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Latest Developments in Low-emission Diesel Engines and Exhaust After-treatment for Tugs and Workboats

Sebastian Schwarz, **Dr Marc Hehle**, **Christoph Glowacki**, **Ralf Speetzen**,
MTU Friedrichshafen GmbH, Germany

SYNOPSIS

Owing to new regulations, emission limits not only for road vehicles but also off-road applications will have to decrease dramatically in the near future. This means major investment will be required to develop new technologies.

The development of MTU's key technologies for diesel engines that take into account future emission limits will be discussed. The focus will be on new innovations, such as the Miller cycle valve timing, which has been implemented with the new generation of Series 4000 for workboats. Discussions will include exhaust gas after-treatment devices such as Selective Catalytic Reduction (SCR) and Diesel Particle Filters (DPF), as well as an overview of actual projects and recent experiences in field testing.

1. EMISSION REGULATIONS

Exhaust emission regulations for mobile or stationary combustion engines cover admissible limits for nitrogen oxides (NOx), particle matters (PM), hydrocarbon (HC), carbon monoxide (CO) and sulphur oxides (SOx).

Although several national and regional emission regulations exist currently, it is obvious that the following regulations must be noted regarding trends for diesel engine technology:

IMO MARPOL 73/78 Annex VI;
US-EPA;
Non-road regulation 40-CFR 89 ,1039;
US-EPA Marine regulation 40 CFR 94, 1042;
Locomotive regulation under 40 CFR part 92,1033;
Stationary compression-ignition regulation 40 CFR part 60, subpart IIII;
EU Non-road regulation 97/68/EC (amended by 2004/26/EC), applicable for non-road mobile machinery, rail and marine applications.

IMO MARPOL emission regulations came into force in 2000, initially limiting exhaust emissions of NOx. *Table 1* describes IMO NOx emission limits and introduction dates. By 2011, the admissible NOx emissions on newly-installed engines will decrease by approximately 20 per cent and in 2016, Tier 3 will further reduce the limit in emission controlled areas (ECA) by approximately 80 per cent, compared to Tier 1. (*See Table 1 at end of paper*).

Marpol Annex 6 also specifies limits for sulphur content of marine fuel. *Table 2* gives an overview of the sulphur limits globally and in ECAs; figures beyond 2015 will be reviewed in 2018.

Date	Sulphur limit in fuel	
	Global	ECA
2000	4,5 %	1,5 %
2010		1,0 %
2012	3,5 %	
2015		0,1 %
2020 *	0,5 %	

* final date subject to review

Table 2: MARPOL Annex VI fuel sulphur limits.

The emission regulations established by the US Environmental Protection Agency (EPA) specify emission limits for NOx + HC, PM and CO for marine engines with less than 30 litres per cylinder, covering both commercial and recreational vessels.

For marine applications, the limits or effective dates vary as functions of total engine power, power density (as of EPA Tier 3) and cylinder displacement. EPA Tier 4 does not apply to recreational vessels and engines with rated power <600kW. For US EPA regulations, the reduction of NOx and PM limits in comparison for marine and non-road applications from 2000 to 2016 is shown in *Figure 1 (see end of paper)*.

The described non-road applications face more stringent limits and earlier introduction dates compared to marine applications. Nevertheless, from EPA Tier 1 Marine (=IMO MARPOL NOx emissions) in 2000 to EPA Tier 3 coming into force in 2012, a reduction of NOx emissions by more than 40 per cent will be achieved. Forecasts are that high-speed marine diesel engines can meet EPA Tier 3 with measures internal to the engine. With EPA Tier 4 coming into force in 2014-2017, there will be a NOx-reduction of more than 80 per cent compared to that of Tier 1. Such reductions will definitely require major technological research and development. Additionally, several classification organisations have established notations assigned to vessels with reduced environmental impact. For propulsion and auxiliary engines they typically imply limits for NOx and SOx.

2. TECHNOLOGICAL DEVELOPMENTS FOR LOW EMISSION DIESEL ENGINES

Technologies

To meet planned emission limits, new technological developments are needed. As a result, alternative approaches have been investigated which, basically, can be divided into two groups:

1. Internal methods, ie integrated inside the engine;
2. External techniques, ie located downstream from the engine.

Figure 2 gives an overview of the two groups: within the internal methods, there are developments such as the Miller cycle valve timing[1] or exhaust gas recirculation (EGR), while the external techniques comprise Oxidation catalysts, Selective Catalytic Reduction (SCR) as well as Diesel Particle Filters (DPF). Each of these techniques aims at reducing the end-of-pipe emissions and a selection will be discussed later in Section 4.

