The Development of HD Diesel Engines - Implications of Future Exhaust Emission Regulations

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ABSTRACT

Worldwide, Europe and the United States are the forerunners to enforce very strict exhaust emission limits. The legislation as proposed for heavy duty diesel engines will require a NOx and particulate emission reduction of more than 90 %. Such a dramatic reduction cannot be achieved by internal engine measures alone and aftertreatment systems, for either one or both of these emission components, plus sophisticated electronic control strategies are required.

In this paper, strategies to comply with EU 4, 5 and US 07 are discussed, also showing their impact on engine performance.

For typical heavy duty truck engines, engine and aftertreatment concepts are compared to assess the most suitable technology essential to meet the requirements in major markets worldwide. The assessment is based on thermodynamic calculations and test-bed results of in-house research still ongoing, plus estimations of engine cost and infrastructure implications.

Key-words: Heavy Duty Diesel Engine, Exhaust Emission Reduction, EGR, Particulate Trap, SCR/UREA

INTRODUCTION

The emission legislation steps EU 4, 5 and US 07, already in force or still under discussion, are milestones for the reduction of exhaust emissions of commercial Diesel engines (Ref. 1, 2). To comply with the proposed limits with competitive fuel economy, exhaust gas aftertreatment (particulate trap and / or DeNOxing) is seen to be necessary. It is however not yet clear, which concept will succeed considering production feasibility, client satisfaction and other parameters. Hence, in the following the issues still unresolved regarding exhaust gas aftertreatment and their impact on the engine and its performance characteristics are discussed.

Based on a comprehensive evaluation of technical criteria and customer benefits the specifications of future commercial diesel engines are predicted considering the above emission scenarios.

EXHAUST EMISSION LEGISLATION AND TECHNICAL SCENARIOS

In the following, NOx and particulate emission are discussed, as they are the only real challenge for Diesel engine development.

Figure 1 depicts the NOx and particulate emission limits for the coming 8 years in Europe, USA and Japan. Until a year ago, the extremely low EU 4 particulate emission limit 0.02 g/kWh was a major topic of discussion, now it is the proposed NOx emission limit US 07, 0.2 g/bhph (0.27 g/kWh), which has an additional strong influence on the discussion of aftertreatment strategies. Without a technological breakthrough the required drastic NOx reduction will deteriorate fuel economy and increase engine cost considerably. Still, the emission reduction strategy has to be, as shown in the bottom part of Figure 1, to find solutions satisfying both, the legislative and the market requirements.

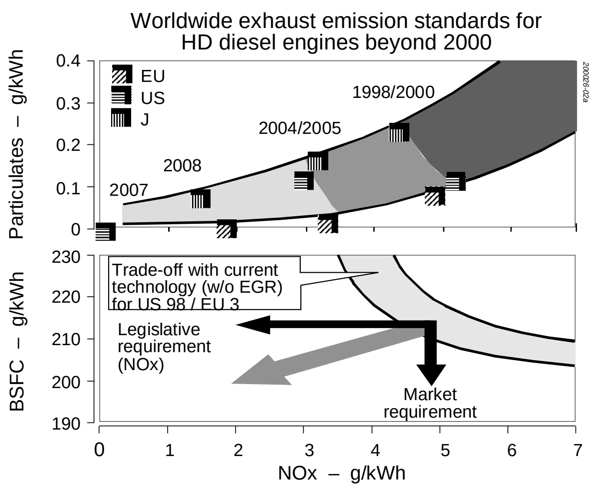

Fig. 1: Conflicting Trends: Legislation and Market Requirements

In Figure 2, the two principal strategies for emission reduction, to comply with EU 5 and US 07, are shown:

– NOx reduction with exhaust gas recirculation (Ref. 3), Particulate reduction with trap technology (Ref. 4).

– NOx reduction with exhaust gas aftertreatment, Particulate reduction with combustion refinement (Ref. 5, 6, 7).

