources of energy:

- Fuel burner: fuel can be combusted in a burner to increase the exhaust gas temperature.
- Fuel injection / DOC system: fuel can be injected into the exhaust stream and oxidized in a Diesel oxidation catalyst (DOC) in order to increase the exhaust gas temperature.
- Electric regeneration: electric heating can be used to increase the temperature of the exhaust gas or the filter and microwaves can be used to directly heat the soot.

### **Fuel Burner**

An active regeneration system based on a fuel burner typically consists of a fuel burner and a DPF. The fuel burner is situated directly upstream of the DPF and initiates regeneration of the filter by raising the exhaust gas temperature to 650 – 700 °C. The fuel burner is controlled by an electronic control unit that monitors exhaust backpressure and temperature, engine load and speed, etc. The control unit aims to deliver under all engine operating conditions the necessary amount of energy to regenerate the DPF without excessively increasing its temperature.

Fuel burner systems are reported in [Zelenka et al. 2002], [Kong et al. 2004] and [Kong et al. 2005].

To enable a soot free flame under all engine operating conditions (and therefore exhaust gas oxygen concentrations) auxiliary air may be required by the burner [Zelenka et al. 2002]. Also, minimal impact of the burner on NO<sub>x</sub>, HC and CO emissions must be ensured under all engine operating conditions [Kong et al. 2005].

### **Fuel Injection / DOC system**

An active regeneration system based on fuel oxidation in a DOC usually consists of a method for introducing fuel into the exhaust stream, a DOC and a catalyzed DPF (CDPF). When the soot mass load of the CDPF reaches a certain threshold value, fuel is introduced into the exhaust stream upstream of the DOC. Fuel injection is controlled by an electronic control unit. If the engine operating conditions are such that the exhaust gas temperature is below the DOC light-off

temperature (usually in the range 200 - 300 °C), an engine management method may be used to increase the exhaust gas temperature. The fuel introduced into the exhaust stream rapidly evaporates and enters the DOC where it is oxidized. The exhaust gas temperature is increased to about 600 °C by the exothermic oxidation reactions in the DOC. The CDPF is situated immediately downstream of the DOC and therefore the temperature of the CDPF is increased to above the soot ignition temperature and the filter regenerates.

Active regeneration systems based on fuel oxidation in a DOC are reported in [Anderson et al. 2004] and [Chiew et al. 2005].

A low light-off temperature is required for the DOC to enable regeneration of the CDPF over a broad range of engine operating conditions [Nakane et al. 2005]. Due to the high temperatures at which the DOC works in this situation, much better thermal durability is also required in comparison to a normal DOC. In this respect, the catalyst can lose its activity due to thermal aging and due to fouling by coke from unburned fuel [Nakane et al. 2005] and therefore durable catalyst formulations are required. Typical catalyst formulations include noble metals such as platinum/palladium mixtures [Nakane et al. 2005]. Also, good mixing of the fuel with the exhaust gas upstream of the DOC is required in order to avoid, on the one hand, hot regions in the DOC resulting in local catalyst aging and hydrocarbon slip, and, on the other hand, cool regions in the CDPF resulting in local incomplete soot oxidation and the possibility of uncontrolled regeneration [Chiew et al. 2005].

## Electric Regeneration

Electric regeneration methods include:

- Electric heating of the exhaust gas, e.g. [Kojetin et al. 1993].
- Electric heating of the filter substrate in the case of conductive substrates, e.g. [Meinig et al. 1998], [DePetrillo et al. 2002].
- Electric heating of the filter substrate in the case of non conductive substrates, e.g. [Sakaguchi et al. 1999].
- Heating of the soot using microwaves, e.g. [van Helden et al. 2005].

Since the electrical energy on-board the vehicle is generated from the chemical bound energy of fuel with efficiency less than one, the use of electrical energy for heating imposes an additional fuel economy penalty compared to heating by fuel combustion/oxidation.

Furthermore, the use of electrical energy for heating imposes an additional load on the electrical system of the vehicle. Therefore, to reduce this load, electric regeneration systems usually employ two or more filter units in parallel that are regenerated one at a time while the other filter units continue filtering. The filter unit being regenerated is usually isolated from the main exhaust flow and regenerated using exhaust gas or an external air supply at low flow rates in order to minimize convective heat losses. Heat losses can also be reduced using reflectors. For example, see [Kojetin et al. 1993], [Meinig et al. 1998] and [Sakaguchi et al. 1999].

Although active regeneration methods based on electric heating have been developed they appear to have not been applied as much as other active regeneration methods. Microwave regeneration methods are in an experimental phase of development.

### 6.3.8 Regeneration Strategies

Several aspects related to DPF regeneration are discussed below. In general, it is important that the regeneration process occurs automatically and does not disrupt the normal operation of the vehicle.

#### Passive and Active Regeneration

Passive regeneration systems only function reliably under certain engine operating conditions and duty cycles and run the risk of uncontrolled regeneration. However, passive systems do not incur a fuel economy penalty other than that due to the backpressure of the DPF. On the other hand, active regeneration systems can be more reliable and offer greater flexibility however they increase system complexity and incur a further fuel economy penalty. In this respect it is possible to combine the catalytic functionality of a passive system with an active system, for example to use engine management methods together with a catalytic fuel additive [Salvat et al. 2000] or engine management methods together with a catalyzed filter (CDPF) [Konstandopoulos et al. 2004a]. This can facilitate lower active regeneration temperatures as well as less frequent active regeneration due to simultaneous passive regeneration, thus reducing the overall fuel economy penalty.

Of the active regeneration systems discussed above, fuel burner systems may be more complex compared to fuel injection / DOC systems however they can enable regeneration under a wide range of engine operating conditions. On the other hand, fuel injection / DOC systems function only above the light-off temperature of the DOC and therefore under certain engine operating conditions engine management methods may be necessary to increase the exhaust gas temperature to above the DOC light-off temperature. As an alternative, engine management methods can be used both to increase the exhaust gas temperature to above the DOC light-off temperature and to supply the necessary hydrocarbons to the DOC [Hiranuma et al. 2003]. As another alternative, a small fuel burner can be installed upstream of the DOC and used to increase the exhaust gas temperature to above the DOC light-off temperature and to supply unburned hydrocarbons to the DOC [Gaiser et al. 2008]. In this approach, the fuel economy penalty may be less compared to engine management methods since heat losses in the engine are avoided [Gaiser et al. 2008]. In this respect, fuel burner systems release their heat just upstream of the DPF.

#### Soot Mass Load

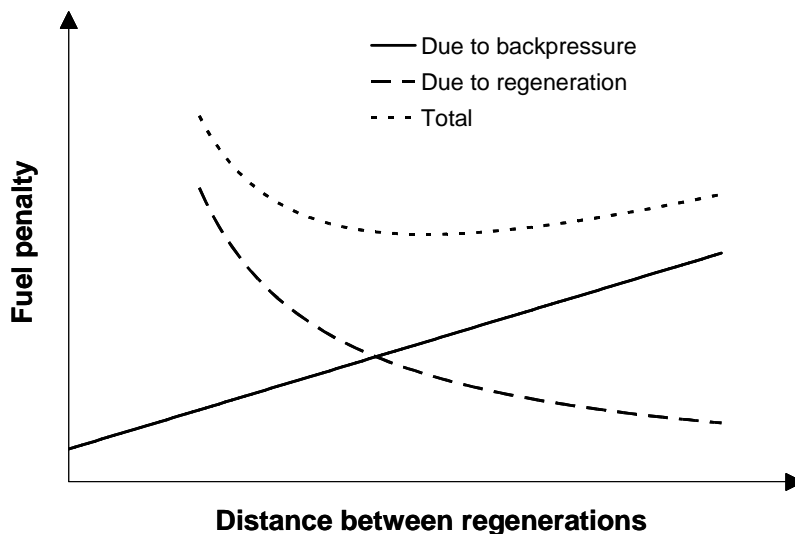
Regeneration strategies work on the basis of the maximum soot mass load in the filter that must not be exceeded in order to ensure that the backpressure is not excessive and that the filter is not exposed to exceedingly high temperatures during regeneration. In this respect the thermal properties of the substrate material can strongly influence the relationship between soot mass load and filter temperature during uncontrolled regeneration [Merkel et al. 2001a]. In active regeneration systems, regeneration is initiated before the maximum soot mass load is reached. On the other hand, passive regeneration systems are designed to regenerate on a continuous basis such that the maximum soot mass load is not exceeded. However, it is not possible to ensure in passive systems that the maximum soot mass load is never exceeded irrespective of the engine operating conditions and duty cycle. Furthermore, in both active and passive systems a certain margin of safety is necessary in the maximum soot mass load due to the possibility of spatial non uniformities in the soot distribution in the filter that can result in local hot spots during regeneration even though the total soot mass load is not above the maximum. Studies of the effects of non uniformities on DPF regeneration are reported in [Konstandopoulos et al. 2001] and [Konstandopoulos et al. 2003].

In rail applications, significant spatial non uniformities may exist in the soot distribution due to the relatively large size of the DPF and therefore a greater margin of safety may be required in the maximum soot mass load in order to avoid excessively high temperatures during regeneration.

Monitoring the soot mass load of the DPF is difficult because there is no direct method to measure it. The filter pressure drop is closely related to the soot mass load however the relationship is not definite because over time an increasing proportion of the pressure drop arises from the accumulated ash and not only the accumulated soot. Therefore the soot mass load has to be calculated using also monitored engine operating parameters in order to account for ash accumulation [Salvat et al. 2000]. Advanced hardware and virtual soot sensors were developed in the IMITEC project discussed in Section 6.5.

### Active Regeneration Interval

For a constant vehicle operating condition, the active regeneration interval can be considered on the basis of the distance travelled by the vehicle between two consecutive regenerations. As discussed in [Salvat et al. 2000] for the case of a passenger car, a lower limit exists on the regeneration interval below which the soot mass load is too low for soot oxidation to propagate through the filter and an upper limit exists above which the soot mass load is too high and can result in high regeneration temperatures that damage the filter.



**Figure 39: Optimum active regeneration interval for constant vehicle operating condition.**

To minimize the total fuel penalty of the DPF and active regeneration system it is necessary to consider the fuel penalty due to the increasing backpressure of the filter and the fuel penalty due to the fuel consumed to regenerate the filter. For a constant vehicle operating condition, the first fuel penalty increases linearly with increasing distance between consecutive regenerations whereas the second penalty decreases because the fuel consumed to regenerate the filter each time is constant [Salvat et al. 2000]. The trend is shown schematically in Figure 39. Therefore, for

a certain distance or regeneration interval the total fuel penalty is minimal and there is a range of distances for which the fuel penalty may be acceptable.

### Active Regeneration Temperature

The DPF inlet temperature during active regeneration is usually in the range of 600 - 700 °C (e.g. fuel burner [Kong et al. 2005], fuel injection / DOC system [Chiew et al. 2005]) but may be lower for a DPF with catalytic functionality (e.g. catalytic fuel additive [Salvat et al. 2000]) and the duration of the regeneration is usually of the order of several minutes. As reported in [Singh et al. 2006] for active regeneration using fuel injection upstream of a DOC, the mass of soot oxidized for a certain amount of fuel depends on the filter inlet temperature. At higher inlet temperatures more soot is oxidized for the same amount of fuel than at lower inlet temperatures. Also, at higher inlet temperatures more soot is oxidized in the same time than at lower inlet temperatures. However, during regeneration the temperature inside the filter can be significantly higher than the temperature at the inlet of the filter because of the heat release from the soot oxidation reactions and therefore it is necessary to ensure that the filter is not exposed to exceedingly high temperatures particularly in the case of a catalyzed filter where high temperatures inside the filter can damage the catalyst.

---

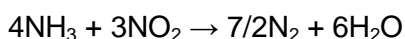
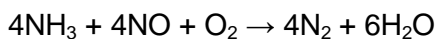
## 6.4 SELECTIVE CATALYTIC REDUCTION

### 6.4.1 Introduction

The NO<sub>x</sub> (NO and NO<sub>2</sub>) emissions of Diesel engines can be reduced by selective catalytic reduction (SCR) to nitrogen using ammonia (NH<sub>3</sub>) produced from the decomposition of urea stored on-board the vehicle. SCR technology has been used in industrial applications to control NO<sub>x</sub> emissions from gas turbines, reciprocating engines, industrial heaters, boilers, and chemical plants [Heck et al. 1994]. It has also been applied to marine engines [Hug et al. 1993] and more recently it has been developed for use in on-road Diesel vehicles, such as heavy duty vehicles, as discussed below.

### 6.4.2 Operation Principle

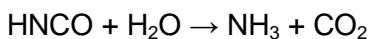
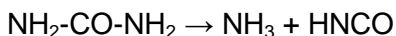
SCR is usually performed in a catalytic reactor through which the exhaust gases containing the NO<sub>x</sub> are passed. The ammonia or urea reducing agent is injected into the exhaust gas upstream of the reactor and is mixed with the exhaust gases. In the reactor, the selective catalytic reduction of the NO<sub>x</sub> by ammonia can proceed via the following reaction paths [Koebel et al. 2000]:



The second reaction path is much faster than the first path. The third reaction path is slower than the first and second paths.

In on-road applications, for safety and toxicity reasons and because of problems associated with the storage, handling and transportation of ammonia, the use of urea (CO(NH<sub>2</sub>)<sub>2</sub>) as a reducing agent / ammonia storage method has been preferred [Koebel et al. 2000] [Muller et al. 2003] [Schmiege et al. 2005]. The urea is usually stored in the form of an aqueous solution. After

injection into the exhaust stream, the urea decomposes thermally to ammonia and isocyanic acid (HNCO), which then hydrolyzes to ammonia and carbon dioxide [Koebel et al. 2000]:



However, low residence times in compact SCR systems could potentially result in incomplete urea decomposition and the delivery of a mixture of urea, isocyanic acid and ammonia to the SCR catalyst, leading to reduced SCR performance and ammonia and HNCO emissions [Koebel et al. 2000].

In on-road applications the urea solution is stored on-board the vehicle in a tank that must be refilled periodically. The level of NO<sub>x</sub> emissions reduction performed determines the urea consumption and in this respect it is useful to consider the urea consumption as a percentage of fuel consumption.

Recently, more compact alternative methods of ammonia storage have also been considered such as ammonium carbamate (NH<sub>2</sub>-CO<sub>2</sub>)-(NH<sub>4</sub>) [Tatur et al. 2009].

### 6.4.3 SCR Catalysts

Three general types of catalysts have been developed for the selective catalytic reduction of NO<sub>x</sub>: precious metal catalysts, base metal catalysts and zeolite catalysts [Heck et al. 1994]. SCR with ammonia was initially applied using precious metal catalysts. Precious metal catalysts operate at low temperatures. Base metal catalysts such as vanadium/titanium catalysts (V<sub>2</sub>O<sub>5</sub> supported on TiO<sub>2</sub>) operate at medium temperatures. Zeolite catalysts can operate at high temperatures. In the case of precious metal and vanadium/titanium catalysts, NO<sub>x</sub> reduction decreases at high temperatures due to ammonia oxidation.

Various vanadium/titanium and copper/iron zeolite catalysts have been tested for the selective catalytic reduction of NO<sub>x</sub> over the range of exhaust gas temperatures usually encountered in on-road Diesel applications [Gieshoff et al. 2001] [Schmieg et al. 2005] [Cavataio et al. 2007]. In general, copper zeolite catalysts have better NO<sub>x</sub> conversion performance at low temperatures compared to iron zeolite catalysts and vice versa [Schmieg et al. 2005] [Cavataio et al. 2007].

Several parameters are important for the selection of SCR catalysts [Cavataio et al. 2007]. Operating parameters such as the exhaust gas temperature profile and NO<sub>2</sub>/NO<sub>x</sub> ratio are important. The ammonia storage capacity of the catalyst at different temperatures is also important. Thermal durability and durability to poisoning by sulphur and hydrocarbons is also important.

SCR catalysts can be based on flow-through substrates that are either extruded from the catalyst material itself, as has been done in the case of vanadium/titanium catalysts (e.g. [Hug et al. 1993], [Miller et al. 2000]), or coated with the catalyst material, in which case ceramic (e.g. [van Helden et al. 2002]) or metallic substrates (e.g. [Gieshoff et al. 2000]) can be used.

