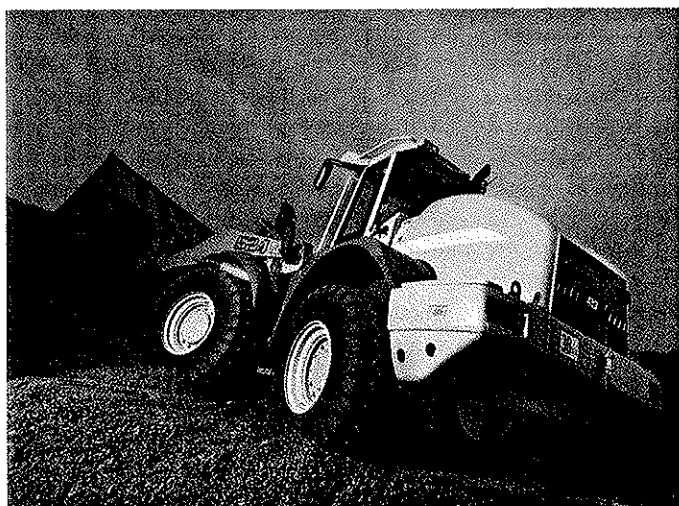


Konzepte für die Emissionsgesetzgebung Non-Road Stage IV / Tier 4

Concepts to Meet Non-Road Stage IV / Tier 4 Emission Legislation



By December 2007, the EC will have to submit a new proposal for Stage IV emission limits for Non-Road Mobile Machinery. Industry is committed to contributing to this process and has asked AVL to carry out a study as a neutral engineering company. The main topics of this study are described in this article

1 Introduction

With introduction of EU Stage IV and US EPA Tier 4 emission legislation, emission limits for Non-Road Mobile Machinery (NRMM) will be reduced significantly. New engine technologies will be introduced but exhaust aftertreatment also has to be applied to meet these stringent targets. Following concepts and technologies and their specific boundary conditions for Non-Road Mobile Machinery will be described.

2 Legislation

2.1 NRMM Regulatory Framework

In **Figure 1** and **Figure 2** EU and US emission regulations are shown for 19 to 560 kW Diesel engines in land based Non-Road Mo-

bile Machinery (NRMM), i.e. agricultural and construction equipment. Both diagrams are only part of a more complex regulatory framework for NRMM. Rules have not only been developed for land based sources but also for rail, inland waterway vessels, recreational marine crafts, seagoing ships and constant speed engines. Furthermore, various regional as well as international authorities place specific requirements. Both figures clearly demonstrate:

- how closely power categories, emission limits and introductory dates are harmonized between the EU and the US
 - the concept of a staggered phase-in of new emission limits by power categories.
- These approaches reflect the most important prerequisites NRMM industry is demanding from any new or revised forth-

Authors:

Thomas Cartus, Holger Herrmuth,
Peter Scherm and Gunnar Stein

coming regulation. For the major challenge manufacturers are facing, is how to allocate their product development resources and manpower to numerous niche markets, i.e. highly diversified applications with low sales volumes in truly global markets. Consequently, other key economic areas in the world, amongst them Japan, India and China, are also following the same approach by complying with existing NRMM regulations.

2.2 Future NRMM Regulations

Major revision processes of emission regulations for NRMM sources are currently proceeding in the EU (Directive 97/68/EC and amendments), in the US (marine and locomotive engines <30 L/Cyl), at the UNECE (Gothenburg Protocol on long range transboundary air pollution) and, on a global scale, at the UN (IMO MARPOL Annex VI and the NO_x Technical Code for emissions from seagoing ships). In the European Union and at IMO, provisions for improving the NRMM in-use fuel quality, above all relating to the sulphur content, are also under discussion.

The technical review of the EU Directive 97/68/EC (as amended by 2004/26/EC) is aiming at both a reassessment of the technical feasibility of existing Stage IIIB and IV regulations and an evaluation of the need for further or new regulations in some of the pre-stage IIIB applications. Potential requirements for in-use compliance procedures and off-cycle emission provisions are also included. Currently the European Commission is about to identify areas of potential new or revised NRMM rulemaking and is requested to provide a report on its findings to the European Parliament and Council by the end of 2007. Euromot is strongly committed to contributing to the overall revision process by providing industry experience and specific experts' knowledge to ensure the paths forward are both environmentally friendly and technically and economically feasible.