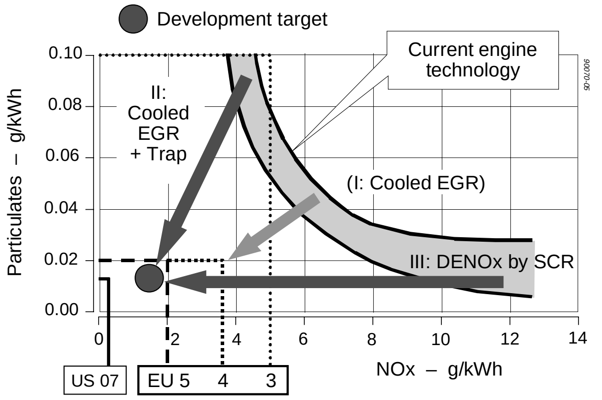

Fig. 2: Emission Reduction Strategies

Table 1 lists potential technical solutions for the above emission legislations, those which are discussed in more detail now are marked with ✔.

For exhaust gas recirculation two technologies are distinguished, with interesting different features, as will be discussed later:

- High Pressure-EGR (HP-EGR), with the exhaust gas recirculated via the short high pressure route
- Low Pressure-EGR (LP-EGR), using the longer low pressure recirculation

Table 1 also depicts the minimum fuel quality required regarding the sulfur content, an important pre-requisite for various aftertreatment technologies. The question mark should indicate, that the 50 ppm sulfur level being legislated for EU 4 and 5, may still be too high, especially for catalytic traps to be sufficiently effective long term (Ref. 4).

	Emission legislation		
	EU 4	**EU 5**	**US 2007**
NOx / PM (g/kWh) (g/hph)	3.5 / 0.02	2.0 / 0.02	 0.2 / 0.01
Technical solutions			
HP-EGR + Trap	✔ S < 50 ?		
LP-EGR + Trap	✔ S < 50 ?	✔ S < 50 ?	
NOx-Adsorber	S < 10		
SCR + (DOC)	✔ S < 50	✔ S < 50	
EGR + Trap + SCR			✔ S < 15

S ... Sulfur content in ppm

Table 1: Emission Legislation vs. Technical Solutions

By intention not covered in this paper is the potential of new combustion systems and alternative fuels. The current development status of new combustion systems - such as various types of homogenous Diesel combustion - does not yet allow a realistic assessment of technical and commercial pro's and con's. Alternative fuels, especially those with oxygen enrichment, show impressive potential for soot reduction, but are only expected to be used in some niche applications in the timeframe until 2008 (Ref. 8).

TECHNOLOGIES FOR EXHAUST EMISSION REDUCTION

EXHAUST GAS RECIRCULATION AND PARTICULATE TRAP

NOx reduction with engine internal measures and exhaust gas recirculation (EGR) will increase soot emission, which has to be reduced with a particulate trap. The challenge with an engine equipped with EGR and a particulate trap is to develop:

- a combustion with low soot emission in spite of high EGR rates
- a cooled EGR system with
  - precise EGR rate control in the entire engine map
  - low pressure losses in transporting exhaust gas to the intake
  - a reliable control, insensitive to fouling
- a particulate trap system which will regenerate under all operating conditions

To get a competitive fuel economy, the timing must be adjusted for combustion as close as possible to top dead center, which will however increase the NOx emission. Hence about 15 % EGR at full load will be required for NOx reduction for EU 4 and about 20 % for EU 5.

Two EGR systems are being applied at AVL, the HP-EGR using the high pressure route, and the low pressure LP-EGR system. In Figure 3, the high pressure - bypass Venturi system is shown, which allows EGR rates sufficient for EU 4, with minimized pressure loss, even in areas of the engine map where the pressure difference between intake and exhaust is negative. An additional check valve will increase the EGR rate at low engine speed.