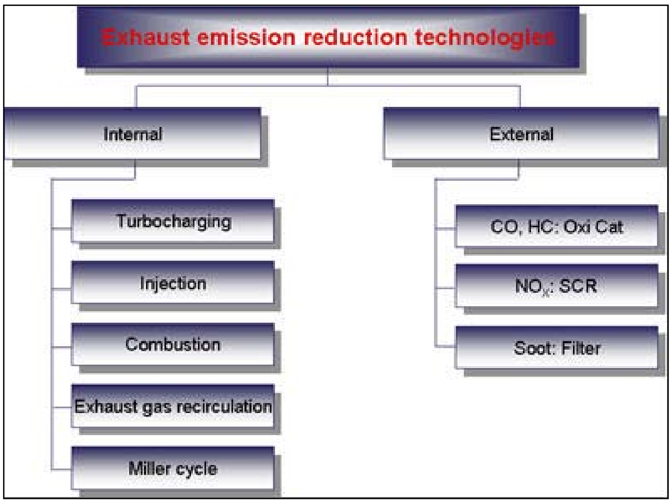

Figure 2: Overview of exhaust emission reduction technologies.

Fuel injection

To reduce particle emissions, in the past 10 years common rail (CR) injection technology has been introduced in off-highway applications, as well as in most on-highway vehicles. CR injection gives a wide range of options of varying the injection timing and is one of the key features in limiting future emissions. Recently, the injection pressure has been increased significantly: for example MTU's first CR-System, which had already been introduced to the market in 1996, was running at 1,200 bar. The actual system, known as LEAD (low emission advanced design), is running at 1800 bar[2]. Actual pressures in on-highway applications are up to 2,500 bar, and so it can be calculated that the CR-pressures will also increase in off-highway applications.

In addition to the high pressures, multiple injections are already in focus today. Especially for future technologies, such as new combustion processes or engine-internal soot reduction, pre- and post-injection will be necessary. This affects the special requirements of the injection system including, for example, reliability. Well designed, fully developed and reliable systems are therefore essential to meet the specific needs of the application. MTU uses the in-house expertise within the Tognum group provided by l'Orange in designing and producing injection systems for its high speed engines. Common rail injection systems are also chosen for medium-speed diesel engines running on heavy fuel oil (HFO)[3].

NOx-reduction

With regard to NOx-emissions the main goal is to reduce the combustion temperature within the cylinder. In the case of internal engines, this can be achieved either by exhaust gas recirculation (EGR) or by using a Miller cycle valve timing. When using EGR, a certain amount of exhaust gas is cooled and fed back into the intake manifold which then acts as inert gas in order to reduce the combustion temperature. The EGR technology has been successfully tested with the Series 4000 on test bench and in rail application with more than 5,000h.

The Miller cycle works differently, whereby the intake valve is closed before bottom dead centre (BDC) so that the air inside the cylinder expands before compression and is cooled by that measure. The main benefit of the Miller cycle is that it has only a minor impact on the engine hardware.

Turbo charging and combustion technology will be discussed in the following section.

3. SERIES 4000 M63 FOR WORKBOATS – DEVELOPMENT AND TECHNOLOGY

The Series 4000 M63 diesel engine has been developed with focus on workboat applications such as tugs. Considering the current emission regulations EPA Tier 2, EUIIIA and IMO Tier 2, the main engineering targets can be summarised as follows:

- Durability;
- Minimum fuel consumption at rated power and part load;
- Wide performance map;
- Agility and transient behaviour;
- Maximum maintenance intervals.

Engine technology features

Thermodynamical and mechanical concepts to fulfil the engineering targets include the optimisation of:

- Cylinder displacement volume;
- Valve timing (Miller cycle):
- Turbo charging;
- Cooling concept;
- Basic MTU diesel engine technology.

Cylinder displacement volume

Rated power at rated speed was realised with reduced cylinder stress by minimising the mean effective pressure (*Figure 3*). This was achieved by increasing the cylinder displacement by approximately 17 per cent compared to the previous engine. This results in a less demanding turbo charging system, as well as an extended degree of freedom for the engine tuning process, and converted into fuel consumption benefits and engine performance advantages such as torque characteristics.