2.3 NRMM Fuel Quality

Currently sulphur levels of up to 2000 ppm are being distributed for NRMM Stage II and Stage IIIA applications in the EU. However, the phase-in of engine technology complying with Stage IIIB from 31 Dec. 2010 will not only require significantly lower sulphur levels but also alignment with on-road fuel parameters, in particular lubricity, cetane number, viscosity and polycyclic aromatic hydrocarbon content as specified by the European standard EN590.

In January 2007, the European Commission published a proposal to amend Directive 98/70/EC on fuel quality for road transport. Among other things, this proposal recommends to introduce 10 ppm sulphur fuel for all land based NRMM by 31 Dec. 2009. Assuming an implementation of the proposal in Europe, the global sulphur level scenario for NRMM fuel in 2010 can be anticipated as is shown in **Figure 3**: levels of up to 15 ppm in the EU, US, Australia and Japan, of up to 500 ppm in India and China and above 500 ppm in the rest of the world.

3 Technology Options to Meet Stage IV Emission Standards

3.1 Engine and Exhaust Aftertreatment Technology

The emission reduction which is required to achieve EU Stage IV / US Tier 4 standards requires a combination of significantly reduced engine-out emission in combination with highly efficient exhaust aftertreatment. These requirements are more or less identical to those of future on-road CI (Compression Ignition) engines, except for various constraints characteristic for NRMM, which will be outlined later.

Based on the different stages of European and US Non-Road Emission Legislations, an attempt has been made to define major technology packages for fulfilling appropriate emission standards, **Figure 4** and **Figure 5**.

In these Figures, seven areas have been identified, which generally consist of identical technology packages for the European as well as the US applications. However, the areas differ between Europe and US regarding engine power class and the date of becoming operative. Following, please find a list of the most important technologies of each area.

- Area 1: Mechanical FIE (Fuel Injection Equipment), no EGR (exhaust gas recirculation)
- Area 2: Mechanical FIE, internal EGR
- Area 3: Electronic FIE, internal EGR and retarded timing or externally cooled EGR
- Area 4: Electronic FIE, internal EGR plus DPF, or IDI (indirect injection) engine plus DPF (diesel particulate filter) plus external regeneration, or gasoline engine with a three-way catalyst
- Area 5: Electronic FIE, internally or externally cooled EGR plus DPF, or electronic FIE (>1800 bar), externally cooled EGR plus passive filter system, (e. g. POC: PM (Particulate Matter) Oxidation Catalyst)

- Area 6: Electronic FIE, externally cooled EGR plus DPF, or electronic FIE (>1600 bar) plus SCR no EGR, no PM filter
- Area 7: Electronic FIE, externally cooled EGR plus DPF and SCR or electronic FIE (>2200 bar), externally cooled EGR plus SCR, no PM filter

As US legislation also considers engines with a power output >560 kW, three additional areas were identified.

- Area 8: Electronic FIE, no EGR
- Area 9: Electronic FIE plus externally cooled EGR
- Area 10: Electronic FIE, externally cooled EGR plus DPF or electronic FIE plus SCR.

For the most critical power range of 56 to 130 kW, common rail injection systems will be the prime choice due to its full flexibility of injection quantity, injection timing and number of injection events, this flexibility being enabled by electronic control. Regarding turbocharging in this power range, fixed geometry turbochargers with a waste gate and maybe also with an actively controlled waste gate will be the prime choice. Cooled EGR will be accomplished along the high-pressure route, and electronic EGR rate control will become necessary. For the power range from 130 to 560 kW, engine technologies will be transferred from those used for on-road engines.

SCR with AdBlue (Urea-water solution) dosage will be the preferred SCR technology solution for NO_x aftertreatment. Therefore, engine-out NO_x emissions of about 2g/kWh will be required by cooled EGR in order to meet the stage IV NO_x development target of 0.36g/kWh (10 % below the limit of 0.40g/kWh) with SCR and the exhaust gas temperature of the Non-Road Transient Cycle. Since heat rejection for Stage IV will increase beyond the levels required for Stage IIIB, special attention has to be paid to the additional capacity of the cooling system.