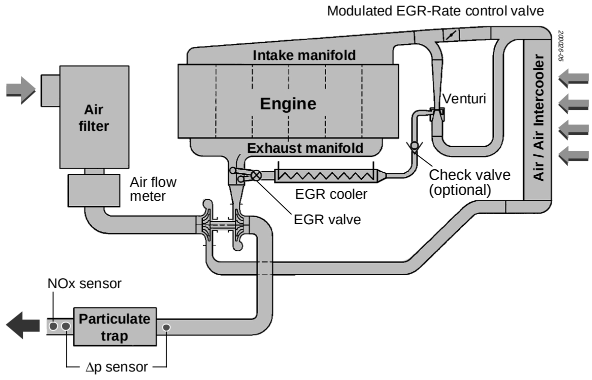

Fig. 3: AVL High Pressure Venturi EGR System

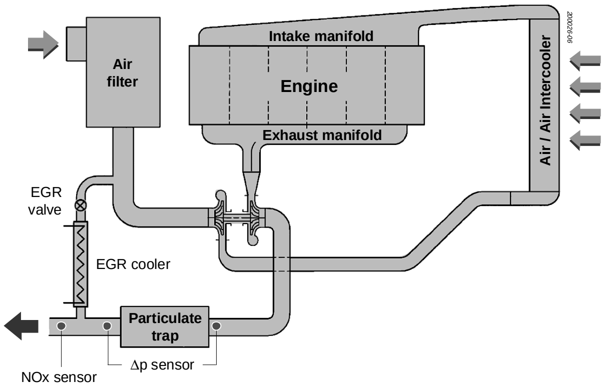

Fig. 4: AVL Clean Low Pressure EGR System

With a variable geometry turbine (VGT), the high pressure system could be designed with the check valve but without the Venturi for simplification. The variation of the VGT vanes allows to control for sufficiently high EGR rates.

The high pressure Venturi EGR system, using contaminated exhaust gas, has a few inherent drawbacks:

- Contamination of components exposed to exhaust gas
- Increased soot content in lubricating oil
- With increasing turbocharger efficiency, the losses increase as the pressure difference between intake and exhaust increases
- The precision of the EGR rate control is affected by the contamination of the system, and is especially difficult to ensure with a VGT
- In combination with a particulate trap the control complexity is further increased, as the variation of the exhaust gas back pressure depending on the trap loading condition needs to be compensated.

Some of these drawbacks can be avoided or at least made less critical, using a low pressure EGR system. As shown in Figure 4, this system has the exhaust gas taken after the particulate trap where it has been cleaned, and routed to the intake before the compressor of the turbocharger. To avoid corrosion in the intake system and to keep the catalytic particulate trap functioning, low sulfur fuel (significantly less than 50ppm) is required.

Apart from avoiding the system contamination (that is, provided the particulate filter is working effectively without any cracks or leakage), the EGR-control complexity is much reduced, as the VGT and the EGR rate may be controlled independently.

In Figure 5, the fuel consumption in the ESC test of comparable engines complying with EU 3, 4 and 5 is shown.

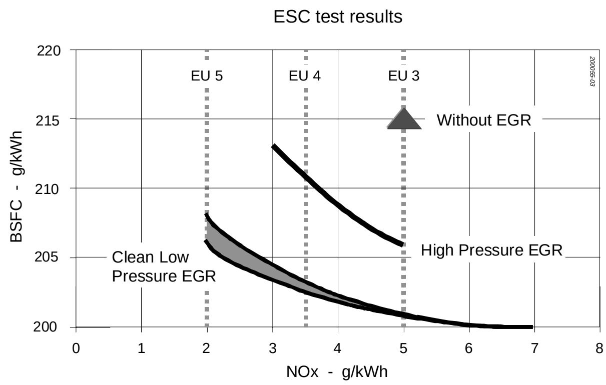

Fig. 5: Fuel Consumption Potential of EGR Systems

The considerably better fuel consumption with reduced NOx of the low pressure EGR system is due to higher EGR rates in combination with optimum turbo tuning possible with this system, which allows earlier injection timing.