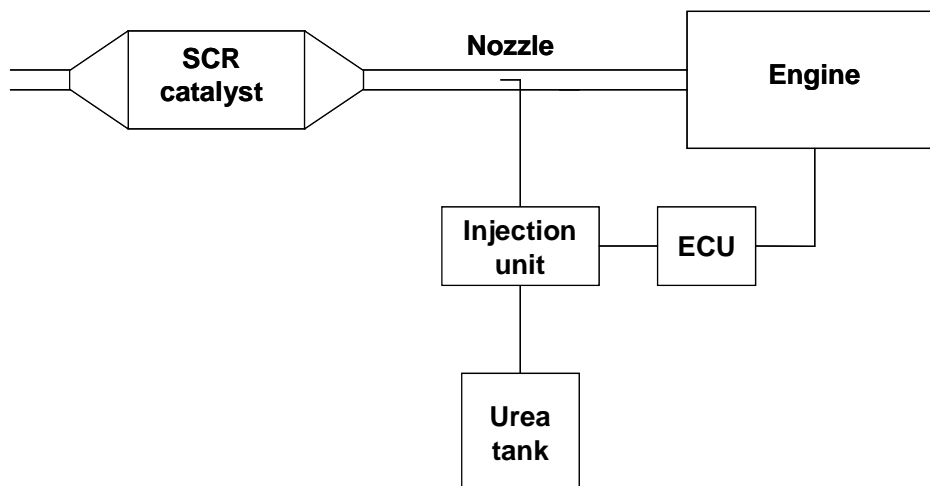
In vehicular applications with space constraints it is important to maximize the volumetric activity of the SCR catalyst in order to minimize its size [Koebel et al. 2000]. One way to do this is to increase the intrinsic activity of the SCR catalyst. Another way is to increase the cell density and therefore the volumetric surface area of the catalyst substrate, e.g. [Miller et al. 2000], [Gekas et al. 2002]. In this respect, SCR catalysts with cell densities of 400 cells per square inch have been reported, e.g. [Gieshoff et al. 2000], [van Helden et al. 2002]. Also, another way is to make use of

the higher reaction rate between ammonia and equimolar amounts of NO and NO<sub>2</sub> by increasing the NO<sub>2</sub> fraction in the exhaust gas using an oxidation catalyst [Koebel et al. 2000].

#### 6.4.4 SCR Systems

SCR systems in on-road applications usually employ an open loop control strategy which (in simple terms) is based on an engine out NO<sub>x</sub> prediction functionality, a post catalyst NO<sub>x</sub> target and a nominal stoichiometric ratio map, from which the necessary urea injection rate to accomplish the required NO<sub>x</sub> reduction while preventing ammonia slip is determined [Willems et al. 2007]. Typical inputs to the system include engine speed and load and exhaust gas temperature. The layout of a generic open loop urea SCR system is shown schematically in Figure 40.

Urea solution is drawn from the urea tank and injected into the exhaust via a nozzle. The urea subsequently decomposes to ammonia via thermolysis and hydrolysis. Hydrolysis can also occur in the SCR catalyst [Koebel et al. 2000] or in a hydrolysis catalyst located immediately upstream of the SCR catalyst, e.g. [Gieshoff et al. 2000]. The produced ammonia then adsorbs on to the walls of the SCR catalyst where it reduces the NO<sub>x</sub> to nitrogen.



**Figure 40: Open loop urea SCR system**

In order to achieve high NO<sub>x</sub> conversion rates in the SCR catalyst it is important to ensure the uniform distribution of the injected urea solution in the exhaust gas [Hug et al. 1993]. In this respect the position of the nozzle, injection pressure, direction of injection and geometry of the exhaust duct between the point of injection and the SCR catalyst are important parameters. Mixing elements can be used to improve the homogeneity of the reaction components and to avoid streaks, wall effects and other irregularities. Also, air can be used in the injection system to transport the urea solution to the nozzle, to improve atomization, to cool the nozzle and to prevent clogging [Servati et al. 2005]. However, airless systems may be important for closed loop control in order to reduce the time delay of the injection system [Willems et al. 2007]. Long term stability and repeatability of injection are also important [Gekas et al. 2002].

One of the important inputs for the control of urea injection is temperature. Below a certain temperature urea injection may have to be stopped due to low catalyst activity and in order to avoid partial urea decomposition. It may also be necessary to stop urea injection at low temperatures in order to avoid deactivation of the catalyst from the condensation of ammonium sulfate [Koebel et al. 2000] [Hug et al. 1993].

An outlook on the prospects of closed loop SCR control is given in [Willems et al. 2007]. Open loop urea dosing strategies have proven sufficient for achieving NO<sub>x</sub> reductions in the range of 50 - 80% in heavy duty applications. However, in achieving much higher conversions it becomes difficult to find calibrations that also achieve low ammonia slip particularly under transient conditions. Also, safety margins related to catalyst ageing and the effect of varying ambient conditions on performance have to be reduced, and transient performance becomes important. In this respect, closed loop control strategies have the potential to reduce the required calibration effort, improve transient control performance and offer robustness for system variations [Willems et al. 2007]. However, the performance of closed loop control is also limited by slow catalyst dynamics, time delays in the urea dosing system and limits on ammonia emissions [Willems et al. 2007]. Furthermore, NO<sub>x</sub> sensors and/or ammonia sensors are necessary for closed loop control. A NO<sub>x</sub> sensor is reported in [Hoffman et al. 2004] and an ammonia sensor in [Wang et al. 2008].

The absence of significant transients in rail engine duty cycles may help in achieving high NO<sub>x</sub> reductions in rail SCR applications.

#### 6.4.5 NO<sub>x</sub> Reduction Performance

The NO<sub>x</sub> reduction performance of SCR systems for heavy duty vehicles is reported in a number of studies, e.g. [Miller et al. 2000], [Amon et al. 2001], [Scarnegie et al. 2003], [Block et al. 2005], [Servati et al. 2005] and [Hinz et al. 2006]. The studies include tests on various steady state and transient cycles as well as on-road tests. The overall range of the reported NO<sub>x</sub> reductions is about 50% – 90%. The NO<sub>x</sub> reductions reported in each study are different. Also, the reported NO<sub>x</sub> reductions vary depending on the test cycle or on-road conditions.

#### 6.4.6 SCR with DPF

After-treatment systems including both an SCR and a DPF may be necessary for the reduction of NO<sub>x</sub> and PM emissions. The SCR and DPF may be arranged in either of two ways:

- DPF followed by SCR
- SCR followed by DPF

In the first arrangement, in the case of a DPF that also includes a NO oxidation functionality, the NO<sub>2</sub> concentration of the exhaust gas entering the SCR may be higher and this could increase SCR performance by promoting the fast reaction between ammonia and equimolar amounts of NO and NO<sub>2</sub> [Koebel et al. 2000]. In this arrangement, the DPF may also be exposed to higher temperatures and NO<sub>x</sub> levels that increase passive regeneration performance. On the other hand, the SCR may be exposed to lower temperatures compared to the second arrangement that result in lower performance. Also, during DPF regeneration the SCR could be exposed to high temperatures that compromise its durability, for example in the case of an uncontrolled regeneration. In the second arrangement, the SCR may be exposed to higher temperatures that improve performance especially under cold starting conditions where catalyst warm-up is

important. However, in this arrangement the DPF would also be exposed to lower NO<sub>x</sub> concentrations that might reduce passive regeneration performance. In these respects, the thermal durability and relative activity of the SCR catalyst at low and high temperatures may be important.

The first arrangement has been reported for heavy-duty applications, e.g. [Chandler et al. 2000], [Walker et al. 2004], [Scarnegie et al. 2003], while the second arrangement has been reported for passenger car applications [Tennison et al. 2004].

## 6.5 PAST RESEARCH

---

CERTH/APTL has participated in the majority of the EU-wide (partially financed by the EC) research projects regarding automotive diesel exhaust after-treatment. The related list includes 16 projects. The most important areas linked to exhaust after-treatment have been researched in these projects: substrate materials, filtration technologies, catalysts and coating techniques for gas treatment and soot particle low temperature oxidation, sensors/diagnostics and system control including filter regeneration.

One of the very first EU collaborative research project was the Integrated After-treatment System of DI Diesels for Cars (**DIDTREAT**) (BRPR-CT95-0048). The project started on January 1<sup>st</sup>, 1996 and ended at the end of 1998. Apart from APTL, other members of the consortium were the FIAT Research Center (CRF), Mercedes-Benz, Johnson Matthey (JM), Zeuna Staerker (ZS) and the universities of Leuven and Genova. The project aimed to achieve better than Euro 3 emissions limits through the incorporation of a Lean NO<sub>x</sub> catalyst and Exhaust Gas Recirculation (EGR) for NO<sub>x</sub> control, a Diesel Oxidation Catalyst (DOC) for HC/CO control and a catalyzed Diesel Particulate Filter (DPF) for the soot particles. A continuously regenerating Diesel particulate filter system and a fuel burner for filter regeneration were also tested. The project succeeded to fulfill its targets and proved the proposed technology on a demonstrator vehicle. Challenging proved to be the DeNO<sub>x</sub> technology applied (especially the limited NO<sub>x</sub> reduction efficiency in the light of stricter emissions limits), the homogenous distribution of the reductant in the exhaust for the Lean NO<sub>x</sub> catalyst operation, and the control of the soot regeneration with the use of the fuel burner. In-filter temperature peaks were not easily controlled with the filter soot mass load. Therefore, low soot mass load limits were necessary for filters made of cordierite or aluminum titanate. Materials with high thermal conductivity like silicon carbide and metal filters were able to withstand thermal regeneration conditions.

Another project of the early development days was the Functionalized Ceramic Membrane Filter for Highly Efficient Soot Particle Removal (**CERFIL**) (BRPR-CT98-0716). The project started on July 1<sup>st</sup>, 1998 and ended June 30<sup>th</sup>, 2001. Apart from APTL, other members of the consortium were NOTOX, CRF, JM, FEV Motorenteknik, AEA Technology and the universities of Delft and Thessaloniki. The project aimed to overcome problems of available at that time ceramic filter technology in terms of material reliability, pressure drop, collection efficiency for fine particles and ease of regeneration by oxidation of collected soot by integrating a silicon carbide (SiC)-based extruded monolithic filter, with very high collection efficiency (>99%) for nano-sized particles, low-pressure drop and high material reliability. A two layer gradient filter structure (a filter membrane with an overlaid highly porous "foamy" layer) functions at the same time as a fine particle separator and as a soot oxidation reactor, through a catalytic coating dispersed into the entire ceramic microstructure. Advanced catalytic coatings for soot oxidation incorporated into the filter microstructure. Two types of novel catalytic coatings were developed: Physical Vapour Deposition (PVD)-based nanoscale catalysts and Supported Liquid Phase (SLP) catalysts. Adaptive control of flow direction in the ceramic filter based on comprehensive computer

modelling tools, were employed for system optimization. The project succeeded in the realization of a composite ceramic filter/membrane-reactor microstructure with locally varying properties to enhance contact of soot particles with catalytic coatings, an optimized autothermal regeneration of the ceramic filter by adaptive flow direction control, the considerable increase in system reliability and avoidance of material failures, the higher removal efficiency of the filter system for nano-sized particles with appreciably lower pressure drop and improved permeability.

A third project that started before 2000 was the Multi-wavelength sensor for sub-micron particle analysis (**MULTISENS**) (BRST-CT98-5537). The project started on February 1<sup>st</sup>, 1999 and ended January 31<sup>th</sup>, 2001. Apart from APTL, other members of the consortium were Wizard Zahoransky, NOTOX, Obernosterer Strickstoffe, Kehagias-Limnidis & Co, Solo Kleinmotoren and the University of Thessaloniki. The objective of this project was the design, development and integration of an optical multi-wavelength sensor suitable for on-line measurements of particulate matter in the raw exhaust of the diesel engine. This sensor represented a state-of-the art instrument in the area of diesel exhaust measurements and it was cheaper than other competing technologies at that time, able to measure soot nanoparticles under both steady state and transient conditions of engine operation. The work included the integration of the sensor in a prototype unit with an interface between the sensor and the exhaust, allowing for accurate measurements without significant particle losses on the walls of the interface. Additionally, a white cell unit able to achieve very high optical path lengths (up to 20 m) in a small volume has boosted the sensor's capabilities to measure in very low soot concentration environments (i.e. behind filters). A purging system which aimed to keep the mirrors of the white cell clean from soot particles has been simulated using CFD codes and successfully implemented. Software components incorporating Mie theory calculations for spherical particles have been extended to account for real soot particle morphology (i.e. fractal aggregates). The sensor's performance was evaluated and cross-compared with the performance of laboratory-grade commercial instruments, namely the SMPS and the ELPI. Extruded and fibrous filters which have been developed and delivered during the first year of the project, together with a prototype two-stroke engine for outdoor powered equipment were used to carry out performance tests of the sensor's capabilities. The sensor was commercially exploited after the completion of the project. Compared to today's particle analysis technology the sensor has the advantages of raw on-line exhaust measurement capability and that it enables to extract valuable information regarding the soot particle morphology. On the other hand it is rather big in size and not easy in its maintenance.



**Figure 41: The MULTISENS sensor.**

By the years 1999 to 2000 and after the preliminary research efforts it was clear that at the EU, both the Commission and the industry should intensify their efforts towards cleaning the diesel engine exhaust and coming up with Low Emission Vehicles (LEVs). A central position among the challenges was engaged by the voluntary 25% CO<sub>2</sub> reduction commitment of the European automotive industry to the European Commission following the Kyoto Earth summit, namely the achievement in 2008 of 140 gr of CO<sub>2</sub> per km traveled, corresponding to an average fuel consumption of 5.7 l/100 km for the new car fleet, an important milestone towards the strategic target of 120 gr CO<sub>2</sub>/km for 2012. The need to increase the share of the diesel engine powered vehicles was evident as the Compression Ignition (CI) engine was considered as the most efficient mobile power production plant. The main barrier to this was the contemporary reduction of NO<sub>x</sub> and particulate emissions up to the level required by the next stages of European legislation, EURO IV and beyond. Moreover the use of diesel particulate filter (DPF) systems appeared to be inescapable for meeting the required Particulate Matter (PM) reductions.

Based on a number of expressions of interest in this area by interested industrial partners and research organizations, APTL set up a cluster of research projects on DPFs in 2000 (**DEXA** cluster). This cluster of projects was encouraged by the European Council for Automotive R&D (EUCAR). The members of the consortium included passenger car manufacturers (FIAT and Renault), exhaust after-treatment system suppliers (ZS, JM), engineering research and development industries (AVL, FEV), instrumentation manufacturers (Wizard Zahoransky), research organizations (Istituto Motori, European Joint Research Center, Christian Doppler Laboratory CDL-ACT), universities (Torino, Napoli), and others.

The DEXA Cluster consisted initially of three closely interlinked projects:

- Advanced Regeneration Technologies for Diesel Exhaust Particulate After-treatment (**ART-DEXA**) (G3RD-CT-1999-00016)
- System Level Optimization and Control Tools for Diesel Exhaust After-treatment (**SYLOC-DEXA**) (G3RD-CT-1999-00014)
- Particulate Size and Composition Measurements for Diesel Exhaust After-treatment (**PSICO-DEXA**) (G6RD-CT-1999-00038)

The ART project focused on the component technology integration aspect, SYLOC on the system design and PSICO on the quality assessment/measurements aspect of research. The main result from ART was the development of advanced catalytic particulate control technologies and their integration on two demonstrator vehicles. SYLOC produced a user-friendly simulation toolkit for the computer-aided design and engineering of integrated diesel exhaust after-treatment systems. PSICO developed particulate size and composition measurement methodologies.

A number of available at that time filter media were tested in ART (SiC, Cordierite, metal and ceramic fibrous). The SiC proved superior regarding the soot loading behavior (the imposing pressure drop) and the filtration efficiency. Several mixed oxide and perovskite type catalysts were evaluated and the best one (a mixed oxide catalyst) was scaled-up by the industrial partners. Specific strategies focusing on combination of boost pressure, EGR rate increase, and fuel injection modification have been developed for active filter regeneration (increase the filter temperature up to the required temperature for thermal soot oxidation). Regeneration control algorithms were developed and implemented in the ECU. Emergency procedures in case of a system (sensors) failure have been taken into account (the regeneration is initiated always after a certain time period). In case that the sensors work correctly again, the program returns to the normal operation mode.

By the year 2000 it was proven that it was not possible to optimize the behavior of the individual components of a Diesel engine exhaust system independently of engine development work: the

optimization had to consider a synergistic interaction of individual elements of the exhaust system and the engine. The identification of successful combinations by building and testing entire after-treatment systems or vehicles required often prohibitive amounts of effort and costs. The project SYLOC offered an alternative to this: the development of predictive computer models for the optimization of entire Diesel engine exhaust systems. These models could be used in such a way that various design options can be assessed rapidly to determine the most suitable design for a particular engine-prototype or vehicle. Research work focused on laboratory experiments and steady-state engine tests for collecting measurement data as input to the simulation software. The consortium investigated many commercial particulate filter types and conversion systems in synergy with the ART-DEXA project. Physical models for each of the candidate after-treatment devices had been implemented in the form of interfaceable sub-programs, which can be coupled to the CFD model of the entire exhaust system for the simulation of component behavior, such as loading and regeneration of the particulate traps. Also, a database containing information on after-treatment device materials and geometric characteristics had been compiled with continuous updates/extensions during the run-time of the project.