The configuration of the exhaust gas aftertreatment system depends on the engine-out emission level. Meeting future NO_x and PM standards with SCR alone, without a DPF, seems technically feasible. If a DPF is required to fulfill the Stage IV / Tier 4 PM standard an open non-plugging and maintenance-free passive filter system, (e.g. POC), could be used as the preferred PM aftertreatment device as an alternative to the wall flow DPF, because the latter requires active regeneration means as an absolute must. However, political decisions may make it necessary to use a wall flow DPF.

In **Figure 6** a schematic diagram of a DPF combined with an SCR system is shown in comparison to the configuration of a passive filter upstream an SCR system. Gener-

ally the arrangement of the PM reducing device, which is upstream the SCR system, is not mandatory but seen as the main trend today. Obviously such complex systems require a high degree of control functionality for their PM regeneration, continuous NO_x reduction and the interaction between the subsystems. By using a passive filter instead of a wall flow DPF, the extent of control functions as well as the effort necessary to calibrate these functions can be reduced significantly.

In this context, the use of fuel with an ultra-low sulphur content is a must in conjunction with exhaust aftertreatment systems, and its lubricity needs to be ensured to prevent any wear problems on the Fuel Injection Equipment. The use of low-ash lubricating oil for providing sufficient DPF durability and acceptable DPF cleaning intervals in the field is just as important.

4 Specific Constraints for Non-Road Applications

Many aspects are different in the non-road industry compared to those of on-highway industry. This may lead to different technological choices. These choices may even vary depending on the machines where they are installed. It is too easy to think that on-highway technologies will work satisfactorily in non-road applications without significant adaptations. The results of the on-highway field experience will provide valuable inputs for the development of the solutions specific to non-road applications and to ensure reliable products once the products are introduced on the market.

Some of the market requirements for non-road engines vary depending on the application as shown in **Figure 7** and **Figure 8**. These requirements also differ depending on the machine size. While small equipment tends to be very sensitive relating to the sales price, life cycle cost is more important for larger equipment. Hence the balance between optimizing fuel consumption and machine cost is different, which is a big influencing factor for the selected technology. For equipment in the power classes 37 to 75 kW, in particular, there will be a big pressure on the engine and equipment manufacturers to choose cost optimized solutions and to come up with user advantages to reach market acceptance.

One consequence of the introduction of aftertreatment systems may change the engine supply business to a certain extent. Traditionally the exhaust system and its in-

stallation were up to the vehicle manufacturer. In view of the upcoming regulations, any aftertreatment systems will be part of the certified engine, and hence the exhaust system installation will require intensive cooperation between the engine and vehicle supplier. In many cases the degree of freedom for the installation will be largely reduced. A new intensive field of activity will be introduced to the industry: the application and calibration of the aftertreatment systems.

Another aspect should be considered carefully during the development of future engine and aftertreatment system technologies, and this is the dynamic response behavior of the engine. The duty cycles of non-road engines can be highly dynamic, showing very sudden increase of torque demand. The experience with Tier 3 engines showed that this is a highly important criterion for the end users while engine developers may easily get carried away with the development to meet the emission targets.

5 Evaluation of Critical Items and Daily Use Challenges

5.1 Packaging of Aftertreatment Systems

Most NRMM are characterised by very strict space constraints, i.e. a very compact design. This means very limited space is available for the integration of exhaust aftertreatment systems. Nevertheless, the size of each of the DPF and the SCR catalysts is about 1.5 to 2 times of the engine displacement, depending on the particular emission mass flow. Additionally the SCR system requires space for the pump module, the dosing unit and the tank for the urea water solution. The size of the urea water solution tank depends on the engine-out emission level of the duty cycle, the appropriate NO_x conversion rate of the SCR catalyst and the refilling strategy. Assuming an engine-out NO_x emission of 2 g/kWh, which is expected for Stage 4 / Tier 4, and the fact that urea-water fuelling is not required earlier than every second of diesel fuelling, a urea water tank volume of approximately 3 to 5 % of the fuel tank volume is necessary. Finally, packaging constraints are seen as the strongest driver for minimizing the needed aftertreatment volume by minimizing the engine-out emissions.