The decisive criterion for the successful development of an EGR system is the availability of a reliably regenerating particulate trap, independent of it being catalytically supported or not.

In Figure 6, the cumulative temperature distribution after the turbine (before trap) is shown for a heavy duty Diesel engine in the European Transient Cycle (ETC), in the USHD Diesel transient test cycle and in real road conditions for a distributor vehicle in the winter period in city traffic.

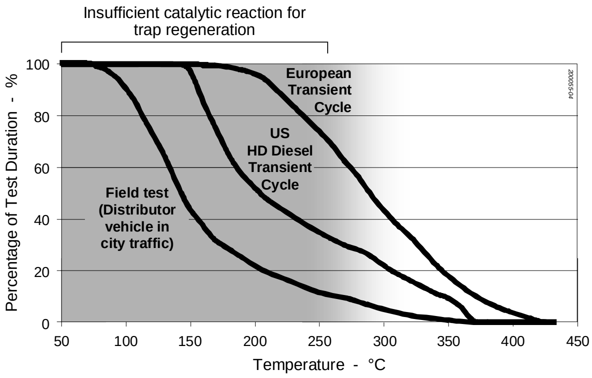

Fig. 6: Cumulative Temperature Distribution after Turbine

It is obvious, that this road condition is unfavorable for catalytically supported trap regeneration.

Catalytic traps need for a fairly continuous regeneration in practical use exhaust gas temperatures of about 250 to 300 deg Celsius. In the example shown in Figure 6, for the ETC test this precondition is fulfilled for about 60 % of the operating time, however in field testing this is only the case in less than 10 %. This makes it obvious, that in real operating conditions a continuous regeneration can not be expected, either the engine management system or any active means on the trap has to enforce it. This will cause a loss in fuel economy, and / or substantially increase the system cost, depending on the technology used: engine internal measures, additives or add-on equipment to the trap.

NOx REDUCTION WITH EXHAUST GAS AFTERTREATMENT

NOx Adsorber Catalyst

NOx Adsorbers store the NOx emitted by the Diesel engine during normal lean operation in the catalyst. To do so, they do not need any additional agent. When the adsorber catalyst reaches a certain NOx load, the engine management will control for a few seconds for a rich understoichimetric air fuel ratio in the exhaust gas for catalyst regeneration.

At AVL, this system has been developed recently for passenger car engines with good results (Ref. 9, 10), it is however as to yet uncertain, if it can be applied also with commercial engines. The experience to date indicates that it would be much more difficult, and will result in a comparatively high system cost.

Apart from the fact, that for a minimum durability the fuel sulfur must be lower than 10 ppm, problems still unresolved include:

– processing a large flow of exhaust gas
– due to regeneration, two systems are required in parallel
– rich exhaust gas is difficult to achieve with engine internal measures at the high bmep values typical for heavy duty diesel engines, due to the high component temperatures associated
– to avoid EGR (but still requiring an additional trap), a conversion rate of up to 90 % is necessary, which seems unrealistic under transient conditions.

DeNOx with SCR

Compared to the NOx-Adsorber, the selective catalytic reduction (SCR) is in a much more advanced development stage. Depending on the temperature level in the test cycle, NOx conversion rates in excess of 80 % are achievable even under transient conditions. This allows the base engine to be tuned for good fuel economy and low particulate emission.

In Figure 7, test results for exhaust emissions and fuel consumption for a 12 liter EU 5 heavy duty Diesel engine are shown (Ref. 7).

