STATE-OF-THE-ART AND EMERGING TRUCK ENGINE TECHNOLOGIES FOR OPTIMIZED PERFORMANCE, EMISSIONS AND LIFE CYCLE COSTS

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ABSTRACT

The challenge for truck engine product engineering is not only to fulfill increasingly stringent emission requirements, but also to improve the engine’s economical viability in its role as the backbone of our global economy. While societal impact and therefore emission limit values are to be reduced in big steps, continuous improvement is not enough but technological quantum leaps are necessary.

The introduction and refinement of electronic control of all major engine systems has already been a quantum leap forward. Maximizing the benefits of these technologies to customers and society requires full use of parameter optimization and other enabling technologies.

The next big step forward will be widespread use of exhaust aftertreatment on all transportation related diesel engines. While exhaust gas aftertreatment has been successfully established on gasoline (Otto cycle) engines, the introduction of exhaust aftertreatment especially for heavy-duty diesel engines will be much more demanding. Implementing exhaust gas aftertreatment into commercial vehicle applications is a challenging task but the emission requirements to be met starting in Europe, the USA and Japan in the 2005-2007 timeframe require this step. The engine industry will be able to implement the new technology if all stakeholders support the necessary decisions.

One decision has already been taken: the reduction of sulfur in diesel fuel being comparable with the elimination of lead in gasoline as a prerequisite for the three-way catalyst. Now we have the chance to optimize ecology and economy of the Diesel engine simultaneously by taking the decision to provide an additional infrastructure for a NO\textsubscript{x} reduction agent needed for the introduction of the Selective Catalytic Reduction (SCR) technology that is already implemented in the electric power generation industry. This requires some effort, but the resulting societal benefits, fuel economy and vehicle life cycle costs are significantly better when compared to other competitive technologies. After long discussions this decision for SCR has been made in Europe and is supported by all truck and engine manufacturers. The necessary logistic support will be in place when it will be needed commercially in 2005. For the US the decision has to be taken this year in order to have the infrastructure available in 2007. It will enable the global engine industry to focus their R & D resources in one direction not only for 2007, but for the years beyond 2010 with the best benefit for the environment, the customers and the industry.
1. THE CHALLENGE FOR COMMERCIAL VEHICLE (CV) ENGINE R&D

Today’s major challenge for R&D work on commercial vehicle engines is to build a bridge between ecological and economical requirements (figure 1).

Engine R&D efforts have to focus on bridging ecological and economical requirements of all stakeholders

![Figure 1: Focus of R&D efforts](image)

Efficient road transport is the backbone of the economy in the US as well as in Europe and other parts of the world, and striving for the optimization of haulage costs is of utmost importance from the hauliers’ and truck makers’ as well as from a national economy standpoint.

The engine and truck industry’s contribution to the life cycle costs of a heavy truck has to be focussed on fuel efficiency, reasonable purchase costs and high reliability with low maintenance requirements (figure 2).

![Figure 2: Life-Cycle-Costs of class 8 trucks in Europe](image)

time of use: 4 years.
mileage/year: 95,000 mls (app. 150,000 km).
fuel consumption: 7.35 mpg (32.5 l/100 km)
The worldwide exhaust emissions legislation (figure 3), focussed mainly on NO\textsubscript{x} and particulate emissions, obviously tends to bring both components close to the zero point.

As we all know, there is a trade-off between NO\textsubscript{x} and particulate matter (PM) (figure 4) in a way that traditional measures to reduce NO\textsubscript{x} emissions cause an increase in particulates. A similar trade-off exists between NO\textsubscript{x} emission and fuel efficiency. Most measures to suppress NO\textsubscript{x} formation reduce the engine’s thermal efficiency which has not only an economical impact but also increases CO\textsubscript{2} emission with the well-known influence on global warming.

Traditional measures aiming at lower peak combustion temperature reduce fuel efficiency and increase PM- and CO\textsubscript{2}-emission

2. ENGINE TECHNOLOGY DEVELOPMENT UNTIL TODAY

How has diesel engine R&D been able to meet this challenge in the past?
A diagnose depicting the average speed and fuel economy of 40 metric tons tractor-trailer combinations tested in Europe over the past years (figure 5) demonstrates that OEMs have been able to increase or at least maintain transport efficiency in spite of more and more stringent emissions regulations. For the next years we expect a further efficiency improvement using the right technology path.