5.2 Exhaust Temperature Level in Duty Cycles

NRMM engines are offered with a large variety in specific power output and applied

for different duty cycles. As a consequence, exhaust temperatures as well as exhaust mass flow rates can vary significantly for a given engine size. To illustrate the broad variety of the different real-life duty cycles, the distribution of the exhaust temperatures downstream of the DPF for various duty cycles estimated on steady state measurement results is depicted in **Figure 9**. The wide range of exhaust gas temperatures during real-life duty cycles is clearly detectable. As a consequence, the worst case operating conditions cannot only be defined by the certification test cycle but also by the real-world duty cycle.

5.3 Engine Operating Challenges

Figure 9 clearly indicates that there are some applications which are mostly operating at low load. In these applications, continuous DPF regeneration by NO₂ cannot be realized, so active regeneration is a must after achieving the soot loading limit of the DPF.

The efficiency of the SCR system mainly depends on exhaust gas temperature and space velocity. The large variety of the exhaust gas temperature results in a large spread of AdBlue consumption in real-duty cycles with a severe impact on the refilling interval of the AdBlue Tank.

5.4 AdBlue Infrastructure

AdBlue is currently widely available on gas stations in Europe but also at most home bases of shipping companies. However, fuel tanks of non-road mobile machinery are usually not refilled at these stations so that different refilling strategies have to be chosen. Depending on the AdBlue consumption of the specific application, it is possible to refill AdBlue by using bottles or small canisters (e.g. on small skid steer loaders on construction sites). For larger machines which are operated at the same place for a longer time, AdBlue tanks have to be positioned at the operating place. Tractors and harvesters can be refilled at the farms. The refilling strategy of harvesters is especially critical since harvesters are often operated for a rather short period of the year and will then stand still until the next harvest season. Since the distributors say the AdBlue storage time is less than 6 months, the AdBlue tank should be emptied at the end of the operating season in such applications.

5.5 Mis-Fuelling with High-sulphur Fuel and Water

High-sulphur fuel causes poisoning of the oxidation catalyst and hence the loss of the CRT effect and SCR catalysts can be poi-

soned by ammonia sulphates. So Mis-fueling with high-sulphur fuel can cause a failure of the exhaust aftertreatment system and has to be avoided.

The SCR system will not be damaged by water only, NO_x reduction will only be significantly reduced by refilling water or diluting AdBlue. However, SCR systems will be damaged by filling fuel into the AdBlue tank.

5.6 Exposure to Dust and Dirt and Mechanical Vibrations

Non-road mobile machinery is often exposed to a dusty and dirty environment. Additional filters serving to remove dirt from AdBlue and the fuel have to be installed and exchanged at regular intervals. Some machines, (e.g. harvesters), are operating in an environment with highly combustible dust. Ignition of this dust at hot engine components or exhaust gas, (e.g. during DPF regeneration), has to be avoided.

Non-road mobile machinery is often cleaned by using high pressure washer so that all connectors and tanks need to be sealed very well. As compared to on-road applications, non-road mobile machinery experiences heavier impacts and mechanical vibrations. The exhaust aftertreatment modules, (e.g. catalysts, dosing systems), need to withstand this high mechanical stress.

6 Summary and Conclusions

The technologies helping to meet EU Stage IV and EPA Tier 4 emission legislation are generally available. All these technologies have already been introduced, and their combinations will be introduced in production in on-road applications soon. However, a simple transfer from on-road to non-road applications is not possible.

The technologies have to be adapted to meet off-road conditions. The components do not only need to withstand extremely high stress but also dirty and dusty environment. Furthermore, it is necessary to develop new packaging concepts for the engine, engine cooling and exhaust aftertreatment.

Special solutions are not only required in view of the costs but also due to boundary conditions specific to non-road applications. Main drivers are the large number of different machines in different markets and comparable low production volumes. Standardization is required to minimize the commercial impact not only on the industry but also on the final customer.

A phase-in of new legislation and a step-by-step introduction of new technologies

will help to develop low-emission and high fuel economy engines with respect to durability and costs. It will also help smaller manufacturers, especially those which do not have access to on-road experience.

Last but not least, the final customer and the user will have to accept the complexity of the engines and also maintain the machine properly so that the investment in new engines is cost effective. ■