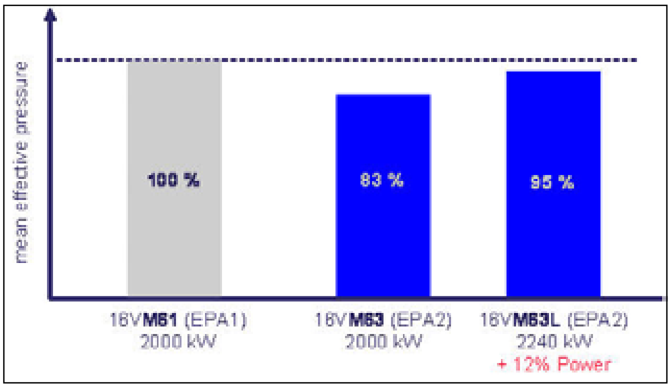

Figure 3: Mean effective pressure M63 compared to M61.

The reduced mean effective pressure allows for an increased compression ratio without increasing engine stress through peak cylinder pressure. This advantage leads to an improved engine (cold) start capability.

Valve timing (Miller cycle)

Different design studies for workboat engines and emission law limits were compared and evaluated. Among these, EGR (Exhaust Gas Recirculation) and advanced valve timing were the most favourable. The advantages of the valve timing technology are: minor design changes only; no additional components; conventional proven technology and lower engine heat loss. This leads to the obvious technical conclusion to develop the new Series 4000 workboat engine without EGR but with a Miller cycle.

The M63 engine camshaft and valve system are based on the classical Series 4000. A significant difference is that the new engine has an adapted valve cycle. The inlet valve is closed earlier (Miller), meaning a lower temperature in the cylinder and, further, a reduction of the NOx formation. Based on this physical property, the NOx emissions could be adjusted in the engine tuning process appropriate to the emission law limits in combination with reduced fuel consumption. *(See Figure 4 at end of paper).*

Meeting the legal NOx emission limits without these measures (eg by means of slowing down the combustion timing only) would result in considerable fuel consumption penalties.

The new MTU workboat engine design and thermodynamic technology leads to optimised fuel efficiencies, both in part load and full load operating range.

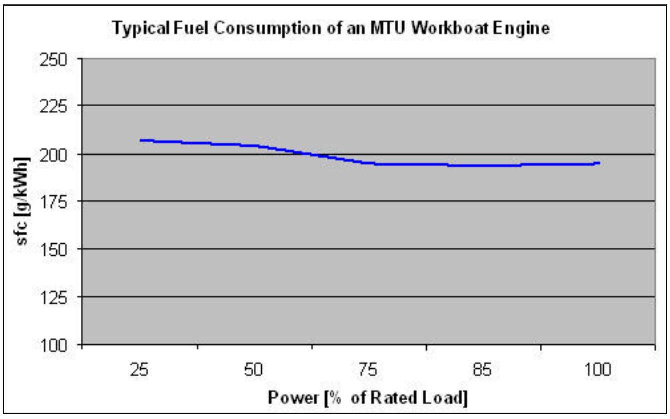

Figure 5: Typical MTU workboat engine fuel efficiency.

Turbo charging

The Series 4000 engine uses the technology of sequential turbo charging, where the engine runs from idle to medium load with only one turbo charger and up to a rated load with an additional, second turbo charger. The cumulative advantage of this is a wide performance map, particularly at medium speed.

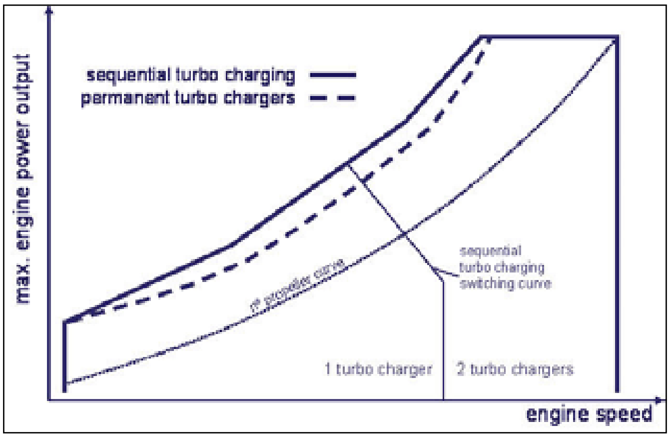

Figure 6: Engine performance map with sequential turbo charging.