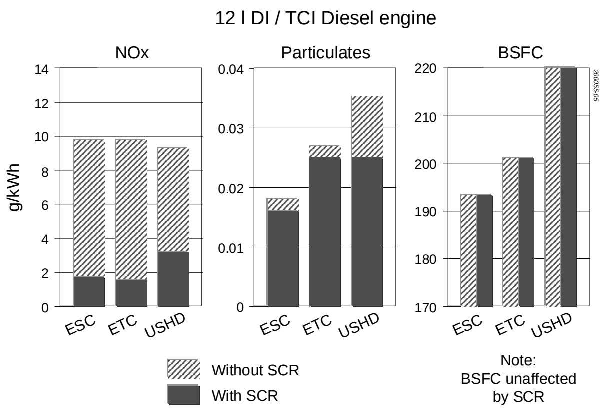

Fig. 7: Test Results: EU 5 Heavy Duty Diesel Engine with SCR

Depending on the injected amount of urea the 2 g/kWh NOx limit in the ESC and the ETC could be undercut, the particulate limit could be met with engine internal measures only. The NOx conversion rates get substantially lower as the exhaust gas temperature reduces, as is the case for example in the USHD Diesel transient test. Current SCR technology is suitable for a temperature window of 250 to 500 deg Celsius. Hence, with a road temperature profile as shown in Figure 6 above, most of the time the exhaust gas temperature is too low to allow urea injection. In other words, the NOx conversion rate depends very much on the load in the test cycle. In real driving conditions under low load the NOx emission may be much higher.

Combination of all Technologies

Should the future emission legislation define limits as low as currently under discussion for US 07: NOx

0.2 g/bhp-h, PM 0.01 g/bhp-h, then only a combination of all technologies discussed above will succeed, see Figure 8:

- Exhaust gas recirculation
- Particulate trap and
- DeNOxing.

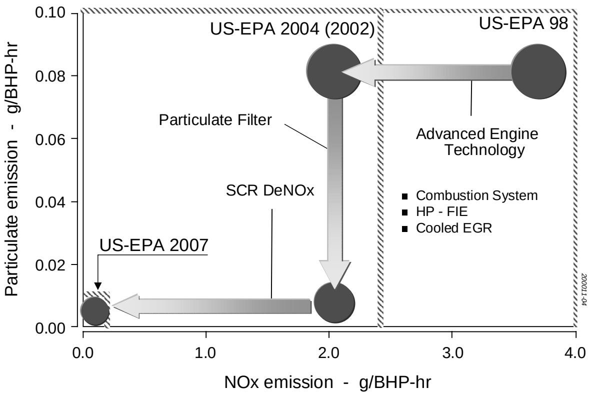

Fig. 8: Emission Reduction Strategies to meet US HD Diesel Standards

In this case, the SCR NOx conversion rate must be above 90 % even under most unfavorable temperature conditions.

This seems not to be feasible with today's technologies and their expected production cost.

EVALUATION OF ENGINE / AFTERTREATMENT SYSTEMS

To allow conclusions on development trends, the effect of the emission legislation as currently discussed on the engine / aftertreatment systems is evaluated. As a benchmark a typical EU 2 heavy duty Diesel engine is used, as it is hardly compromised regarding fuel economy and has no EGR causing soot-in-oil or system contamination problems.

Specific Performance, Effect of Altitude

With SCR a significant increase in specific performance without affecting altitude operation is feasible, limited only by turbocharger spec.'s and engine peak firing pressure potential.

With high pressure EGR a slight reduction in specific performance must be accepted, not so with the low pressure EGR. However, with about 20 % EGR rate, as required for EU 5 and US 07, the low pressure EGR will have up to 10 % less power compared to the EU 2 engine because of the high compressor outlet temperature.

It is to be noted that for both EGR and SCR the peak firing pressure will increase with future engines toward 180 to 200 bar. This is due to the fact that with EGR it is aimed at maintaining the air excess ratio and advancing the injection timing as far as possible, and with SCR injection timing is advanced anyway for best BSFC.

Fuel / Urea Consumption

To allow a fair comparison of the EGR with the SCR system, the urea consumption needs to be included as well.