Various size measurement techniques were deployed and assessed within the PSICO project. The available measurements indicated that the majority of particles measured with the electrical mobility and aerodynamic techniques lie in the range of 30-200 nm. The optical techniques on the other hand, resulted in measurements representative of the primary particle diameters, which were found to lie in the range of 8 to 40 nm. Transmission Electron Microscopy (TEM) pictures of mobility segregated particles demonstrated the big difference that geometric and “operational” particle size can have for soot aggregates. Correlations of the aerodynamic (ELPI) to mobility (SMPS) determined diameters were obtained enabling thus the characterization of the fractal morphology of the diesel particles. An important result of the research work was the confirmation of the existence of a universal size distribution for the emitted soot particles (irrespective of combustion technology, and its interpretation using a population balance description of the random continuous oxidative fragmentation and coagulation of fractal aggregates.



**Figure 42: The DEXA cluster vehicle demonstrators.**

As a result of the three years DEXA cluster, two demonstrator vehicles, characterized by Euro IV compliant NOx and particulate emissions (particulate emission lower than 0.0025 g/km on NEDC cycle have been assessed, i.e. –90 % compared to Euro IV limits) have been built up, combining the most promising particulate filter solution (catalyzed silicon carbide wall-flow filter) with the most effective active regeneration strategy (capable to promote the particulate filter regeneration

in all driving conditions). The average increase of fuel consumption was lower than 2 %. The cost and the environmental impact (LCA) estimated for the whole system appeared to be competitive compared to a fuel-additive based solution.

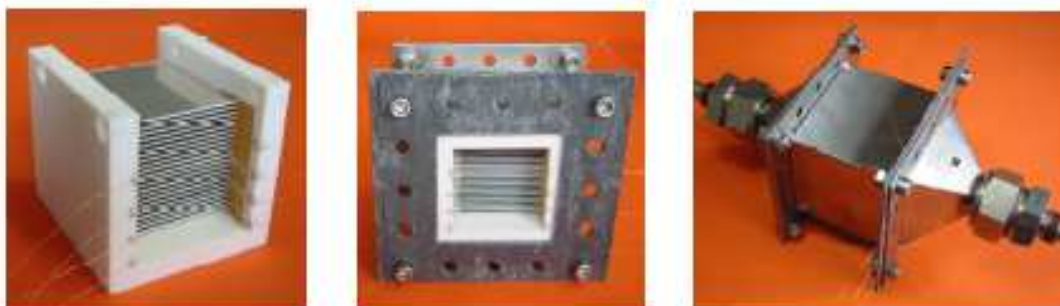
On July 1<sup>st</sup>, 2002, another project entered the DEXA cluster of projects. This had the title "Simulation Tool for Dynamic Flow Analysis in Foam Filters" (**STYFF-DEXA**) and ended in September, 2005. Among the partners of the project were the APTL, CRF, ArvinMeritor and CDL-ACT. The comparison between Diesel particulate filtration technologies revealed some important advantages of ceramic or metallic foams: due to their peculiar structure, the particulate distribution along the device is quite uniform and, as a consequence, the pressure drop is not very sensitive to the particulate loading. During trap regeneration the thermal load is homogeneous, limiting thermal-mechanical stresses that the substrate has to withstand. Moreover, the cellular structure assures a high thermal shock resistance; on the contrary, the wall flow monolith structure can suffer from cracks and mechanical failure due to thermal gradients and vibrations. Finally, for the development of a passive system with a supported catalyst, an open-pore ceramic foam allows a better contact between the catalyst and the particulate, since the "cake formation" is avoided.

In order to evaluate the real advantages of foam based traps, the STYFF project aimed to get a deeper understanding about optimization of the foam material for low pressure drop, high separation and regeneration efficiency. As a consequence a more detailed insight into the physical and chemical phenomena taking place inside the filter material via computer modeling and accompanying experimental work had been gained. The computational tools developed would aid the design of foam filter material to fit specific applications. Additionally filter regeneration models were generated and partially validated by experimental work. Within the last phase of the project a Demonstrator utilizing a novel slits concept was designed and tested in laboratory and engine test bed work. This filter concept showed superior filtration efficiency to existing at that time foam stack based filter designs but still lower than conventional SiC filters.

At the same time the sintered metal filter for heavy duty applications was the subject of the research for the Coated Sintered Metal Trap (**COMET**) (G3RD-CT-2002-00811) project. This started on August 1<sup>st</sup>, 2002 and ended 3 years later. The participant list included DaimlerChrysler, AVL, JM, PUREM, APTL and the universities of Trento, Leuven, Haute Alsace and Kaiserslautern. Several sintered metal materials were considered and numerous zeolite based coatings were screened. Many catalysts (Ru-zeolites, Pt-zeolites, Nitrated Ag/Al<sub>2</sub>O<sub>3</sub>) demonstrated significant catalytic activity in the thermal and/or the NO<sub>2</sub>-assisted soot oxidation. The main problems recognized concerned gradual catalytic activity losses due to aging. Catalytic coating in some cases increased the corrosion resistance of the substrate material. Coating techniques were developed that allowed the precise control of the catalyst loading. A full-scale coated sintered metal filter was built. This was extensively tested under steady state and transient engine conditions. The PM reduction measured was 80 – 90 % depending on the engine test cycle. During the project a number of innovations were realised: A fast ageing technique for the determination of the effect of ash particles on the filter and coating materials was developed; Soot and ash deposit evolution mathematical models at the micro-scale were formulated and verified; Soot and ash deposit microstructural properties were measured; User Defined Functions (UDFs) for the coupling of the transport and deposition of soot/ash particles through the inflow spaces of the full-scale filter, filtration efficiency, flow resistance, soot loading and regeneration models.

In 2002, another project was initiated. The project title was "Smart NOx abatement systems for next-generation Environmental Technologies (**SMART**) (G5RD-CT-2002-00710)". It started in April, 2002 and ended in March, 2005. The project was coordinated by Bosch. CRF, JM, APTL, the Swiss Federal Institute of Technology and the universities of Cambridge, Messina, Patras and

Warsaw were the partners of this project. The aim of the project was to develop an integrated device of coupled NO<sub>x</sub> reduction catalyst and NO<sub>x</sub>-sensor functionality which self-adjusts to changes in operating conditions. The concept involved controlling the performance of an electrochemically promoted catalyst by means of an electrical output derived from a NO<sub>x</sub> sensor able to operate in oxygen concentrations up to 20 %. A Constant Current Potentiometric NO<sub>x</sub> Sensor (CCPS) based on a Rh/YSZ/Au cell was developed and demonstrated. Performance tests showed high sensitivity to NO variation and tolerable interference from other exhaust components. The operation temperature of this sensor is nearly the same as that of the electrochemically promoted NO<sub>x</sub>-reduction system developed in the project and as such it enables the integration of the CCPS into a sensor-catalyst unit. Multilayer Ceramic Amperometric NO<sub>x</sub> sensors (MCA) had also been successfully developed in their principles. A completely new operation mode together with the implementation of very pure materials led to a very low offset signal and temperature dependence of the sensor signal. Both types of sensors were able to detect NO<sub>x</sub> at concentrations lower than 100 ppm. Different types of NO<sub>x</sub> catalysts and reactor configurations for electrochemical promotion were explored: single-pellet, structured catalysts having film-type noble metal (bipolar tubular, multi-channel, plate-type) and having dispersed noble metal (YSZ coated monoliths, YSZ foams and felts). This broad investigation resulted in the design of a new type of reactor: the monolith-type electrocatalytic promoted reactor (MEPR). The main objective of coupling the sensor and the catalyst in a single integrated device has been achieved, and a Monolithic



**Figure 43: Integration of the MEP device.**

Electrochemically Promoted (MEP) device locating up to 22 catalyst/sensor elements (defined as semi-scale device) has been designed. The device has the advantage of easy assembling/dismantling, no need of gas tightness, versatility of either simple reactor (MEPR) or integrated reactor/sensor (MEPRS) operation and use of flat or ribbed elements. During the assessment of the MERPS in real engine exhaust conditions it was demonstrated that the catalysts' performance under "slightly" lean atmosphere ( $O_2$  concentration  $< 2\%$ ) was sufficient. However, significant NO<sub>x</sub> conversion under the "real" lean exhaust environment with an  $O_2$  concentration of the order of 10 % could not be obtained without an additional reductant medium (e.g. HC).

As early as in 2002, it became obvious that the forthcoming diesel emission control systems would be complex assemblies of "chemical reactors" and "separators" to achieve demanding requirements in space and cost, especially in passenger cars. APTL coordinated a research project titled "Integrated Material and Information Technologies for Novel Emission Control Systems (IMITEC) (IST-2001-34874)" with the aim to deliver a sensor platform which would

enable the optimised control of these next generation diesel engine emission control systems gain fuel savings and enable the compliance with the ever becoming stricter emissions regulations. The project started in April 2002 and lasted for three years. Apart from APTL the other partners were Bosch, CRF, JM, AVL and CDL-ACT. Both hardware and software accomplishments were made during the project. Two soot sensors prototypes have been developed and manufactured based on soot-contact principles. These were calibrated and successfully evaluated over steady-state and transient engine operating conditions. A NOx sensor has been benchmarked, tested and integrated into the sensor platform. The sensor (soot and NOx) prototypes have successfully passed the accelerated ageing tests. Apart from the hardware sensors, virtual sensors have been developed able to calculate the soot mass trapped into the Diesel Particulate Filter and trigger the filter regeneration based on the filter soot loading state. Moreover, measurement data from the IMITEC platform was used to train a Neural Network (NN) which was then used to predict successfully the DPF soot mass load and assisted in the interpretation of the sensor signals. All hardware and software sensors have been integrated into a single sensor platform able to communicate with the engine ECU via appropriate communication interfaces. This platform together with the emission control system was successfully installed on a test vehicle. The sensor platform operation with the emission control system was successfully evaluated on the testing vehicle enabling intelligent DPF regeneration management resulting in improved fuel economy.

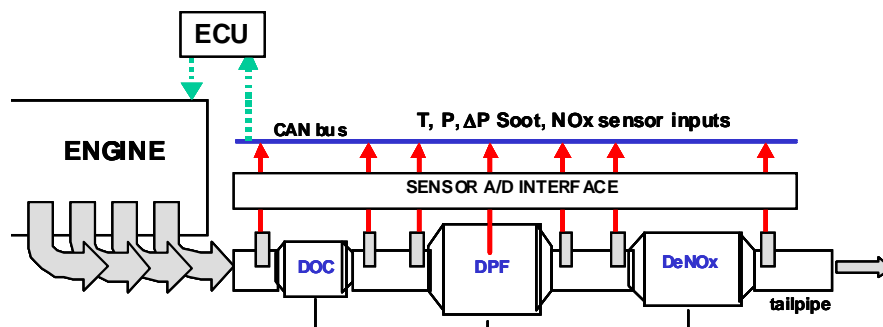


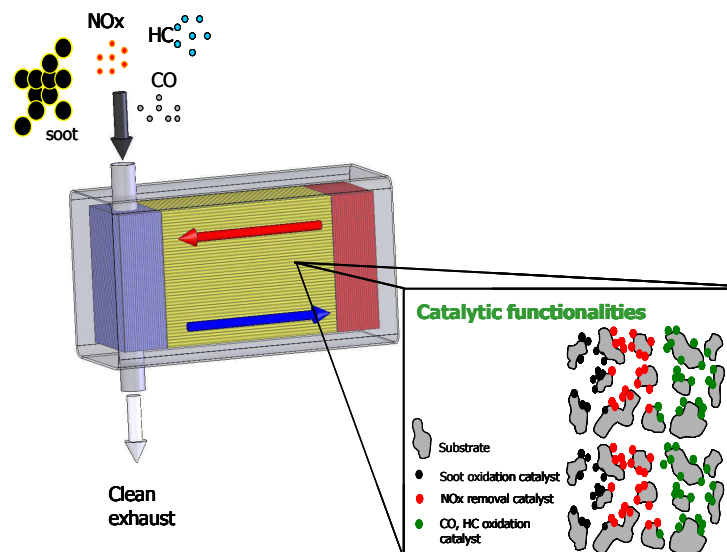
Figure 44: The IMITEC sensor platform.

Sensors and diagnostics were also the subject of the project titled “Infrared Microsystem for Polluting Emission Control on Cars 2 (IMPECC2) (EU FP6-PLT-506507). The project started in January, 2003 and ended two years later. The participants were Renault, Delphi, Swatch, APTL, CEA, CSEM and ULIS. The aim of the project was to develop a fast and accurate optical sensor for the determination of the HCs, CO and soot particle concentration in the exhaust. The sensor would be integrated in the On Board Diagnostic (OBD) system in order to optimize engine operation regarding the exhaust emissions. The system would also be possible to warn the driver in case the operation of the engine and/or the exhaust emission control was not any more within certain specifications. The sensor would also comply with automotive reliability requirements. The reference transparency measurements, necessary to correct for any opacity changes in the optical path was used to extract the information on the exhaust gas particle content. The gas absorption physics were extensively studied to comprehend the measuring principle of the sensor and qualify the signal derived from the device. The exhaust gas sampling and conditioning strategies were defined by studying the interactions of the proposed measuring technology with ambient variables like pressure and temperature. Finally the sensor was realised by the

integration of the emitter controls, the detector amplifiers and the signal processing algorithms. The final prototype was evaluated in real engine exhaust conditions with the main difficulties being the noise signal in some cases and long term measurement stability.

The projects described up to now have all finished. Currently, five more projects are running at APTL on diesel exhaust after-treatment or at least they are closely related to this area. Three of those started in the beginning of 2006 and they are to be finished in the end of 2009. These are IPSY, PAGODE and TOP-EXPERT. The central challenge of these projects is placed in the emission control diesel engines operating in advanced combustion modes like the Homogeneous Charge Compression Ignition (HCCI).

The full title for **IPSY** is “Innovative Particle Trap System for Future Diesel Combustion Concepts (IPSY) (FP6-SUSTDEV-031410)”. Partners were FEV, IFP, APTL, CIDAUT, Instituto Motori, and the universities of RWTH Aachen, Cracow and Valencia. The IPSY project aimed to develop a catalyzed DPF tailored for the HCCI engine exhaust. Since the NO<sub>x</sub> concentration in the HCCI exhaust is very low, NO<sub>2</sub> based DPF regeneration methods will not be sufficient. Moreover the CO and HC concentrations are quite high under HCCI conditions. The IPSY emission targets were set to be beyond the EURO 5 emission limits and the fuel consumption as in the EURO 4 engine calibration. During the first period of the project the HCCI soot was characterized and the soot oxidation kinetics defined. During simulation developments existing filter models were used to couple the macroscopic information regarding the flow and temperature distribution in the DPF with the microscopic description of the soot and ash deposition processes.



**Figure 45: The concept of the Multifunctional Filter Reactor (MFR)**

A full-scale filter was manufactured and named as Multi-Functional Reactor (MFR) since it comprised catalytic functionalities for soot oxidation (catalytic and NO<sub>2</sub>-assisted), HC and CO oxidation. The different catalytic functionalities were carefully distributed in the 3-D space of the filter. Moreover the design of the filter was based on a novel geometry enabled internal heat recovery to decrease the fuel consumption associated with the filter regeneration. The filter is under evaluation under both HCCI and conventional combustion engine operation.

The full title for **PAGODE** is “Post-treatment for the next Generation Of Diesel Engines (PAGODE) (TST5-CT-2006-031404)”. The project focused on the fact that next generation diesel

engine with advanced combustion operation would emit several orders of magnitude CO and HCs. Moreover, new fuel formulations will obviously have an impact on the next-generation after-treatment processes. Conventional oxidation catalysts of Euro 4 technology will no more be sufficient and therefore advanced oxidation catalyst technologies should be developed. During the project low-temperature oxidation of CO and HC, was thoroughly examined and the oxidation mechanisms in the HCCI exhaust were defined. A reliable simulation tool was built to help in the optimisation of the advanced catalysts. Advanced catalysts formulations were exploited for high CO and HC concentration conditions and low-temperature operation. A plasma-assisted system was also evaluated towards CO and HC concentration with encouraging results. Finally, the integrated system was tested under next-generation engine exhaust conditions.