Figure 5: Average fuel consumption and speed of a 40t tractor-trailer combination

European OEMs have been able to increase transport efficiency in spite of more stringent emissions regulations

This successful development of the past was achieved by a step by step implementation of new technologies (figure 6) combined with continuous improvement. The introduction and refinement of electronic control of all major engine systems has been a quantum leap on this way. Making the engine intelligent has opened the door for meeting the most demanding requirements. This development was started in the US, and DDC was the first to start production of a fully electronic engine.

Figure 6: Measures to fulfill emission standards
3. AFTERTREATMENT SYSTEMS AS EMERGING TECHNOLOGIES ALSO FOR CV DIESEL ENGINES

Now it seems clear that we have to have another quantum leap in engine development which will be exhaust aftertreatment.

The three-way catalyst was the basis for bringing gasoline engines to their low emissions level of today, but unfortunately the air-to-fuel ratio (AFR) requirements of the diesel engines have been prohibitive for its introduction with regards to NOx reduction.

Today we have exhaust aftertreatment systems under development for NOx as well as for PM reduction (figure 7). For reducing nitric oxides two different systems are presently discussed.

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The first one is the adsorber catalyst which is able to adsorb the nitric oxides generated in the engine’s cylinder during normal operation which is characterized by the high AFR required by the diesel combustion process. From time to time the adsorbed NOx have to be reduced again by operating the engine below the stoichiometric AFR.

In contrary to this non-continuous catalyst operation the Selective Catalytic Reduction (SCR) directly reduces the nitric oxides by adding a reducing agent to the exhaust gas in a continuous process.

For particulate emission reduction it is relatively easy to take the particulates out of the exhaust gas by a filter. The technical challenge is to regenerate the filter by oxidizing the particulates before the exhaust back-pressure becomes too high.

Let me now discuss the different aftertreatment systems in more detail.

Figure 8 depicts the adsorption of the nitric oxides during normal “lean” engine operation and their reduction in a subsequent “rich” operation mode with excess fuel. In this mode CO and hydrogen are effective for NOx reduction. Up to now it is not yet clear if the additional fuel quantity can be injected into the cylinders as a “late post injection” or if an injection into the exhaust system is required.

**Figure 7:** Today’s exhaust aftertreatment systems for Diesel engines in development

**Figure 8:** Mode of operation of an adsorber catalyst
For the “rich” operation mode air throttling is necessary besides excess fuel injection. As heavy duty truck operation requires this process also at full load this results in high operating temperatures for the engine and its components and is considered much more critical compared to light duty vehicle operation.

The SCR system (figure 9) reduces the nitric oxides by ammonia which is generated in the exhaust system out of an aqueous urea solution by hydrolysis. This aqueous urea solution which has to be added in a quantity of about 6% of the consumed fuel requires an extra tank and is injected corresponding to the NO\textsubscript{x} level generated in the engine which is determined by the engine’s “NO\textsubscript{x} map” and its operating point.

The SCR Technology uses urea, respectively ammonia (which forms after decomposition of urea at temperatures >200°C) to convert nitric oxides (NO\textsubscript{x}, NO\textsubscript{2}) into harmless molecular nitrogen N\textsubscript{2} and water.

As NO\textsubscript{x} reduction is achieved downstream the engine, its combustion process does not have to be compromised by peak temperature reduction, but can be optimized with regard to fuel efficiency and low particulate emission. This means that despite the lower NO\textsubscript{x} level required for MY07 fuel efficiency can be even higher than on MY98 engines which helps considerably to reduce operating costs of trucks and CO\textsubscript{2} emission.

Let me now come to particulate aftertreatment. As already mentioned, until today the regeneration of particulate filters is their main problem. The most promising solution is the Continuously Regenerating Diesel Particulate Filter (CDPF) shown in figure 10.

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Upstream the filter an oxidation catalyst transforms NO to NO₂ which reacts with the trapped carbon in the filter forming CO₂ and N₂. This reaction requires an appropriate NOₓ/PM ratio which is easily achieved by installing the CDPF upstream an SCR system as with this combination the exhaust gas entering the CDPF contains much NOₓ and relatively little PM.