Compared to EU 2 the fuel economy of EU 3 engines deteriorates by about 2 to 5 %, depending on the NOx reduction strategy: engine internal measures, with or without EGR.

This negative trend can be reduced for EU 4 and also for EU 5. In spite of the required further NOx reduction of 30 % (EU 4) or 60 % (EU 5), the fuel consumption with low pressure EGR will be about the same for EU 4, and only deteriorate by about 3 % for EU 5 compared to EU 2 engines.

Significantly better fuel consumption, about 195 g/kWh in the ESC test, can be expected with SCR for EU 4 and for EU 5. However, considering also the urea consumption and a cost ratio of 3:1 of fuel to urea solution, the equivalent total consumption will increase by 4 g/kWh for EU 4 and 5 g/kWh for EU 5. Nevertheless, such an EU 4/5 engine will still be equal to or lower in fuel consumption than the base EU 2 engine.

For US 07 engines, fuel economy will be determined by the required 2 g/kWh engine-out NOx emission, assuming a 85 % NOx conversion efficiency of the SCR, which will result in a fuel consumption similar to the EU 5 engines with low pressure EGR.

From this comparison it can be concluded, that the fuel consumption will not be the decisive factor for defining the emission reduction strategy.

Cooling System Load

All systems with EGR need about 10 to 15 % (of rated power) more cooling performance at rated power. The low pressure EGR has 30 % lower EGR cooler heat load but requires more cooling performance from the charge air cooler. The clean low pressure EGR has the advantage, that the intake manifold temperature is about 30 deg Celsius lower compared to the high pressure EGR at same total heat flow, because the recirculated exhaust is routed through compressor and intercooler.

Fouling

Fouling is defined as deposit build-up in the intake system, and considers also the soot-in-oil problem.

Both is to be found especially in the uncleaned high pressure EGR, and much less pronounced in the low pressure EGR and non-existent with SCR alone.

Packaging

Packaging concerns the installation space requirements, the system arrangement and, if so required, the cooling system adaptation. In this regard all systems have a considerable disadvantage, especially so, when SCR and particulate trap are combined.

Durability

Durability includes the effects on the base engine as well as on aftertreatment systems. All systems with particulate trap have to be downrated, as the combination EGR / particulate trap / regeneration system did not yet show the necessary lifetime.

System Integration

The mutual effects and dependence of engine and aftertreatment systems make it obvious, that the engine management system (EMS) needs to be optimized for both together. The new systems need be adapted to the very application and integrated: EGR, EGR cooler, particulate trap or SCR catalyst, urea tank and dosage system including sensors and actuators. On-board diagnosis functions (OBD) are to be integrated in the EMS to ensure that emission stay on the certified low level over the entire life of the vehicle.

Cost

Cost estimations available today are relatively vague and scattering, also because the cost of trap regeneration systems is estimated vastly different. As a rough estimation, both the EGR plus trap and the SCR system are assumed to cost the same. If both systems become necessary, considerable development and cost reduction is needed.

RATING OF ENGINE / AFTERTREATMENT SYSTEMS

All future technologies are rated worse than EU 2 due to their complexity and cost, see Table 2. SCR has an advantage for both engine categories as well as for both emission steps EU 4 and 5. While this technology has advantages in a number of criteria compared to trap systems, its main drawback is the need for an additional operating medium and its infrastructure requirement.

The situation changes substantially when both aftertreatment functions, DeNOxing and exhaust filtering become necessary due for example to additional legislative requirements. Then the total rating for EGR plus trap and SCR plus trap become about similar. This means, that in a next step a further discriminating assessment of the aftertreatment technology, especially regarding the potential of combined SCR / particulate trap systems, becomes necessary (Ref. 10).