The “Tailored On-board Activated Agents Production for Exhaust After-treatment Performance Enhancement (**TOP-EXPERT**) (FP6-SUSTDEV-2005-031471)” project was focused on NO<sub>x</sub> after-treatment technology. CRF was the coordinator. Participants were JM, ArvinMeritor, APTL and the universities of Liverpool, Leoben and Torino. The performance enhancement regarding NO<sub>x</sub> reduction was pursued via generation of activated chemical agents via two alternative approaches:

- Catalyst based approach: the activated chemical agents was produced by reforming diesel fuel by a short-contact-time reactor, and injected in the exhaust line upstream the main catalyst capable of exploiting them.
- Energy based approach: two devices were included in this system concept. The first one was an energy based fuel processor, using corona discharge generated plasma to reform the fuel into active species. The second was a low-cost microwave resonance based cold plasma generator placed on the main exhaust gas stream and acting directly on gaseous (HC, CO, NO<sub>x</sub>) and solid (PM) pollutants.

The processed gases, mixed with the activated agents stream, were finally treated by an auxiliary catalyst to complete pollutants abatement. Efforts were made to improve each component of the pursued integrated technology via a rigorous scientific approach, following the guidelines of a typical automotive development to ease technology transfer and industrial exploitation. Lab-scale testing of single devices and pre-prototype assembled systems was followed by scaling-up. Testing on engine benches is on-going and results will be disseminated in 2010.

The **Atlantis** project (Aerosol Technologies and Hierarchical Assembly/ Manufacturing for Advanced Nano-structured Porous Materials, FP6-NMP-2004-026678) is a large Integrated Project (IP) with CRF as a coordinator and many partners among which is APTL. It was started in January, 2007 and will last until the end of 2010. This project was motivated by the fact that suitably 3-D engineered and functionalized porous structured reactors can bring important breakthroughs in the market of the automotive emission control systems. The project also aimed to innovations on the emerging biotech markets of bacterial-cells-derived polymers and of mammalian-cells-derived recombinant protein antibodies. The project main tasks related to exhaust after-treatment were:

- The development of a software tool capable to simulate all relevant physical phenomena occurring in porous structures.
- The functionalization of porous systems by the application of novel Aerosol Technology routes.
- The design of appropriate building blocks spanning from 0-D to 3-D dimensionalities, suitable for hierarchical assembly/manufacturing of porous media with 3-D controllable pore space structure and properties suited to the functionalization processes.

- The design and development of a compact, integrated emission control system for the simultaneous treatment of gaseous pollutants (CO, CxHy, NOx) and particulate emissions.

Finally, another running 4 year IP is **HiCEPS** (Highly Integrated Combustion Electric Propulsion System TIP5-CT-2006-031373). This IP will end at the end of 2010 too. It is related to hybrid vehicles. The coordinator is CRF. Three other major European automotive OEMs and four suppliers participate together with a large number of research institutes and universities. Three different hybrid solutions are considered in the project: the gasoline, the diesel and the natural gas. In the diesel hybrid a fibrous metal filter was proposed for particle emission control. In the hybrid case the metal filter offers the advantage of easy and fast electrical regeneration of the filter. A metal filter was built and is currently under evaluation.

## 6.6 CONCLUSIONS

---

Diesel exhaust after-treatment technologies such as DOC, DPF and SCR have been proven in road going vehicles and show good potential for transfer to rail Diesel applications in order to meet Stage IIIB and future emission limits.

Diesel exhaust after-treatment technologies can address HC, CO, PM and NOx emissions, among others, and therefore for given emission limits they may allow a certain degree of freedom in the design of the engine that could benefit overall life cycle cost.

The primary concern for the transfer of Diesel exhaust after-treatment technologies to rail applications is the much larger size of the after-treatment devices and therefore the impact of spatial non uniformities on the performance and durability of the devices. Low exhaust gas temperatures and prolonged idling when encountered in rail applications could also negatively impact DPF regeneration. On the other hand, the absence of significant transients in the operation of rail engines compared to road vehicle engines may help to simplify the design and operation of the after-treatment devices.

A large body of knowledge and experience in Diesel exhaust after-treatment, accumulated through EU funded collaborative research, already exists and can aid the transfer of after-treatment technology to the rail sector.

## 6.7 REFERENCES

---

- Allansson R., Cooper B.J., Thoss J.E., Uusimäki A., Walker A.P., Warren J.P. (2000), "European Experience of High Mileage Durability of Continuously Regenerating Diesel Particulate Filter Technology", SAE Technical Paper 2000-01-0480.
- Allansson R., Goersmann C., Lavenius M., Phillips P.R., Uusimaki A.J., Walker A.P. (2004), "The Development and In-Field Performance of Highly Durable Particulate Control Systems", SAE Technical Paper 2004-01-0072.
- Amon B., Keefe G. (2001), "On-Road Demonstration of NOx Emission Control for Heavy-Duty Diesel Trucks using SINOx™ Urea SCR technology - Long-term Experience and Measurement Results", SAE Technical Paper 2001-01-1931.

- Anderson M., Angelo T., Hou J., Protas M., Steinbrueck E., Wagner W., Way P., Zhang W. (2004), "Development of an Active Regeneration Diesel Particulate Filter System". U.S. Department of Energy, 2004 Diesel Engine Emissions Reduction (DEER) Conference Presentations, August 29 - September 2, 2004, Coronado, California, U.S.A. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.
- Andersson J.D., Wedekind B.G.A., Hall D., Stradling R., Wilson G. (2001), "DETR/SMMT/CONCAWE Particulate Research Programme: Light Duty Results", SAE Technical Paper 2001-01-3577.
- Ball B., Hully D., Lauseur P., Lyons N. (2004), "Experience of Continuously Regenerating Particulate Traps on City Buses in Europe", SAE Technical Paper 2004-01-0078.
- Biddinger J. (2005), "Requirements From Particulate Filter Technology For Commercial Vehicles: Sintered Metal Particulate Filter Opens A New Dimension Of Performance". U.S. Department of Energy, 2005 Diesel Engine Emissions Reduction (DEER) Conference Presentations, August 21 - 25, 2005, Chicago, Illinois, U.S.A. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.
- Blanchard G., Colignon C., Griard C., Rigaudeau C., Salvat O., Seguelong T. (2002), "Passenger Car Series Application of a New Diesel Particulate Filter System Using a New Ceria-Based Fuel-Borne Catalyst: From the Engine Test Bench to European Vehicle Certification", SAE Technical Paper 2002-01-2781.
- Blanchard G., Seguelong T., Michelin J., Schuerholz S., Terres F. (2003), "Ceria-Based Fuel-Borne Catalysts for Series Diesel Particulate Filter Regeneration", SAE Technical Paper 2003-01-0378.
- Block M., Clark N., Wayne S., Nine R., Miller W. (2005), "An Investigation into the Emissions Reduction Performance of an SCR System Over Two Years' In-Use Heavy-Duty Vehicle Operation", SAE Technical Paper 2005-01-1861.
- Brillant S., Zikoridse G. (2005), "Metal Fibre Diesel Particulate Filter : Function and Technology", SAE Technical Paper 2005-01-0580.
- Brown K.F., Rideout G., Rostkowski J., Meyer N. (2004), "Durability Studies of a Base Metal Catalyzed Particulate Filter in a Severe Non-road Application", SAE Technical Paper 2004-01-0077.
- Bunting B., More K., Lewis S., Toops T. (2005), "Phosphorous Poisoning and Phosphorous Exhaust Chemistry with Diesel Oxidation Catalysts", SAE Technical Paper 2005-01-1758.
- Cavataio G., Girard J., Patterson J.E., Montreuil C., Cheng Y., Lambert C.K. (2007), "Laboratory Testing of Urea-SCR Formulations to Meet Tier 2 Bin 5 Emissions", SAE Technical Paper 2007-01-1575.
- Chandler G.R., Cooper B.J., Harris J.P., Thoss J.E., Uusimaki A., Walker A.P., Warren J.P. (2000), "An Integrated SCR and Continuously Regenerating Trap System to Meet Future NOx and PM Legislation", SAE Technical Paper 2000-01-0188.
- Chiew L., Kroner P., Ranalli M. (2005), "Diesel Vaporizer: An Innovative Technology for Reducing Complexity and Costs Associated with DPF Regeneration", SAE Technical Paper 2005-01-0671.
- Cooper B.J., Thoss J.E. (1989), "Role of NO in Diesel Particulate Emission Control", SAE Technical Paper 890404.

- Cordiner S., De Simone G., Mulone V. (2007), "Influence of Washcoat Distribution on the Performance of Diesel Oxidation Catalysts", SAE Technical Paper 2007-01-4007.
- Cutler W.A., Merkel G.A. (2000), "A New High Temperature Ceramic Material for Diesel Particulate Filter Applications", SAE Technical Paper 2000-01-2844.
- DePetrillo F.S., Nardi Z., Saeid A., Lubinsky K. (2002), "Rypos Trap: Active Diesel Emission Control System: Field Demonstrations". U.S. Department of Energy, 2002 Diesel Engine Emissions Reduction (DEER) Conference Presentations, August 25-29, 2002, San Diego, California, U.S.A. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.
- Dimopoulos Eggenschwiler P., Tsinoglou D.N., Seyfert J., Bach C., Vogt U., Gorbar M. (2009) "Ceramic foam substrates for automotive catalyst applications: fluid mechanic analysis", *Exp Fluids* (2009) 47:209-222.
- Eaton S., Nguyen K., Bunting B. (2006), "Deactivation of Diesel Oxidation Catalysts by Oil-Derived Phosphorus", SAE Technical Paper 2006-01-3422.
- EMCON Technologies GmbH. (2009), "Compact Catalytic Converter", [www.emcontechologies.com](http://www.emcontechologies.com). (viewed Nov. 2009)
- Floerchinger P., Ortiz M., Ingram-Ogunwumi R. (2004), "Comparative Analysis of Different Heavy Duty Diesel Oxidation Catalysts Configurations", SAE Technical Paper 2004-01-1419.
- Gaiser G., Mucha P., Damson B., Rudelt J. (2008), "The Fuel Processor for Accelerated Catalyst Light-Off and Engine-Independent Active Regeneration Measures", SAE Technical Paper 2008-01-0068.
- Gekas I., Gabrielsson P., Johansen K., Nyengaard L., Lund T. (2002), "Urea-SCR Catalyst System Selection for Fuel and PM Optimized Engines and a Demonstration of a Novel Urea Injection System", SAE Technical Paper 2002-01-0289.
- Gieshoff J., Schafer-Sindlinger A., Spurk P.C., van den Tillaart J.A.A., Garr G. (2000), "Improved SCR Systems for Heavy Duty Applications", SAE Technical Paper 2000-01-0189.
- Gieshoff J., Pfeifer M., Schäfer-Sindlinger A., Spurk P.C., Garr G., Leprince T., Crocker M. (2001), "Advanced Urea SCR Catalysts for Automotive Applications", SAE Technical Paper 2001-01-0514.
- Harlé V., Pitois C., Rocher L., Garcia F. (2008), "Latest Development and Registration of Fuel Borne Catalyst for DPF Regeneration", SAE Technical Paper 2008-01-0331.
- Hashimoto S., Miyairi Y., Hamanaka T., Matsubara R., Harada T., Miwa S. (2002), "SiC and Cordierite Diesel Particulate Filters Designed for Low Pressure Drop and Catalyzed, Uncatalyzed Systems", SAE Technical Paper 2002-01-0322.
- Heck R.M., Chen J.M., Speronello B.K. (1994), "Operating Characteristics and Commercial Operating Experience with High Temperature SCR NOx Catalyst", *Environmental Progress*, Vol. 13, No. 4, pp. 221-225, November 1994.
- Hinz A., Jarvis T., Abul-Milh M., Amar P., et al. (10 additional authors) (2006), "Field Test Trucks Fulfilling EPA'07 Emission Levels On-Road by Utilizing the Combined DPF and Urea-SCR System", SAE Technical Paper 2006-01-0421.
- Hiranuma S., Takeda Y., Kawatani T., Doumeki R., Nagasaki K., Ikeda T. (2003), "Development of DPF System for Commercial Vehicle - Basic Characteristic and Active Regenerating Performance -", SAE Technical Paper 2003-01-3182.

- Hofmann L., Rusch K., Fischer S., Lemire B. (2004), "Onboard Emissions Monitoring on a HD Truck with an SCR System Using Nox Sensors", SAE Technical Paper 2004-01-1290.
- Hossfeld C. et al. (2006) "Katalysatorkonzept für Reduzierung des Dieselpartikelfilter Volumens", MTZ 67:628-635.
- Hug H.T., Mayer A., Hartenstein A. (1993), "Off-Highway Exhaust Gas After-Treatment: Combining Urea-SCR, Oxidation Catalysis and Traps", SAE Technical Paper 930363.
- Itoh A., Shimato K., Komori T., Okazoe H., Yamada T., Niimura K., Watanabe Y. (1993), "Study of SiC Application to Diesel Particulate Filter (Part 1): Material Development", SAE Technical Paper 930360.
- Jacobs T., Chatterjee S., Conway R., Walker A., Kramer J., Mueller-Haas K. (2006), "Development of Partial Filter Technology for HDD Retrofit", SAE Technical Paper 2006-01-0213.
- Johansen K., Dahl S., Mogensen G., Pehrson S., Schramm J., Ivarsson A. (2007), "Novel base metal-palladium catalytic diesel filter coating with NO<sub>2</sub> reducing properties", SAE Technical Paper 2007-01-1921.
- Johnson T. (2008) "Diesel Emission Control in Review", SAE Technical Paper 2008-01-0069.
- Kimura K., Alleman T.L., Chatterjee S., Hallstrom K. (2004), "Long-Term Durability of Passive Diesel Particulate Filters on Heavy-Duty Vehicles", SAE Technical Paper 2004-01-0079.
- Kittelsohn D.B. (1998), "Engines and Nanoparticles: A Review", J. Aerosol Sci. Vol. 29, No. 5/6, pp. 575-588.
- Kladopoulou E., Yang S.L., Johnson J.H., Parker G.G., Konstandopoulos A.G. (2003), "A Study Describing the Performance of Diesel Particulate Filters During Loading and Regeneration - A Lumped Parameter Model for Control Applications", SAE Technical Paper 2003-01-0842 (SP-1755).
- Koebel M., Elsener M., Kleemann M. (2000), "Urea-SCR: a promising technique to reduce NO<sub>x</sub> emissions from automotive diesel engines", Catalysis Today 59 (2000) 335-345.
- Kojetin P., Janezich F., Sura L., Tuma D. (1993), "Production Experience of a Ceramic Wall Flow Electric Regeneration Diesel Particulate Trap", SAE Technical Paper 930129.
- Koltsakis G.C., Katsaounis D.K., Samaras Z.C., Naumann D., Saberi Sh., Bohm A. (2006), "Filtration and Regeneration Performance of a Catalyzed Metal Foam Particulate Filter", SAE Technical Paper 2006-01-1524.
- Kong Y., Huffmeyer C., Johnson R., Taylor B., Crawley W., Hayworth G. (2004), "Applications of an Active Diesel Particulate Filter Regeneration System", SAE Technical Paper 2004-01-2660.
- Kong Y., Kozakiewicz T., Johnson R., Huffmeyer C., Huckaby J., Abel J., Baurley J., Duffield K. (2005), "Active DPF Regeneration for 2007 Diesel Engines", SAE Technical Paper 2005-01-3509.
- Konstandopoulos A.G., Johnson J.H. (1989), "Wall-Flow Diesel Particulate Filters – Their Pressure Drop and Collection Efficiency", SAE Technical Paper 890405.
- Konstandopoulos A.G., Kostoglou M., Skaperdas E., Papaioannou E., Zarvalis D., Kladopoulou E. (2000), "Fundamental Studies of Diesel Particulate Filters: Transient Loading, Regeneration and Aging", SAE Technical Paper 2000-01-1016 (SP-1497).