The two main issues of particulate filters are adequate temperature levels for regeneration and ash deposits from oil additives. This requires "active exhaust thermomanagement", low engine oil consumption and low ash oils which are under development in cooperation with the mineral oil industry. To make the filter less sensitive against blocking by ash deposits a version from sintered metal (figure 11) seems to be very promising.

![Monolith with a high number of filter channels](image1)

![Sintered metal filter with a low number of filter plates](image2)

**Figure 11: Versions of particulate traps under evaluation**

After describing what aftertreatment systems we are working on, the strategy options to meet future emissions limit values are to be discussed.

Let me start with Europe. When fixing the Euro 4/5 limit values the legislators assumed that SCR systems and particulate filters would be state of the art when Euro 4 would become effective, and they intended to enforce the introduction of these aftertreatment systems through the Euro 4/5 limit values.

As the industry started to transform SCR technology from large power plant applications, where it is well established, to commercial vehicles already around 1990, European manufactures indeed believe in its production maturity in the beginning of 2005 and pursue SCR as the preferred technology at least for long haul trucks because SCR is the only solution enabling NOₓ and fuel consumption reduction at the same time.

The SCR catalyst is also able to reduce particulate emissions by 30% in the ESC test, and the combustion design can be optimized for fuel efficiency and low particulates as well, so that also the particulate limit of Euro 4/5 can be achieved without an additional particulate trap. This is very positive, as a particulate trap field test in the beginning of the 1990's revealed a lot of difficulties with the traps, and also today the filters installed in urban buses do not demonstrate the durability which is required for heavy duty trucks, apart from the need of low sulphur fuel. We are working hard to achieve an adequate maturity level for MY07 production, but for Euro 4 with SOP in 2005 we appreciate not to need particulate filters.

As the European legislators as well as truck and engine OEMs have decided in favor of SCR, the installation of the supply infrastructure of the reducing agent “AdBlue”, as the aqueous urea solution was named, is proceeding.

So far the situation in Europe.
4. WHAT WILL BE THE RIGHT TECHNOLOGY FOR US MY 07?

Figure 12 demonstrates that basically there are two ways to achieve the necessary NO\textsubscript{x} reduction: Either considerably increasing the MY04 EGR rate or making use of denoxation aftertreatment.

![Figure 12: Strategies for emission reduction for US MY07](image)

A particulate trap will be needed in any case, but its required efficiency would be much higher in the case of high EGR as this solution generates an elevated particulate level. In addition, the NO\textsubscript{x}/PM ratio is not favorable for filter regeneration as the low NO\textsubscript{x} level is achieved already upstream the filter.

Figure 13 depicts the high EGR+CDPF approach with nearly twice the EGR rate compared to MY04. This means even more heat rejection to the coolant, engine contamination and also power loss.

**The EGR system for US'07 features approximately twice the EGR rates of US'04**

![Figure 13: High EGR with CDPF approach](image)

The high level of heat rejection requires radiators of a size which in the case of high engine ratings will be difficult to install (figure 14), apart from higher fan-on time.
The brake mean effective pressure (bmep) loss of the engine is caused by the requirement of a high AFR despite the high EGR rate. Two-stage turbocharging is not an attractive solution from a cost and installation standpoint. So the high EGR option will require larger displacement engines with additional weight.

Figure 15 shows the combination of an SCR system with a particulate filter. In this case the SCR system works as a closed-loop system with an ammonia sensor, I will come to this later on.

As the need of an additional reducing agent is considered a major drawback of the SCR solution especially in the US, much effort in DaimlerChrysler’s R & D has been dedicated to the adsorber catalyst. Meanwhile it is obvious that this technology cannot have the necessary maturity for launch in heavy duty trucks of MY07.

Figure 16 shows the timelines as we see them realistically. It demonstrates that SCR is the only heavy duty denoxation aftertreatment that will be ready for introduction with MY07. But timely availability is not the only argument in favor of SCR.
Fuel efficiency has high importance from the economical as well as from the global warming and resources conservation viewpoint. Figure 17 shows the evident superiority of the SCR solution.

Despite the system costs and the reducing agent consumption it offers the lowest life cycle costs (figure 18).