	EU 4			**EU 5**			**US 07**
Technology / **Criteria**	**HP-EGR + Trap**	**LP-EGR + Trap**	**SCR**	**LP-EGR + Trap**	**SCR**	**SCR + Trap**	**LP-EGR + SCR + Trap**
Specific performance	-	=	+	=	+	+	=
Altitude operation	-	-	=	--	=	=	-
Fuel consumption	-	=	+	-	+	+	-
Additional media	=	=	--	=	--	--	--
Cooling system load	-	-	=	-	=	=	-
Fouling	--	=	=	=	=	=	=
Packaging	-	-	-	-	-	--	---
Durability	--	--	-	--	-	--	--
System integration	--	-	-	--	-	--	--
Cost	--	--	--	--	--	---	---
Total	--	-	- (=)	--	- (=)	-	---

+ better, lower cost than EU 2
= close to EU 2
- worse and more expensive than EU 2
-- much worse and considerably more expensive than EU 2
--- not acceptable with today‘s technology level

Table 2: Emission Reduction Technology Evaluation compared to EU 2 Engines

SUMMARY

The assessment of emission reduction technologies for commercial vehicles in view of future European emission limits reveals obvious advantages for the SCR technology. The effects on the base engine are relatively small. For a high specific performance the peak firing pressure potential of 180 to 200 bar must be considered. Lowest soot emission requires fully flexible fuel injection systems with up to 2000 bar injection pressure.

For the technology variant EGR with particulate trap, the biggest challenge is the durability development for the whole system to meet the typical needs of commercial vehicles. This results in additional requirements on the base engine such as:

- development of engine internal measures to support trap regeneration, such as reduction of gas mass flow or late post injection
- Adaptation of the cooling system to cope with about 20 % more heat rejection
- Broader operating range of the TC compressor with increased thermal load capability
- Two step turbocharging is an interesting alternative to cope with the continuing trend to increase performance without limiting altitude capability

The comparatively bad total rating of the US 07 scenario may be interpreted in such a way, that the targets are in principle attainable, requiring however substantial development effort to find solutions for all open issues.

REFERENCES

[1] Moser F.X., Development Trends in Heavy Duty Diesel Engines for Commercial Vehicles, JSAE-Conference, May 1999, Yokohama

[2] Cartellieri W., Zelenka P., Evaluation of Future Diesel Engine Technologies, AM-00-56, NPRA Meeting, March 2000

[3] Zelenka P., Aufinger H., Reczek W., Cartellieri W., Cooled EGR - A Key Technology for Future Efficient HD Diesels, SAE Paper 980190

[4] Allansson R. et. al., The Use of the Continuously Regenerating Trap and SCRT Systems to Meet Future Emissions Legislation, 21. Internationales Wiener Motorensymposium, Mai 2000

[5] Miller W.R., et. al., The Development of Urea-SCR Technology for US Heavy Duty Trucks, SAE Paper 2000-01-0190

[6] Jacob E., Döring A.,Allansson R. et. al., GD-Kat: Abgasnachbehandlungssystem zur simultanen Kohlenstoffpartikel-Oxidation und NOx-Reduktion für EU 4/5 Nfz-Dieselmotoren, 21. Internationales Wiener Motorensymposium, Mai 2000

[7] Cartellieri W., Havenith C., et. al., Entwicklung eines verbrauchsoptimierten EU 5 NFZ-Dieselmotors mit Harnstoff-SCR Abgasnachbehandlung, VDA Technischer Kongress, Sept. 2000

[8] Ofner H., Gill D.W., Krotscheck C.; Dimethyl Ether as Fuel for CI Engines – A New Technology and its Environmental Potential, SAE Paper 981158

[9] Cartus Th., Strigl Th., Neunteufl K., Herzog P., Effiziente und saubere PKW-Diesel mittels NOx-Adsorbertechnologie 21. Internationales Wiener Motorensymposium, Mai 2000

[10] Herzog P., Breitegger B., Cartus Th., Strigl Th., Neunteufl K., NOx Adsorber and HSDI Diesel – A New Partnership, JSAE-20005304, May 2000, Yokohama