- Konstandopoulos A.G., Kostoglou M., Housiada P. (2001), "Spatial Non-Uniformities in Diesel Particulate Trap Regeneration", SAE Technical Paper 2001-01-0908 (SP-1582).
- Konstandopoulos A.G., Kostoglou M., Housiada P., Vlachos N., Zarvalis D. (2003), "Multichannel Simulation of Soot Oxidation in Diesel Particulate Filters", SAE Technical Paper 2003-01-0839 (SP-1755).
- Konstandopoulos A.G., Zarvalis D., Papaioannou E., Vlachos N.D., et al. (34 additional authors) (2004a), "The Diesel Exhaust Aftertreatment (DEXA) Cluster: A Systematic Approach to Diesel Particulate Emission Control in Europe", SAE Technical Paper 2004-01-0694.
- Konstandopoulos A.G., Kladopoulou E. (2004b), "The Optimum Cell Density for Wall-Flow Monolithic Filters: Effects of Filter Permeability, Soot Cake Structure and Ash Loading", SAE Technical Paper 2004-01-1133.
- Konstandopoulos A.G., Kostoglou M., Vlachos N., Kladopoulou E. (2005a), "Progress in Diesel Particulate Filter Simulation", SAE Technical Paper 2005-01-0946 (SP-1940).
- Konstandopoulos A.G., Papaioannou E., Zarvalis D., Skopa S., Baltzopoulou P., Kladopoulou E., Kostoglou M., Lorentzou S. (2005b), "Catalytic Filter Systems with Direct and Indirect Soot Oxidation Activity", SAE Technical Paper 2005-01-0670.
- Konstandopoulos A.G., Zarvalis D., Dolios I. (2007), "Multi-Instrumental Assessment of Diesel Particulate Filters," SAE Technical Paper 2007-01-0313.
- Lemaire J., Mustel W., Zelenka P. (1994), "Fuel Additive Supported Particulate Trap Regeneration Possibilities by Engine Management System Measures", SAE Technical Paper 942069.
- LeTavec C., Uihlein J., Vertin K., Chatterjee S., Wayne S., Clark N., Gautam M., Thompson G., Lyons D., Hallstrom K., Chandler K., Coburn T. (2002), "Year-Long Evaluation of Trucks and Buses Equipped with Passive Diesel Particulate Filters", SAE Technical Paper 2002-01-0433.
- Lylykangas R. et al. (2002) "Particle Oxidation Catalyst for Heavy-Duty Diesel Engines", *AutoTechnology*, 5/2002, pg. 57-59.
- Makino M., Kondo T., Kunz A., Ohara E., et al. (9 additional authors) (2006), "Evaluation of Advanced Diesel Oxidation Catalyst Concepts: Part 2", SAE Technical Paper 2006-01-0032.
- Mayer A., Buck A., Bressler H. (1993), "The Knitted Particulate Trap: Field Experience and Development Progress", SAE Technical Paper 930362.
- Mayer A., Czerwinski J., Matter U., Wyser M., Scheidegger, Kieser D., Weidhofer (1998) "VERT: Diesel Nano-Particulate Emissions: Properties and Reduction Strategies", SAE Technical Paper 980539.
- Mayer A., Matter U., Scheidegger G., Czerwinski J., Wyser M., Kieser D., Weidhofer J. (1999), "Particulate Traps for Retro-Fitting Construction Site Engines VERT: Final Measurements and Implementation", SAE Technical Paper 1999-01-0116.
- Mayer A., Nöthiger P., Zbinden R., Evéquo R. (2001), "Particulate Trap Selection for Retrofitting Vehicle Fleets Based on Representative Exhaust Temperature Profiles", SAE Technical Paper 2001-01-0187.
- Mayer A., Czerwinski J., Legerer F., Wyser M. (2002), "VERT Particulate Trap Verification", SAE Technical Paper 2002-01-0435.

- Mayer A., Ulrich A., Czerwinski J., Matter U., Wyser M. (2003), "Retention of Fuel Borne Catalyst Particles by Diesel Particle Filter Systems", SAE Technical Paper 2003-01-0287.
- Meinig U., Spies K.-H., De Bruyne R. (1998), "Tests on a New Diesel Particulate System with Traps of Metal Fleece", SAE Technical Paper 982597.
- Merkel G.A., Cutler W.A., Warren C.J. (2001a), "Thermal Durability of Wall-Flow Ceramic Diesel Particulate Filters", SAE Technical Paper 2001-01-0190.
- Merkel G.A., Beall D.M., Hickman D.L., Vernacotola M.J. (2001b), "Effects of Microstructure and Cell Geometry on Performance of Cordierite Diesel Particulate Filters", SAE Technical Paper 2001-01-0193.
- Miller W.R., Klein J.T., Mueller R., Doelling W., Zuerbig J. (2000), "The Development of Urea-SCR Technology for US Heavy Duty Trucks", SAE Technical Paper 2000-01-0190.
- Mizutani T., Ito M., Masukawa N., Ichikawa S., Yuuki K., Kurachi H., Toyoshima T., Ito T., Lappas I., Schaefer-Sindlinger A., Vogt C.D. (2006), "The Study for Structural Design of the Segmented SiC-DPF", SAE Technical Paper 2006-01-1527.
- Müller W., Ölschlegel H., Schäfer A., Hakim N., Binder K. (2003), "Selective Catalytic Reduction - Europe's NOx Reduction Technology," SAE Technical Paper 2003-01-2304.
- Nakane T., Ikeda M., Hori M., Bailey O., Mussmann L. (2005), "Investigation of the Aging Behavior of Oxidation Catalysts Developed for Active DPF Regeneration Systems", SAE Technical Paper 2005-01-1759.
- Neeft J.P.A., Makkee M., Moulijn J.A. (1996), "Diesel particulate emission control", Fuel Processing Technology 47 (1996) 1-69.
- Ohno K., Shimato K., Taoka N., Santae H., Ninomiya T., Komori T., Salvat O. (2000), "Characterization of SiC-DPF for Passenger Car", SAE Technical Paper 2000-01-0185.
- Ogunwumi S.B., Tepesch P.D., Chapman T., Warren C.J., Melscoet-Chauvel I.M., Tennent D.L. (2005), "Aluminum Titanate Compositions for Diesel Particulate Filters", SAE Technical Paper 2005-01-0583.
- PAGODE (2006) "Post-treatment for the next Generation Of Diesel Engines", European Union FP6 Project TST5-CT-2006-031404.
- Pfeifer M., Votsmeier M., Kögel M., Spurk P.C., Lox E.S. (2005), "The Second Generation of Catalyzed Diesel Particulate Filter Systems for Passenger Cars - Particulate Filters with Integrated Oxidation Catalyst Function-", SAE Technical Paper 2005-01-1756.
- Pfeifer M., Kogel M., Spurk P.C., Jeske G. (2007), "New Platinum/Palladium Based Catalyzed Filter Technologies for Future Passenger Car Applications", SAE Technical Paper 2007-01-0234.
- Presti M., Pace L., Carelli G., Spurk P., Kogel M. (2005), "Innovative metal supported catalysts for EU V Diesel Engines", SAE Technical Paper 2005-24-003.
- Quigley M., Seguelong T. (2002), "Series Application of a Diesel Particulate Filter with a Ceria-Based Fuel-Borne Catalyst: Preliminary Conclusions after One Year of Service", SAE Technical Paper 2002-01-0436.
- Rappé K., Li L., Male J., Silver R., Zemskova S., Eckstein C., Moss B. (2007) "Low-Temperature Hydrocarbon/CO Oxidation Catalysis in Support of HCCI Emission Control". U.S. Department of Energy, 2007 Diesel Engine-Efficiency and Emissions Research (DEER)

Conference Presentations, August 13-16, 2007, Detroit, Michigan, U.S.A. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

- Sakaguchi T., Ohgushi A., Suzuki S., Kita H., Ohsumi K., Suzuki T., Kawamura H. (1999), "Development of High Durability Diesel Particulate Filter by Using SiC Fiber", SAE Technical Paper 1999-01-0463.
- Salvat O., Marez P., Belot G. (2000), "Passenger Car Serial Application of a Particulate Filter System on a Common Rail Direct Injection Diesel Engine", SAE Technical Paper 2000-01-0473.
- Scarnegie B., Miller W.R., Ballmert B., Doelling W., Fischer S. (2003), "Recent DPF/SCR Results Targeting US2007 and Euro 4/5 HD Emissions", SAE Technical Paper 2003-01-0774.
- Schmieg S.J., Lee J.-H. (2005), "Evaluation of Supplier Catalyst Formulations for the Selective Catalytic Reduction of NOx With Ammonia", SAE Technical Paper 2005-01-3881.
- Servati H., Petreanu S., Marshall S., Su H., et al. (12 additional authors) (2005), "A NOx Reduction Solution for Retrofit Applications: A Simple Urea SCR Technology", SAE Technical Paper 2005-01-1857.
- Setiabudi A., Makkee M., Moulijn J.A. (2003), "An Optimal Usage of Nox in a Combined Pt/Ceramic Foam and a Wall-Flow Monolith Filter for an Effective Nox-Assisted Diesel Soot Oxidation", SAE Technical Paper 2003-01-0379.
- Shirk R., Bloom R., Kitahara Y., Shinzawa M. (1995), "Fiber Wound Electrically Regenerable Diesel Particulate Filter Cartridge for Small Diesel Engines", SAE Technical Paper 950153.
- Singh P., Thalagavara A.M., Naber J.D., Johnson J.H., Bagley S.T. (2006) "An Experimental Study of Active Regeneration of an Advanced Catalyzed Particulate Filter by Diesel Fuel Injection Upstream of an Oxidation Catalyst", SAE Technical Paper 2006-01-0879.
- Spurk P., Pfeifer M., van Setten B., Söger N., Hohenberg G., Gietzelt C., Garr G., Bailey O. (2003), "Examination of Engine Control Parameters for the Regeneration of Catalytic Activated Diesel Particulate Filters in Commercial Vehicles", SAE Technical Paper 2003-01-3177.
- Stobbe P., Petersen H.G., Høj J.W., Sorenson S.C. (1993), "SiC as a Substrate for Diesel Particulate Filters", SAE Technical Paper 932495.
- Sumiya S., Oyamada H., Fujita T., Nakamura K., Osumi K., Tashiro Y. (2009), "Highly Robust Diesel Oxidation Catalyst for Dual Mode Combustion System", SAE Technical Paper 2009-01-0280.
- Tennison P., Lambert C., Levin M. (2004), "NOx Control Development with Urea SCR on a Diesel Passenger Car", SAE Technical Paper 2004-01-1291.
- Tatur M., Tomazic D., Lacin F., Sullivan H., Kotrba A. (2009), "Solid SCR Demonstration Truck Application". U.S. Department of Energy, 2009 Directions in Engine-Efficiency and Emissions Research (DEER) Conference Presentations, August 3-6, 2009, Dearborn, Michigan, U.S.A. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.
- van Helden R., van Genderen M., van Aken M., Verbeek R., Patchett J.A., Kruithof J., Straten T., Gerentet de Saluneaux C. (2002), "Engine Dynamometer and Vehicle Performance of a Urea SCR-System for Heavy-Duty Truck Engines", SAE Technical Paper 2002-01-0286.
- van Helden R., Willems F., van Aken M., Strijbos H. (2005), "Engine Demonstration of Microwave Assisted Particulate Trap Regeneration", SAE Technical Paper 2005-01-2141.

- van Setten B.A.A.L., Makkee M., Moulijn J.A. (2001), "Science and technology of catalytic diesel particulate filters", *Catalysis Reviews*, 43(4), 489-564 (2001).
- Vakkilainen A., Lylykangas R. (2004), "Particle Oxidation Catalyst (POC) for Diesel Vehicles", SAE Technical Paper 2004-28-0047.
- Verdier S., Harle V., Huang A., Rohart E., Larcher O., Allain M. (2006), "Doped Zirconia with High Thermal Stability, for High Sulfur Resistance Diesel Oxidation Catalysts", SAE Technical Paper 2006-01-0031.
- Vlachos N., Patrianakos G., Kostoglou M., Konstandopoulos A.G. (2008), "Micro-Simulation of NO-NO<sub>2</sub> Transport and Reaction in the Wall of a Catalyzed Diesel Particulate Filter", SAE Technical Paper 2008-01-0442.
- Wang D.Y., Yao S., Shost M., Yoo J.-H., Cabush D., Racine D., Cloudt R., Willems F. (2008), "Ammonia Sensor for Closed-Loop SCR Control", SAE Technical Paper 2008-01-0919.
- Walker A.P., Blakeman P.G., Ilkenhans T., Magnusson B., McDonald A.C., Kleijwegt P., Stunnenberg F., Sanchez M. (2004), "The Development and In-Field Demonstration of Highly Durable SCR Catalyst Systems", SAE Technical Paper 2004-01-1289.
- Willems F., Cloudt R., van den Eijnden E., van Genderen M., Verbeek R., de Jager B., Boomsma W., van den Heuvel I. (2007), "Is Closed-Loop SCR Control Required to Meet Future Emission Targets?", SAE Technical Paper 2007-01-1574.
- Yoshida K., Asanuma T., Nishioka H., Hayashi K., Hirota S. (2007), "Development of NOx Reduction System for Diesel Aftertreatment with Sulfur Trap Catalyst", SAE Technical Paper 2007-01-0237.
- Zelenka P., Telford C., Pye D., Birkby N. (2002), "Development of a Full-Flow Burner DPF System for Heavy Duty Diesel Engines", SAE Technical Paper 2002-01-2787.
- Zinola S., Lavy J., Jaecker-Voirol A. (2008), "Towards CO and HC Aftertreatment Devices for the Next Generation of Diesel Engines", SAE Technical Paper 2008-01-1543.

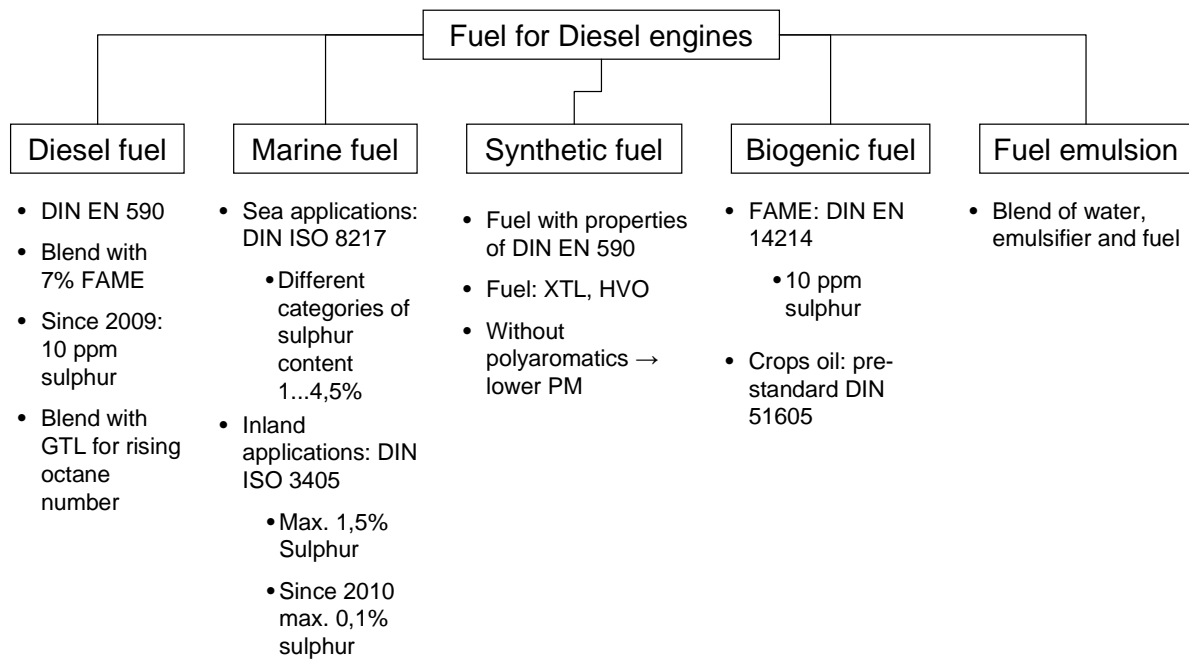
## 7. DIESEL FUEL AND EXHAUST AFTER-TREATMENT

Incomplete combustion inside the engine originates pollutants, whose kind and composition are depending on the used fuel. To meet future emission regulations, exhaust gas after-treatment systems are required. Besides, different fuel qualities and fuel compositions have direct impact on the operation of the exhaust gas after-treatment system. In addition negative impacts (e.g., catalyst poisoning) and positive options by fuel blends or fuel substitution must be considered.

### 7.1 PAST RESEARCH

#### 7.1.1 Standards for Diesel Fuel

In Diesel engines several kinds of fuels can be used. Figure 46 gives an overview.



**Figure 46: Kinds of fuel for Diesel applications**

In the countries of the EU, except UK, Diesel according to EN 590 is used as standard fuel for rail applications. In UK gas oil according to BS 2869: 2006 Class A2 [HENTY] is used which has a clearly higher sulphur concentration (in 1000 ppm) than Diesel fuel according to EN 590.