This concept also offers benefits in fuel consumption because the compressor operating range can be limited to high efficiencies. The reduced air flow at high loads helps to avoid extensive measures to secure SOLAS surface temperature requirements (max. 220 degrees C) in the charge air system. Large insulation packages, which can be easily damaged, are not needed. Compressor and turbine characteristics and efficiencies were calculated and optimised in-house by means of computational fluid dynamics (CFD) , thus resulting in an optimised charge air and exhaust gas system configuration. *(See Figure 7 at end of paper)*.

Cooling concept

The engine cooling system has a significant influence on the charge air temperature, the component or structural temperature and the oil system. The Series 4000 concept can be adapted to different types of cooling systems by simple design changes, eg one or two circuit cooling systems. For the M63 engine, a split circuit cooling system was chosen with the ability of keeping the engine operating temperatures within the optimum range, even for low ambient temperatures or low engine load, when the charge air cooler acts as a heat exchanger to warm up the cold air intake. The advantage of this is that the engine can be operated at optimum conditions, eg specific fuel consumption (sfc), keeping a low emission level (UHC). The charge air cooler size was optimised for additional benefits in sfc with the designed charge air temperature.

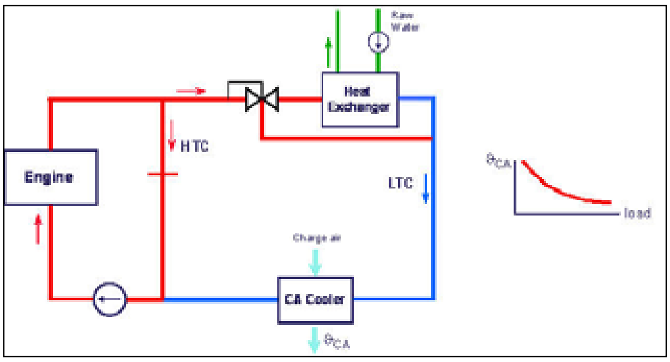

Figure 8: Split-circuit cooling system with a high temperature circuit (HTC) and a low temperature circuit (LTC) to optimise both engine cooling water temperature and charge air temperature for low NOx emissions.

Basic MTU diesel engine technology

The M63 engine contains a number of components, features and concepts from different heavy-duty applications, such as in rail or mining, where engine functions and durability have been tested and proven. Some parts, eg the piston and injector, have the most direct impact on combustion, operating data and emissions. These (and other) key components were optimised for engine performance in marine workboat applications, with only minor changes to their existing format. The basic engine components (including the drive and crankcase) and the engine management system, ADEC, also share a common platform with the rail and industrial applications (*See Section 4*).

4. FURTHER DEVELOPMENTS – EXHAUST GAS AFTER-TREATMENT

In order to keep within future limits of exhaust emission beyond Tier 3, several processes can be considered. Besides the engine-internal measures (which have already been outlined in previous sections) engine-external measures, such as exhaust after-treatment, offer extensive potential to achieve remarkable emission reductions.

NOx reduction

One technique to reduce the NOx-Emissions is the selective catalytic reduction (SCR), whereby urea is injected in the exhaust system and catalytically converted to ammonia, which is able to reduce the NOx by forming N2 and H2O. A representation of the process is shown in *Figure 9*. One of the advantages of the SCR technology is that it offers the possibility of enabling an engine calibration which is fuel-consumption optimised (with higher engine-out emissions for NOx) and realizing the NOx-reduction engine-external by using a SCR system. With this approach there is some potential to reduce the engine's CO2-emissions, even if the CO2-emissions caused by the production of the reducing agent are considered. Applications with frequent and fast variations of engine load or speed require an advanced control strategy for the urea dosing.

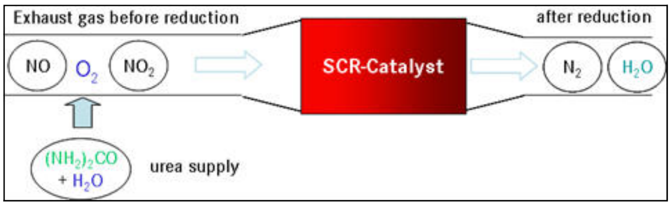

Figure 9: Working principle of the SCR-System.