This is why DaimlerChrysler and other truck and engine manufacturers are testing trucks with SCR systems and particulate filters also under US operating conditions (figure 19). Soon the number of Freightliner trucks with SCR technology in customer operation will be close to 50. Truck fleets are highly interested in this attractive technology and are willing to handle the additional reducing agent.
5. PREREQUISITES TO BE ESTABLISHED

Despite all enthusiasm on the SCR solution we are realistic enough to see that two issues have to be resolved to achieve acceptance of this system:

- The necessary supply infrastructure for the reducing agent has to be built up.

- We have to make sure that the reducing agent with the right concentration is on board and also injected. As tampering may save costs for urea we have to secure that loopholes for engine operation without urea will be closed as far as possible.
Let me say some words about the reducing agent. Urea is colorless, non-toxic and is used in agricultural fertilizers, food, cosmetics, pharmaceuticals etc. “AdBlue” is the European trade name for a 32,5 % aqueous urea solution. The installed production capacity allows commercial vehicle supply without additional investment.

In Europe the AdBlue infrastructure will be built up stepwise with the urea supply industry having a strong interest to be involved. Truck fleet owners having their own diesel fuel supply system handle 80% of the entire truck diesel fuel consumption. They will install their own urea filling stations. In addition large highway truck-stops will be equipped for urea supply. Other gas filling stations will install urea equipment gradually. Figure 20 shows two smaller filling stations for truck operators which can be installed very easily.

Figure 20: Local AdBlue filling stations

For the US a study carried out by the consulting firm TIAX*) came to the following conclusions:

- “Economics favor the SCR/urea technology over the NOx adsorber technology for most applications of long haul and vocational trucks in the long-term”.

- “Economics also generally favor the SCR/urea technology over the NOx adsorber technology in the near-term if early NOx adsorbers have a high fuel penalty (≈ 5%) and a higher initial incremental cost.”

- The study furthermore states that provision of urea is both possible and economically reasonable if “strong signals regarding manufacturers’ integration to provide SCR-equipped trucks” are sent to truck operators and other stakeholders starting 3rd quarter 2003 and not later than mid 2004.

Indeed we are in close contact with all stakeholders to make it happen as we have done in Europe.

The issue of monitoring urea injection and tampering prevention will be solved by a further development step for US MY07 compared to the first system introduction for Euro4. As shown in figure 15 the US07 system will not only add the adequate urea quantity as calculated by the ECU based on the engine NOx map, but will be a “closed loop system” based on a special ammonia sensor.

At the time being this sensor which is based on a DaimlerChrysler patent is under development in close cooperation with a leading US component supplier and will be marketed also to our competitors.

*) TIAX is a consulting firm which formed from Arthur D. Little’s Technology and Innovation business
This sensor will considerably increase the SCR catalyst efficiency. It will be possible to inject more urea, as the ammonia quantity in the catalyst is closely monitored, and any ammonia slip leaving the exhaust muffler and causing the typical ammonia smell can be safely avoided by this highly sensitive sensor.

In the case of not injecting urea the sensor will also detect this fault and any action from warning the driver to torque reduction or complete engine shut-down can be taken. The details of this are under discussion with authorities as well as operators to find an appropriate solution.

Let me sum up: For the next emission limit stages in Europe as well as for US07 an aftertreatment solution is available that will bring us a quantum leap in the combination of ecology and economy.

<table>
<thead>
<tr>
<th></th>
<th>High EGR</th>
<th>SCR</th>
<th>NOx Adsorber</th>
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</thead>
<tbody>
<tr>
<td><strong>Fuel Economy</strong></td>
<td>-3%</td>
<td>+6%</td>
<td>-3%</td>
</tr>
<tr>
<td><strong>Cooling Requirements</strong></td>
<td>up to 55%</td>
<td>-20%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Power Density</strong></td>
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<td>+6%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
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<td>-100 lbs.</td>
<td>+200 lbs.</td>
</tr>
<tr>
<td><strong>Oil Exchange Intervals</strong></td>
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<td><strong>Urea Infrastructure</strong></td>
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<td><strong>Driver’s Responsibility</strong></td>
<td>None</td>
<td>Urea Refill</td>
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**Figure 21: Emission technology comparison**

Figure 21 summarizes the benefits of the SCR+CDPF solution. To make use of it requires more than R & D efforts and capital investment in the truck and engine industry but cooperation of many stakeholders including authorities to create the necessary prerequisites. As this country has always had the power to make innovations of this kind happen, I am optimistic that we will be able to pursue this path also in the US.