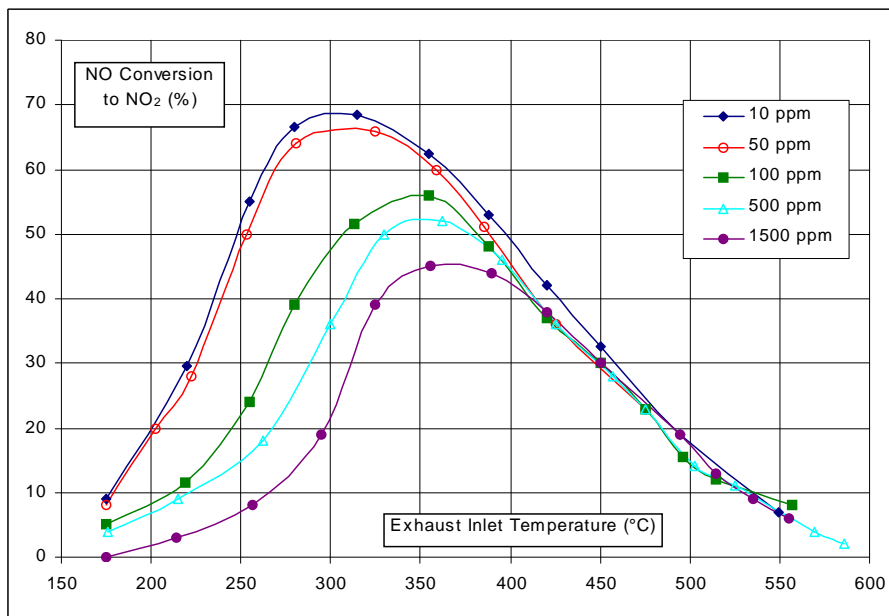
#### 7.1.2 Diesel Fuel Components and their Impact on After-treatment Systems

##### Sulphur

When using sulphur-containing fuel an undesirable secondary reaction in the oxidation catalyst preferentially occurs. This is the oxidation of sulphur dioxide to sulphur trioxide which could

further react with the substrate. Thus stable sulphates on the filter surface could be formed. In addition the converting rate of NO to NO<sub>2</sub> (see Figure 47) decreases with available sulphur. This affects the regeneration temperature of passive DPF-systems i.e. this is unfavourably for the soot oxidation.

The extent of the dependence on the sulphur content is described by the shift of the so-called balance-point. This is a situation where a balance between filter loading and filter regeneration exists. In [ACEA] an increase of the balance-point of about 40 K is described by using Diesel with 350 ppm sulphur content in comparison to 10 ppm. The shift is about 2% for 50 ppm in comparison to Diesel free of sulphur. The increase of the balance-point can be critical in particular for low load operating points of modern Diesel engines. In addition, using Diesel with very high sulphur contents such a strong loading of the filter can happen that a spontaneous regeneration takes place. This can cause a destruction of the filter material due to the high temperature gradients originate at spontaneous regeneration.



**Figure 47: Dependence of NO-oxidation from temperature and sulphur-concentration for a platinum catalyst [WALK]**

Walker et al [WALK] examined the dependence of sulphur content for a typical oxidation catalyst (Pt-basis) on the conversion temperature. With increasing sulphur content the start temperature as well as the temperature at which the maximum of NO oxidation appears is shifted to higher temperatures. This is caused by the fact that SO<sub>2</sub> is in competition to NO and has a stronger affinity to the platinum contact and thus it strongly inhibits the NO oxidation. At higher temperatures the SO<sub>2</sub> is released from the platinum contacts. Hence, the oxidation rate of NO is independent of the sulphur content for temperatures higher than 400 °C.

The extend of the dependence of the catalyst activity on the sulphur content is also influenced by the kind of used precious metal. After [TRUEX] the following ranking regarding the sensitivity to sulphur is given within the platinum group: Pd > Pt >> Rh. Despite of the high sulphur sensitivity of

Pd it is increasingly used in state of the art after-treatment systems due to its high effectiveness and good thermal stability.

The  $\text{SO}_3$  formed in the oxidation catalyst react with the water of the exhaust gas to sulphuric acid. This is strong hygroscopic. Hence, together with the attached water it rise the particle mass, so that according to sulphur content of the fuel emission values are reached which are above the demanded maximum limits. The dependence of the particle mass on the sulphur content of the fuel measured after a CRT filter is displayed in Figure 48. A roughly linear function between sulphur content and particle emission is observed.

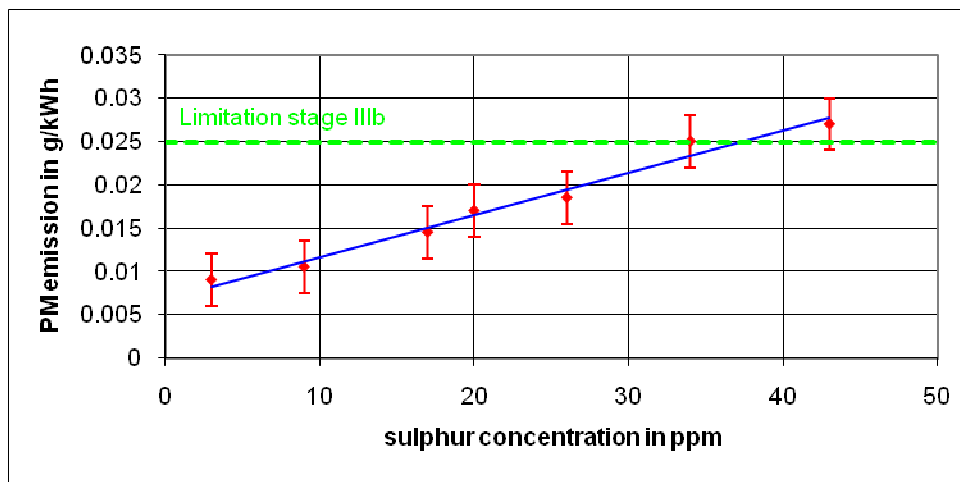


Figure 48: Influence of sulphur concentration on PM emission of a CRT-filter [ACEA]

After [HAGE] a desulphurisation is known only for  $\text{NO}_x$ -storage catalyst (NSC). For this purpose temperatures higher than  $620^\circ\text{C}$  are used. These lead to a quickened thermal ageing of the after-treatment system, which result in an increasingly coarse structure of the platinum coating within the Diesel oxidation catalyst (DOC) and in a reduction of the active surface of the NSC which can bind less nitric oxides then.

## Phosphate

Phosphates enter the Diesel fuel via the engine oil [GAERT] or via the increasing fraction of bio-Diesel [FAL], [REMM]. Castellino et al [CASTE] describe a strong deactivation of a  $\text{V}_2\text{O}_5\text{-WO}_3$  catalyst by an aerosol from a  $\text{H}_3\text{PO}_4$ -dissolution. Baker et. al. [BAKER] could also prove these results for a  $\text{V}_2\text{O}_5$  based SCR-catalyst. Even low phosphate concentrations significantly decrease the catalyst activity. Thereby the phosphor compounds could penetrate up to  $50\ \mu\text{m}$  into the catalyst. This poisoning could be proved by Kröger et al [KROEG] also in a platinum-coated oxidation catalyst.

## Ash

The regeneration of the DPF remains ash inside the filter structures and this affects the durability of the filter. Gärtner et al [GAERT] lists sources and degree of impact (see Table 4) for the ash generation. In particular it was pointed out that bio-Diesel according to DIN 14214 permits a 2-fold higher ash content compared to Diesel fuel according to EN 590. Furthermore there are international differences regarding the allowed ash content. Gärtner et al [GAERT] states that ash

cleaning of a heavy duty filter is necessary for several times during life cycle. This can occur by thermal pre-treatment followed by back flushing with air or water. Larger cleaning success is expected from the process with water.

source	parameter
motor oil	fuel and oil consumption
fuel	ash content in oil and fuel
intake air	additives
wear / abrasion	percentage of fuel ash in PM-emission

**Table 4: Sources and influences on ash accumulation in DPF [GAERT]**

In the EU (except to UK) only Diesel fuel according to EN 590 is used for railway applications. Therefore the knowledge about catalyst poisoning and ash accumulation in the DPF can be adapted from heavy duty vehicles to rail applications. According to these experiences the cleaning intervals for the DPF can be defined.

### 7.1.3 Alternative Sources for Diesel Fuel

The present Section deals with alternative fuels as a blend or total substitution of mineral based Diesel fuel in the context of rising oil prices and the shortage of crude oil. CO<sub>2</sub> is released by the combustion of fossil fuels. With the blending of Diesel fuels with renewable feedstock (biogenic fuels) or the entire use of biogenic fuels the CO<sub>2</sub>- emission (CO<sub>2</sub>-balance) is decreased.

In addition, biogenic fuels of the 2nd generation (xtL-fuels) show certain properties which favour the combustion process and allow for lower raw emission.

#### Bio-Diesel

Groth et al [GROTH] listed the following vegetable oils for the production of bioDiesel:

- rapeseed oil
- palm oil
- sunflower oil
- peanut oil
- coconut oil
- cottonseed oil
- soy-bean oil

Vegetable oils consist of 99% triglycerides which are composed of saturated and unsaturated fatty acids. Their structure and composition determine the specific parameters for the engine operation. Disadvantageously, the properties of the oil are influenced by plant species, climate of the cultivation area and also kind and intensity of the refinement [KLING]. In Europe primarily rapeseed oil is used for the production of bio-Diesel. Remmele et al [REMM] defined following variable properties for rapeseed oil:

- overall pollution
- neutralisation number

- oxidation stability
- phosphor concentration
- ash concentration
- water content

For this reason a regulation is necessary which defines important fuel parameter → pre-standard DIN 51605.

The esterification with methanol causes an adaption of the physical properties of the rapeseed oil to that of Diesel fuel. Thus the use of biogenic fuels in the Diesel engine is possible without modification of the engine.

The European legislation has decided a blending of fatty acid methyl ester (FAME) to the mineral Diesel fuel in the rule EN 590. The percentage is mandatory to 5 Vol.%. In Germany this percentage was raised to 7 Vol.% in 2009 and is regulated in the DIN 51628.

### Concepts of Converting Other Sources to Diesel Fuel

Harndorf et al [HARN] gives an overview (Figure 49) which shows the different paths of fuel production. The production of synthetic fuels needs to convert the feedstocks (natural gas, coal, biomass) into the gas phase. The subsequent step about the Fischer-Tropsch-synthesis is the same to all. After Harndorf et al [HARN] biomass has the biggest saving CO<sub>2</sub>-potential because of its regenerative origin. The fuels are widely free of sulphur and aromatics and own a high cetane number.

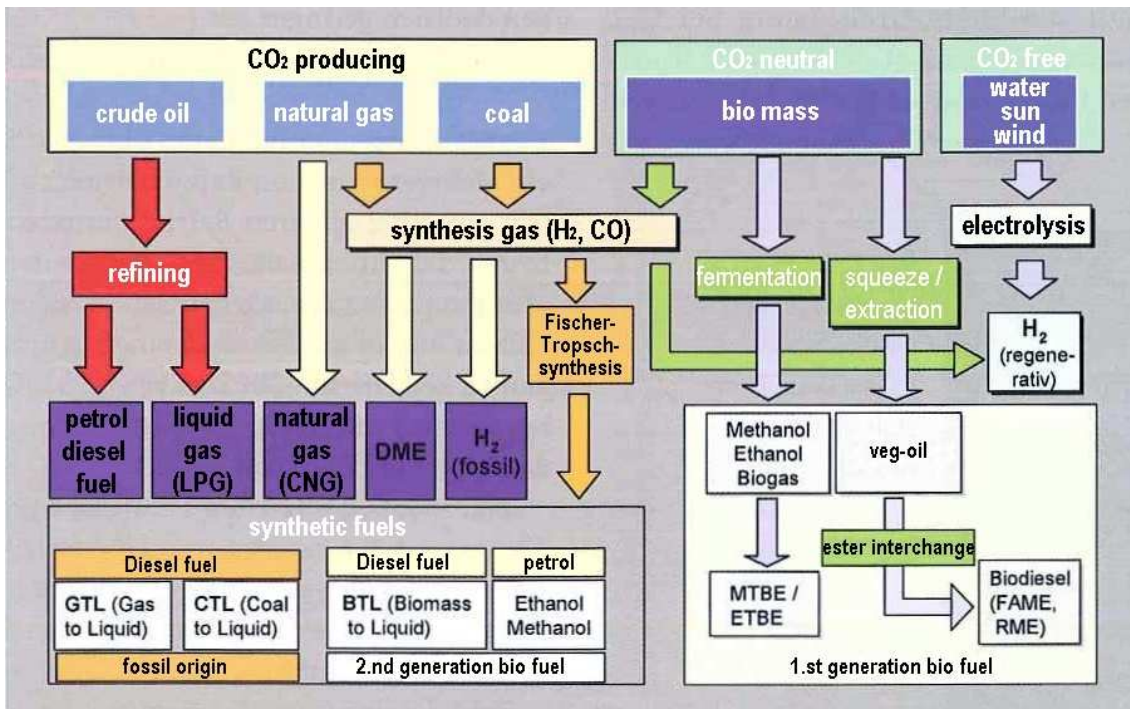


Figure 49: Converting paths from fossil and regenerative energy source to fuel [HARN]

After an evaluation of Leible et al [LEIBLE] only a one-digit percent amount of the annual needed fuel can be substituted by BTL even if all biogenic waste in Germany would be used for the production of bio fuels. In the same source a comparison was made with regard to the production costs of BTL and mineral Diesel fuel. Without subsidies BTL can compensate the competitive disadvantage as a result of higher production costs only at a crude oil price of 120 to 130 \$/bbl. These relations can be also found for other European industrial states (e.g., UK, France).

Honkanen et al [HONK] introduced a fuel similar to BTL called NExBTL which is produced from hydrogenated biomass. For this reason this fuel is named HVO (hydro treated vegetable oil). The production process is displayed schematically in Figure 50.

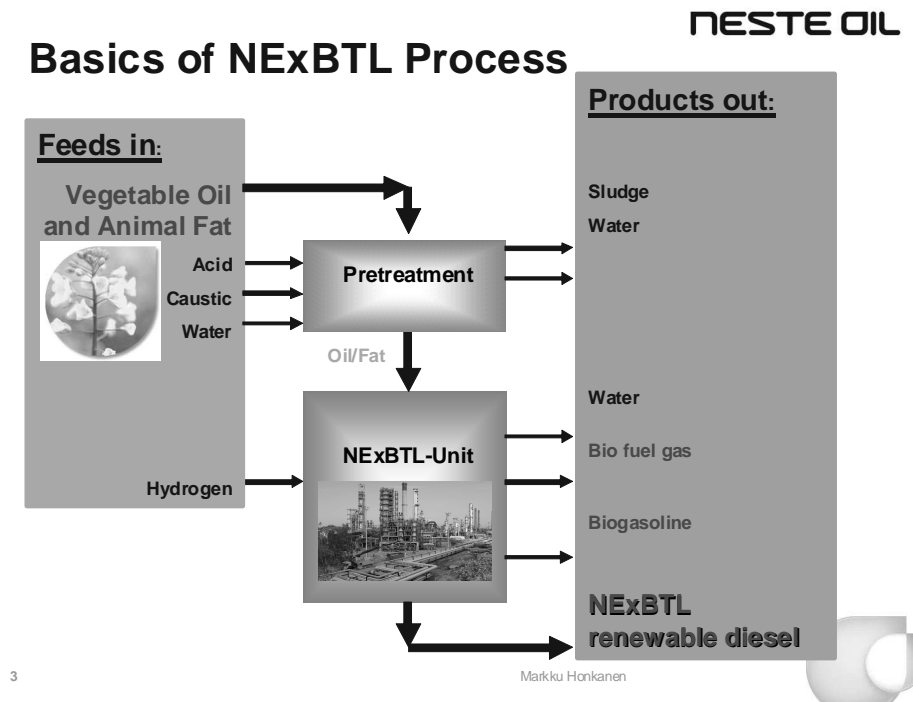


Figure 50: Basics of NExBTL-process [HONK]

#### 7.1.4 Alternative Diesel Fuels and their Impact on After-treatment Systems

##### Bio-Diesel

Hofmann et al [FIF] carried out a comparison of different bio-Diesel-blends. Starting with the standard Diesel fuel with 5 Vol.% of bio-Diesel (B5) up to B100 = 100 Vol.% bio-Diesel were added to the Diesel fuel during different steps. The proved emission differences within the test cycle ISO 8178 C1 are displayed in Figure 51. The HC, CO and particle emissions drop with increasing bio-Diesel fraction in comparison to B5. This could be explained by the higher oxygen content in bio-Diesel (compare Figure 51) and a quicker heat release. This result in higher temperatures in the combustion chamber which favours the soot oxidation but also increase the NOx emission. The measured particle size distribution (see Figure 52) reflects the reduced fraction of aromatics in the fuel with increasing bio-Diesel fraction. Aromatics are the nuclei's for the soot agglomeration. The positive impact of the bio-Diesel on the particle emission leads to

longer soot loading time, less regeneration cycles and less ash entry for the investigated after-treatment system.

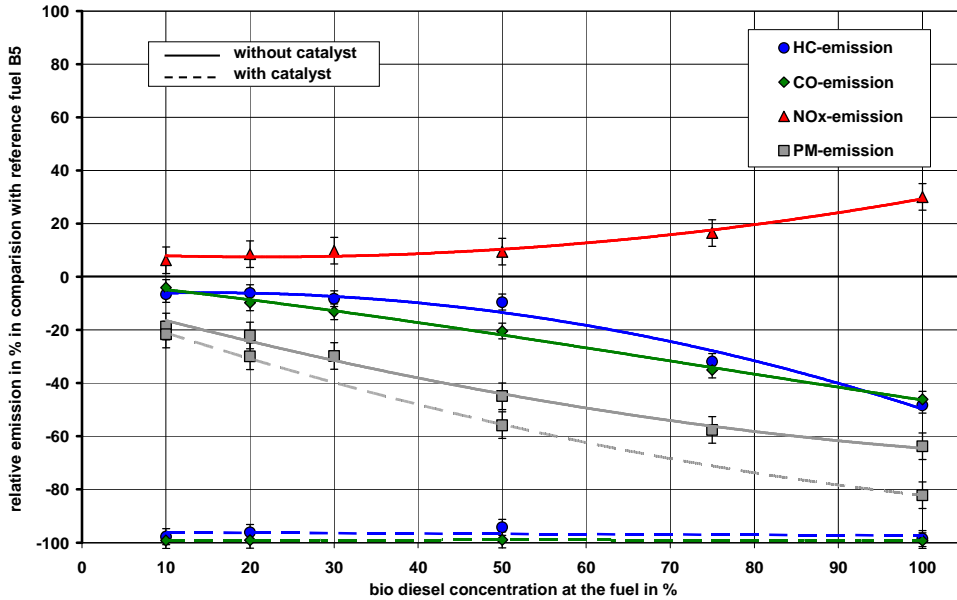


Figure 51: Course of emissions for C1-Test ISO 8178 [FIF]

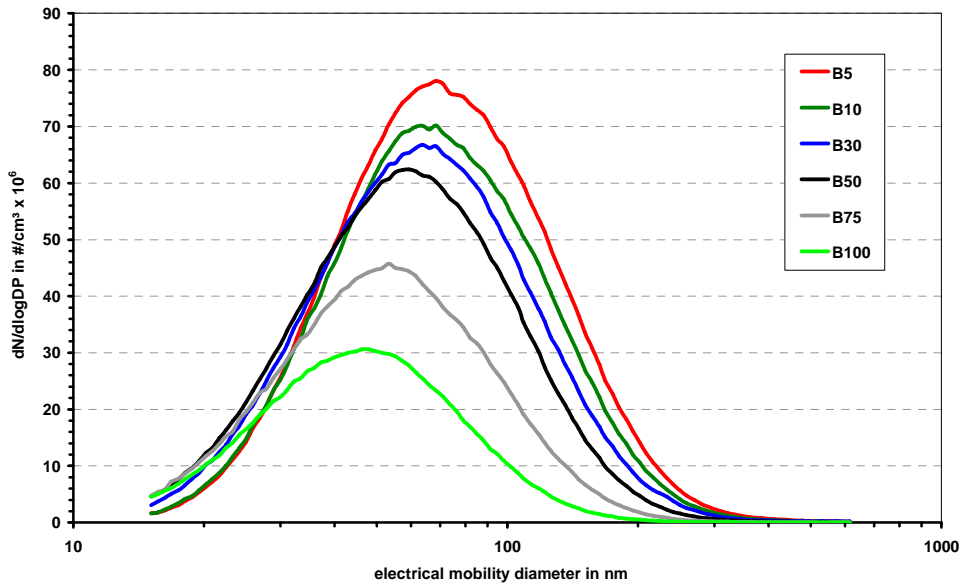


Figure 52: Course of particle size distribution for Bio-Diesel blends at  $n = 2300 \text{ min}^{-1}$ ;  $M_D = 282 \text{ Nm}$  [FIF]

In a project of the federal research institution for agriculture (FAL) [FAL] the exhaust gas emissions were compared between bio-Diesel fuel and Diesel fuel by a direct injection engine IVECO F4A at the European stationary cycle (ESC) for 1000 hours. A phosphor composition has been added to the bio-Diesel to reach the valid maximum content for phosphor in the bio-Diesel fuel according to EN 14214. A SCR-system was used for the reduction of NOx-emission. These

investigations confirm the statements by Hofmann et al [FIF] about the development of raw emission of the limited pollutants at engine operation with bio-Diesel fuel compared to the operation with Diesel fuel according to EN 590. The measured emission downstream the after-treatment system shows the same tendency. The limit for NO<sub>x</sub> of 3,5 g/kWh demanded after EURO IV which has also been met for stage IIIb could not be complied with bio-Diesel according to EN 14214 in this test. The authors in [FAL] explain this with the phosphor concentration of 10 ppm in the bio-Diesel fuel.

Taken these investigations into account the use of bio-Diesel for rail applications, if they are equipped with a SCR-system, makes no sense. Considering the higher raw emission for NO<sub>x</sub> when using bio-Diesel fuel in-cylinder concepts should be checked for reaching stage IIIb.

### Diesel Fuel from Other Sources

Harndorf et al [HARN] carried out comparing tests with Diesel fuel, rapeseed oil and GTL. As a test engine a passenger car direct injection engine with Common-Rail injection system and waste-gate charger was used. The results from the tests (Figure 53) showed clear advantages for rapeseed oil and GTL regarding FSN. The higher HC and CO emissions for low load for rapeseed oil are explained by a longer ignition delay. Summarizing the tests it was stated that alternative fuels show a higher EGR compatibility. This property can be used for future applications due to the more favourable NO<sub>x</sub>-PM-trade-off.

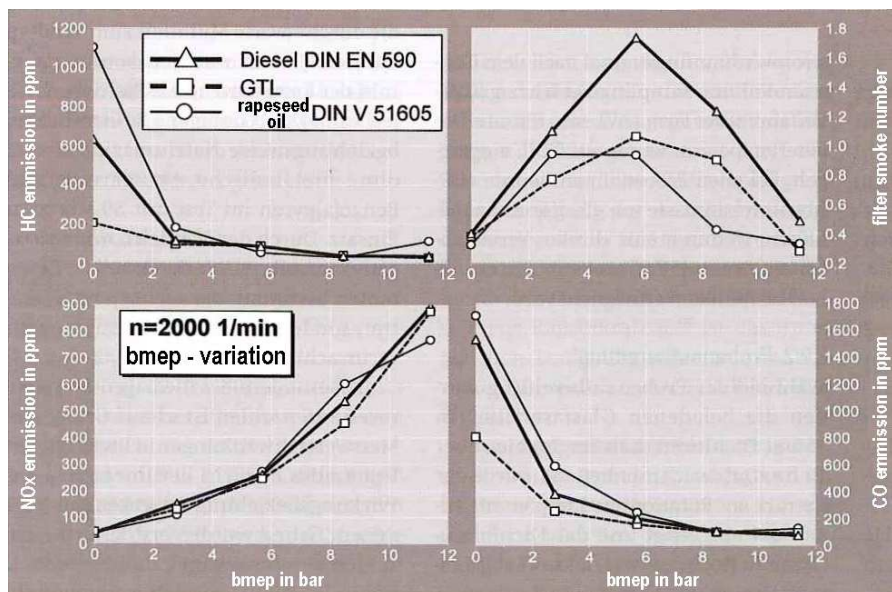


Figure 53: Raw emission from Diesel fuel, rapeseed oil and GTL [HARN]

Honkanen et al [HONK] published a fleet test with buses in Helsinki. Buses with pollutant specifications of EURO II to EEV (enhanced environmentally friendly vehicle) have been selected. As a fuel Diesel fuel, NExBTL-blends and pure NExBTL fuel were used. With increasing NExBTL fraction a decline of the limited emissions could be observed on average in comparison to Diesel fuel. Blending Diesel with 10 Vol.% NExBTL result in measurably lower emissions on average.

At time synthetic fuels like xTL and HVO have little relevance for rail applications. Their availability is uncertain. Currently from all known oil suppliers only Shell offers V-power-Diesel™,

a premium fuel, which includes 5 Vol.% GTL. The use in rail applications is very unlikely because of the significantly higher price per litre.

### Micro- Emulsified Fuel on the Basis of Diesel and Water

A clear reduction of the pollutant emission can be reached by the addition of water to the combustion process. Velji et al. [VELJI] described reductions of the  $\text{NO}_x$ -, CO- and soot emissions with increasing water fraction in the Diesel fuel. Due to the low shelf-life of this new fuel mostly based on emulsions this concept was not realised. A promising approach for overcoming this problem arises at the university to Cologne [BEM] with the development of water Diesel micro emulsions which distinguish from the old approaches by its thermodynamic stability.

Engine tests at the University of Applied Science Trier (Figure 54) with a 4-Cylinder-DEUTZ engine without EGR showed a significant decrease of the emission. This was especially evident in the filter smoke numbers.

The associated mechanism for these emission reductions are not complete investigated.

This emulsified fuel is interesting for rail applications because for stage IIIb a decrease of the PM emission of about 87.5% and  $\text{NO}_x$  reduction of about 33% comparing to stage IIIa is necessary. In case of an application of this emulsified fuel the exhaust gas after-treatment measures could be clearly reduced.

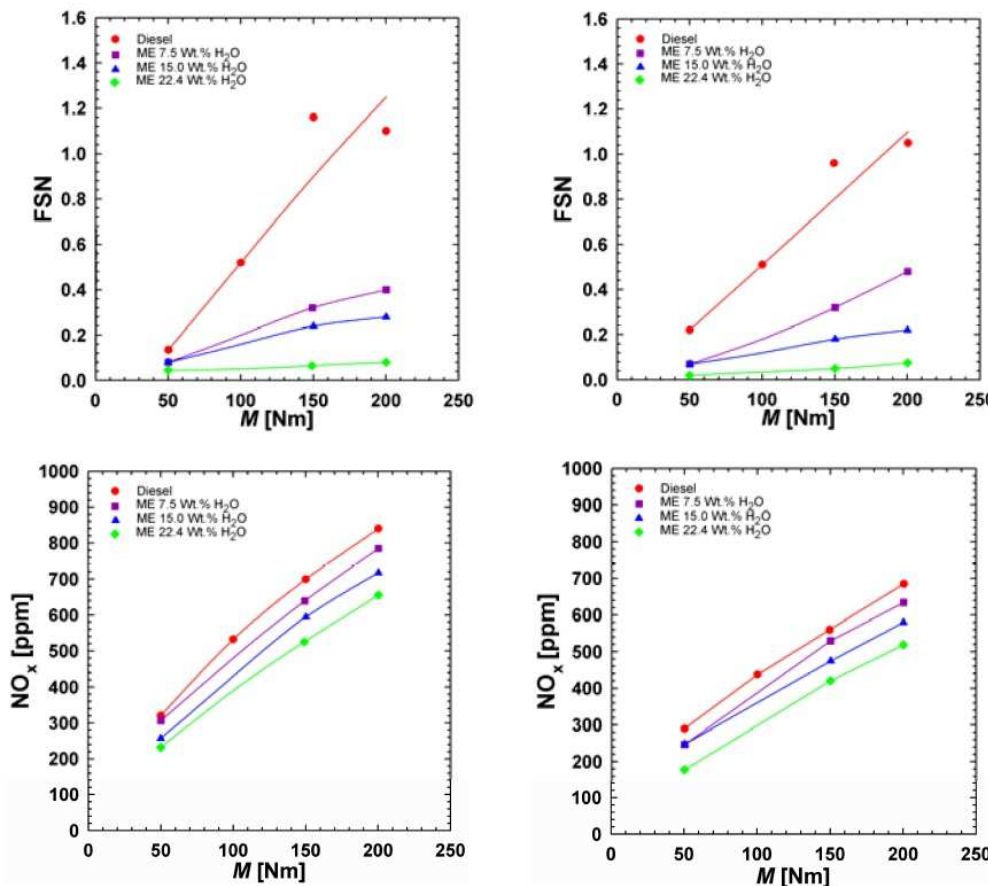


Figure 54:  $\text{NO}_x$ -emission and FSN by using micro emulsified fuels with different water fraction for speed = 1500 min<sup>-1</sup> (left) and speed = 1800 min<sup>-1</sup> (right) [BEM]

## 7.2 CONCLUSIONS

In order to guarantee the constant and entire operation of exhaust after-treatment systems, diesel fuel has to comply with the standard EN 590 for sulphur-, phosphor and ash content limit values. That applies also to the usage of substitution fuels or diesel-blends.

If diesel particle filters (DPF) are used the ash insertion is depend on a lot of factors. One of the elementary possibilities in ash reduction is the usage of special engine oil with low ash concentration (lowSAPS-oil). Nevertheless, the experiences from the heavy duty engines show that several ash cleanings will be necessary during the life cycle.

Investigations with biogenic fuels of the 1st generation (biodiesel) and 2nd generation (xTL, HVO) as well as their diesel blends in heavy duty engines show reduced emissions for PM, HC and CO as well as increased or same level emissions for NO<sub>x</sub> in comparison with diesel fuel. With it the complexity of the exhaust gas after-treatment can be reduced. The compliance with future emission limits only by the substitution of fuels without exhaust after-treatment measures can not be expected.

The application of micro-emulsified fuels is a promising approach. Nevertheless, the mechanism must be still investigated.

## 7.3 REFERENCES

- [ACEA] N.N.:  
ACEA data of the sulphur effect on advanced emission control technologies.  
Report July 2000
- [BECK] Beck, J.;Brandenstein, J.; Unterberger, S; Hein, K.:  
The behaviour of phosphorus in flue gases from coal and secondary fuel co-  
combustion  
In: Chem. Ing, Technik 76 (2004), S. 1499
- [BEM] Bemert, L.; Strey, R.:  
Diesel-Microemulsionen als alternativer Kraftstoff  
Dresden, 5. FAD-Konferenz, 2007
- [CASTE] Castellino, F.; Rasmussen, B.; Jensen, A.; Johnsson, R.; Fehrmann, R.:  
In: Applied Catalysis B: Environmental, 83, 2008, S.110 ff
- [FAL] Munack, A.; Bünger, J.; Krahl, J. et al.:  
Bestimmung der Emissionen und der Partikelgrößenverteilung (Feinstaub) im  
Abgas eines modernen Euro-4-Nutzfahrzeugmotors mit SCR-Abgasreinigung im  
Betrieb mit BioDiesel  
Braunschweig, Bundesforschungsanstalt für Landwirtschaft, 2006
- [FIF] Hofmann, U.; Lindner, R.; Zikoridse, G.:  
Einfluss von BioDiesel- und Pflanzenöl- Dieselkraftstoff- Mischungen auf das  
Emissionsverhalten und die Funktionalität von Abgasnachbehandlungssystemen  
Dresden, 8. Dresdner Motorenkolloquium, 2009
- [GAERT] Gärtner, U.; Koch, T.; Dittler, A.:  
Wohin mit der Asche – Grundlagen der Partikelfiltertechnik im Nutzfahrzeug  
Dresden, 8. Dresdner Motorenkolloquium, 2009

- [GROTH] Groth, K.; Hesse, A.; Vögtle, G.; Krause, D.; Spitzmüller, K.:  
Brennstoffe für Dieselmotoren heute und morgen  
Ehningen, expert-Verlag, 1989
- [HAGE] Hagelüken, C.; et.al.:  
Autoabgaskatalysatoren  
Renningen, Expert-Verlag, 2001
- [HARN] Harndorf, H.; Schümann, U.; Wichmann, H.; Fink, Ch.:  
Motorprozessverhalten und Abgasemissionen alternativer Kraftstoffe im Vergleich  
mit Dieseldieselkraftstoff  
In: MTZ 69 (2008) Nr. 07/08, S. 640 ff
- [HENTY] Spezifikation of Gas Oil to BS 2869: 2006 Class A2  
<http://www.hentyoil.com/docs/industrial/gas-oil-class-a2.pdf>
- [HONK] Honkanen, M.; Dörr, S.:  
Einfluss von NExBTL hydrierten PflanzenDiesel auf das Emissionsverhalten im  
Praxiseinsatz  
Dresden, 8. Dresdner Motorenkolloquium, 2009
- [KLING] Klingenberg, H.:  
Automobil-Messtechnik, Band C Abgasmesstechnik  
Berlin/Heidelberg, Springer-Verlag, 1995
- [KROEG] Kröger, V.; Kanerva, T.; Lassi, U.; Rahkamaa-Tolonen, K.; Vippola, R.; Keiski, R.:  
The Effect of SO<sub>2</sub> and H<sub>2</sub>O on the Activity of Pd/CeO<sub>2</sub> and Pd/Zr–CeO<sub>2</sub> Diesel  
Oxidation Catalysts  
In: Topics in Catalysis. (45) 2007 S. 153
- [LEIBLE] Leible, L.; Kälber, S.; Kappler, G.:  
Biomass-to-Liquid: Hoffnungsträger für eine umweltfreundliche mobile Zukunft?  
In: energie | wasser-praxis 04/2009
- [REMM] Remmele, E.; Thuneke, K.:  
Begleitforschung zur Standardisierung von Rapsöl aus Kraftstoff für  
Pflanzenöлтаugliche Dieselmotoren in Fahrzeugen und BHKW  
München, Bayrisches Staatsministerium für Ernährung, Landwirtschaft und Forsten,  
2000
- [TRUEX] Truex, T.J.:  
Interaction of Sulfur with Automotive Catalysts and the Impact on Vehicle Emissions  
–A Review.  
SAE Technical Paper 1999-01-1543
- [VELJI] Velji, A., Eichel, E., Remmels, W., and Haug, F.:  
Dieselmotoren erfüllen mit Wassereinspritzung zukünftige NO<sub>x</sub>- und Rußwerte  
In: MTZ 57 (1996) Motortechnische Zeitschrift
- [WALK] Walker, A. et. al.:  
The use of the Continuously Regenerating Trap (CRT™) and SCRT™ System to  
meet future emission legislation.  
Wien, 21. Internationale Wiener Motorensymposium, 2000, Band 2, S. 343 ff

## 8. CLEAN DIESEL ENGINES IN RAILWAY VEHICLES

---

This section provides an overview of the state-of-the-art in terms of Diesel engines currently being used introduced in the railway market. In addition, a review of the literature on this topic highlighting research with potential application to railways has been carried out.

### 8.1 PAST RESEARCH

---

The introduction of the European Parliament and Council Directive 2004/26/EC [EC, 2004] on amendments to the Non-Road Mobile Machinery (NRMM) Directive 97/68/EC meant that extension of the original scope to cover all new Diesel engines used for railway application. This resulted in a new set of emission values being introduced in 2006 (Diesel multiple units), known as stage IIIA (2009 for locomotives). This has now updated with a more restricting stage IIIB scheduled to enter into force in 2012. In addition, the International Union of Railways (UIC) II standard [UIC, 2003a] was introduced in 2003 for Diesel locomotives setting the first considerable group of technical and emission requirements.

The leap in requirements towards achieving a clean Diesel railway means that in the past few years the research and development of these technologies has increased significantly. This is particularly relevant as the move from stage IIIA to IIIB means that in-engine improvements are no longer sufficient to meet the requirements, and after-treatment systems need to be used for the first time in railway applications.

A number of initiatives and projects have addressed these issues to certain extent. The most relevant include the UIC Diesel Rail Study [UIC, 2006] and the GREEN heavy duty Engine (GREEN) co-financed by the EC (project No. TIP4-CT-2005-516195) [UIC,2008].

The Diesel Rail Study was carried out during the January-December 2005 period and was a prompted by the Diesel Action Plan [UIC, 2003b] developed in 2003 also by the UIC were a need for actions was highlighted in order to actively reduce the emissions produced by Diesel railway vehicles. The study developed projections for the Diesel traction market as well as assessing the most promising approaches to reduce emissions from existing fleets, their costs and the implications for adopting these technologies leading to a set of recommendations for further work. The findings listed the most suitable technologies based on their cost-benefit ratio as follows:

1. Re-engining;
2. Selective Catalytic Reduction (SCR)
3. Selective Catalytic Reduction (SCR) combined with Diesel Particle Filter (DPF)
4. Diesel Particle Filter (DPF)

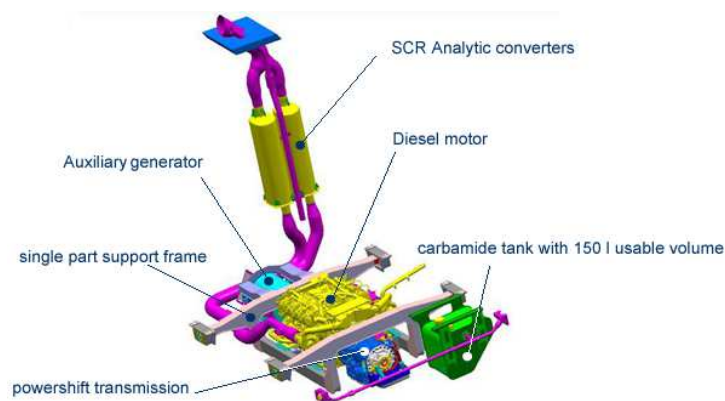
An updated take on this results means that due to the levels required by stage IIIB re-engining is almost impossible for the majority of vehicles [GREEN, 2008]. Therefore, the most promising technologies identified were SCR and SCR combined with DPF. However concerns about the technical feasibility of these technologies applied to railways were raised.

The GREEN project [EU,2008] was co-funded by the European Commission during the 6th Framework Program. The rail-related work of the project focused on developing a test bench engine able to comply with stage IIIA as well as Stage IIIB emission standards. The results suggested that it would be possible to transfer the technology used on heavy duty vehicles

engines to railway Diesel multiple units (power up to 560kW). However, achieving the requirements of stage IIIB to higher output rail vehicles (locomotives, which range from 1000kW to 3000kW) would require more extensive technical modifications of the engine and its environment.

Specifically, the rail-related activities of the project followed a three-step approach. The first stage included a study on the suitability of using in-cylinder measures to reduce NO<sub>x</sub> raw emissions from road heavy duty applications to railway applications. This showed that Exhaust Gas Recirculation (EGR), homogenous combustion and variable valve actuation are the most promising technologies from railway application. Based on this, a second phase developed and tested a new combined combustion process using conventional combustion with an EGR system and homogenous charge combustion ignition (HCCI). This proved promising albeit limited to part-load what led to the decision of choosing pure heterogeneous combustion coupled with EGR, a concept coming from the latest generation of on-road heavy duty technology. A prototype was built on the third and final phase using EGR technology for meeting the NO<sub>x</sub> emission limits of stage IIIB and a DPF for the particle levels. The engine will be in-service tested during CleanER-D.

The Catalyst based Low Emission Application (C.L.E.A.N) project was developed by Bombardier [Bombardier, 2008]. The project started in 2006 and was completed in 2008. It studied the potential technology transfer from the automotive sector to railway applications in the region of 500 kW power output. The results report a significant reduction on exhaust gas emissions of up to 83% compared with previous similar DMUs and a 20% weight reduction in the power packs. The solution is based on a 560kW eight-cylinder Diesel engine supplied by FPT (Fiat Powertrain Technologies) using SCR catalytic converter as after-treatment system connected to a powershift transmission unit. The SCR after-treatment system uses an electronic control unit (DCU) to record data from the engine, exhaust, and train control systems and a urea pump unit (AdBlue™-carbamide-water reducing agent), which is supplied by the DCU based on information received from these systems.



**Figure 55: Power Pack including exhaust gas post-treatment system (Source: Bombardier)**

Four Bombardier Itino DMUs using this solution have been ordered for the Frankfurt - Eberbach – Stuttgart - Odenwald line in Germany, entering service at the end on October 2009. A further thirteen DMUs have been ordered by a number of Swedish operators, with the first for Västtrafik due for delivery in December 2009.

In addition, the market leading companies (engine manufacturers and systems integrators) in the sector have developed solutions based on their resources and knowledge. The following Table 5 gives an overview of these solutions.

company	solution	Description	Legislation met	Availability
Alstom	PRIMA II locomotives	Diesel locomotives family on the medium and high power end of the market	EU Stage IIIA	available
Bombardier	C.L.E.A.N. Diesel vehicle pack	The solution uses a SCR system on a 560kW Diesel engine, reporting compliance with stage IIIB. Already fitted in the Itino DMU fleet	EU Stage IIIA	available
			EU Stage IIIB	available
	TRAXX locomotives	Diesel locomotives family on the medium and high power end of the market	EU Stage IIIA	available
Caterpillar	ACERT™ technology	In-engine technology that is applied to its family of horizontal engines for DMU applications as well as locomotive applications.	EU Stage IIIA	available
			EU Stage IIIB	2011/12
Cummins	QSB, QSK, QSX	Engine solutions for a range of railway products. EGR and DPF after-treatment technologies planned to meet Stage IIIB	EU Stage IIIA	available
			EU Stage IIIB	2011
EMD	Class 66 locomotives	EMD locomotive in Europe using a 2420 kW engine.	EU Stage IIIA	available
	Locomotive engine (model 16-710 G3C-U2)	High power 16 cylinder engine producing 3178kW. Used on VOSSLOH's Euro 4000 locomotives	EU Stage IIIA	available
GE transportation	Powerhaul™ locomotives	Range of locomotives using V16-cylinder twin-turbo PowerHaul Series engine	EU Stage IIIA	available
			EU Stage IIIA	available
MTU	Series 4000	Diesel engine family with 8V, 12V, 16V and 20V cylinder configurations.	EU Stage IIIA	available
			EU Stage IIIB	2011/12
	PowerPack® 6H1800	Range of engines for DMUs (315-390 kW) meeting Stage IIIA and able to achieve Stage IIIB using SCR technology	EU Stage IIIA	available
			EU Stage IIIB	available
TEDOM	TRAIN242 & 265	Engine solutions for DMUs	EU Stage IIIA	available
Voith Turbo	Maxima® locomotives	Two engine options with power output of 2750 kW (Maxima® 30CC) & 3600 kW (Maxima® 40CC).	EU Stage IIIA	available
Vossloh	1700, 2000 and 4000 series Locomotives	Diesel locomotives families on the high power end of the market. DPFs have been used in orders of 1700 Series by SBB	EU Stage IIIA	available

**Table 5 Clean rail Diesel technologies**

MTU offers a range of engines (Series 4000) for locomotive applications [MTU, 2008a] meeting stage IIIA emission requirements as well as UIC leaflet 624 [UIC, 2003a]. The Series 4000 Diesel engines from 1000kW to 3000kW power output. The PowerPack<sup>®</sup> 6H1800 solution [MTU, 2008b] is designed to comply with Stage IIIA regulation, being able to also achieve the Stage IIIB requirements using SCR technology. As part of CleanER.D (SP04), MTU is testing a locomotive engine using EGR combined with DPF to meet Stage IIIB limits.

Caterpillar has developed its own technology for the reduction of emissions called ACERT<sup>™</sup>. This technology uses complex technology solutions to improve control of the combustion process leading to fewer emissions. It is applied via three interconnected systems to control air and fuel delivery and utilisation within the engine [Caterpillar, 2006]. Its product range includes a family of horizontal engines for DMU applications (C18, C32, C175) as well as larger power output engines for locomotive applications. Caterpillar is currently testing a solution for stage IIIB using EGR and DPF as part of SP03 together with Vossloh.

TEDOM has a solution for DMUs on the market meeting stage IIIA, the TRAIN engines (242kW and 265Kw).

Cummins has a number of Diesel engines for railway applications complying with stage IIIA in its product range [Cummins, 2009]. The company plans to meet Stage IIIB requirements using EGR and DPF as core solutions.

GE transportation has recently entered the European market with a heavy haul locomotive compliant with stage IIIA regulation. Two Powerhaul<sup>™</sup> locomotives of a 30 unit total order have been delivered in October 2009 to the freight operator Freightliner. These locomotives have a power output of 2750Kw [GE, 2009]. The company reports reductions in fuel use by approximately 9% compared to current operating fleet averages, leading to a reduction in exhaust gas emissions.

Bombardier has recently introduced the C.L.E.A.N. Diesel vehicle pack. This solution is based on the Catalyst based Low Emission Application (C.L.E.A.N) project [Bombardier, 2008?] which used technology transfer from the automotive industry. The solution uses a SCR system on a 560kW Diesel engine, reporting compliance with stage IIIB. Bombardier's Itino fleet has been equipped with this new solution with units entering service in October 2009 (see above). The company also offers the TRAXX family of locomotives that are stage IIIA compliant.

VOSSLOH produces the Euro 4000 locomotive meeting the stage IIIA using a 16 cylinder EMD engine with 3178kW power output [Vossloh, 2009]. It also produces the G1700 series locomotive that is powered by a Caterpillar 3512 4-stroke Diesel engine which the Swiss Railways (SBB) took delivery of 73-unit order in 2004. This locomotive, although not fully compliant with Stage IIIA (it was not in force at the time) was equipped with DPFs as part of the SBB specification.

ALSTOM's Diesel locomotives family Prima II is compliant with stage IIIA and available for delivery in 2011.

Voith Turbo has recently introduced the Maxima<sup>®</sup> family of locomotives. These have two engine options with power output of 2750 kW or 3600 kW, both meeting Stage IIIA requirements [Voith, 2009].

EMD offers one locomotive in Europe (class 66), which latest generation is now compliant with stage IIIA using a 2420 kW engine. The company also supplies engines in Europe to Vossloh for their Stage IIIA-compliant Euro 4000 locomotive [EMD, 2009].

In addition to the research initiatives already described, the literature does not contain relevant publications on rail-related work dealing with Diesel traction and developments aiming to meet the

emission levels set in the regulation. The US Manufacturers of Emission Control Association (MECA) published in 2006 a report presenting some of the technologies solutions being applied at the time and included a number of case studies of locomotives using DPFs [MECA, 2006]:

- California Emissions Program (CEP);
- DPF Applications for New and Retrofit Locomotives in Switzerland and Europe;
- Union Pacific DOC Demonstration Project;
- Massachusetts Bay Transportation Authority (MBTA) Locomotive Demonstration Project;
- California Advanced Locomotive Emission Control System Project;
- Retrofit of Head End Power Units on Commuter Rail Locomotives;

The report concluded that Diesel Oxidation Catalysts (DOCs), DPFs, and SCR technologies are feasible to be used on railway applications and strongly recommended the US Environmental Protection Agency (EPA) to press ahead with Tier 4 non-road Diesel emissions regulation.

Although not capable on their own to meet the level of emissions required by stage IIIB, a range of complementary strategies and technologies are being assessed and slowing being introduced as part of cleaner Diesel products. These include driver training of optimized performance, driver assistance technologies, more efficient auxiliary systems (climate control for instance) and engine management systems.

As a summary of the above, compliance with EU Stage IIIA emission limits has been achieved using engine development and in-cylinder innovation. However, to meet the far more restrictive Stage IIIB limits, these developments alone are not sufficient. After-treatments are required to bring the levels of exhaust gas emission within the legislation. The use of such technologies in the railway environment is very limited to date. A lot of work led by the industry has been done in recent years to understand the implications and develop solutions, using the knowledge gained on other industries (automotive in particular) to this extend. As a result, prototypes for a new generation of Diesel engines using Exhaust Gas Recirculation (EGR) in combination with Diesel Particle Filters (DPF) or Selective Catalytic Reduction (SCR) are being developed and tested. However, more knowledge is needed to fully understand the true impact of these technologies.

## 8.2 REFERENCES

---

- Bombardier, 2008. "eco<sup>4</sup>-ecoActive technologies-C.L.E.A. Diesel powerpack", Henningsdorf (D);
- Caterpillar, 2006 "Caterpillar introduces new high-efficiency, low-emission horizontal Diesel engine for DMU railway applications", press release number: R01PR06, Berlin, Germany;
- Cummins, 2009 "Cummins - The Tier 4 Technology Leader", press release;
- EMD, 2009 "Class 66 freight locomotive", Heusenstamm, Germany;
- European Commission, 2004. "European Parliament and Council Directive 2004/26/EC on amendments to the Non-Road Mobile Machinery (NRMM) Directive 97/68/EC", Official Journal, L146;
- GE Transportation, 2009 "GE Ships First New PowerHaul<sup>®</sup> Series Locomotives to U.K", press release;

- Manufacturers of Emission Controls Association - MECA, 2006 "Case studies of the use of exhaust emission controls on locomotives and large marine Diesel engines", Washington, USA;
- MTU, 2008a "Series 4000 Diesel Engines for Push-pull Trains and Locomotives with Emissions Stage EU III A", data sheet, Friedischshafen, Germany;
- MTU, 2008b "PowerPack<sup>®</sup> for railcars", Friedischshafen, Germany;
- Tedom, 2009 "TRAIN Diesel engines-data sheet", Czech Republic;
- Union Internationale des Chemins de fer - UIC, 2003a: "leaflet 624-Exhaust emission tests for Diesel traction engines". 2nd edition, Paris, France ;
- Union Internationale des Chemins de fer - UIC, 2003b: "Diesel Action Plan", Paris, France ;
- Union Internationale des Chemins de fer - UIC, 2006: "Diesel rail study". Paris, France ;
- Union Internationale des Chemins de fer - UIC, 2008: "GREen heavy duty ENgine-Final report for the railway sector". Paris, France;
- Voith Turbo, 2009 "The Maxima<sup>®</sup> Locomotive Family", Kiel, Germany
- Vossloh, 2009 "Euro 4000 locomotives-passenger/freight", Valencia, Spain