Particle reduction

During combustion, soot particles are formed and, as these are subject to legislation, care has to be taken by the engine manufacturer. The use of diesel particle filters (DPF) is one approach, as well as increased injection pressure as an engine-internal measure. Here, the focus will be on DPFs. The working principle of a DPF is shown in *Figure 10.* Soot from combustion and ash particles, resulting from oil additives in the exhaust gas, are deposited when the gas flow passes the porous filter walls. One of the main challenging topics is the regeneration of the DPF as the pressure drop increases when loading the filter. As this pressure drop causes an increase in fuel consumption, the aim is to keep this increase as small as possible by regenerating the filter at intervals. The regeneration can be either active or passive. The basic principle is to create conditions for the oxidation of the soot particles. In the case of active regeneration this could mean a burner, while passive regeneration can be carried out, for example, by the use of a fuel-borne catalyst which reduces the oxidation temperature of soot. In any case, ash has to be removed at certain service intervals, which has to be considered when designing maintenance plans.

Exhaust gas after-treatment systems have, depending on the design and materials, sound attenuation properties which allow either downsizing or replacement of the exhaust silencer. The use of the described emission reduction technologies in field tests will be discussed in the next section.

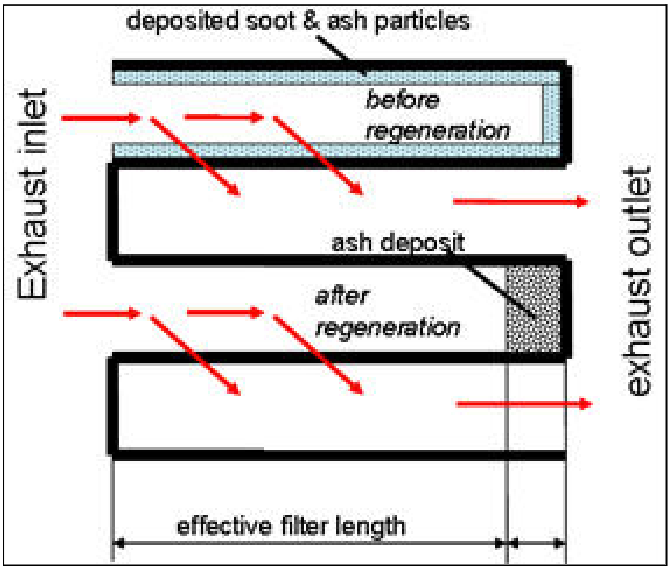

Figure 10: Working principle of DPF.

DPF technology and experience of inland cargo vessel

The following describes the exhaust after-treatment system of inland cargo vessel ***Willi Raab***, which has been repowered with a Tier 2 engine combined with a DPF. The objective of the field test programme initiated by the German Federal Ministry of Transport, Building and Urban Affairs (BMVBS) is to gather field experience on the filtration efficiency, operating and maintenance costs, as well as the general impact on vessel operations. Up until now ***Willi Raab*** has accumulated more than 2,000 hours with the new installation.

Operating profile and regeneration concept

Typical load profiles for ship-assist tugs have extended periods with part-load and little operation at rated power. Average load factors are usually below 60 per cent of rated power. Despite the fact that coastal and inland freighters are typically considered as continuous duty applications with high/average load factors, the example here underlines the importance of knowing the real operating profile.

Figure 11 (see end of paper) shows the recorded load profile of ***MGS Willi Raab*** up to November 2008 with a total of 1,800 operating hours. The load profile is also characterised by high percentage of idle operation and part load. This naturally depends on the operating area of the vessel, typically comprising navigation up and down the rivers, in canals and with regular stops in locks.

For the explanation of the selected soot regeneration method, the engine load profile is transformed into a profile operating time over exhaust gas temperature. *Figure 12* shows an example of the accumulation of one month. Since the minimum temperature for soot oxidation is approximately 430 degrees C, the accumulated operating time at high exhaust temperature enabling passive regeneration is only 15 per cent, hence an active regeneration system with fuel burner has been chosen to ensure a safe operation and regeneration, regardless of engine load or speed.

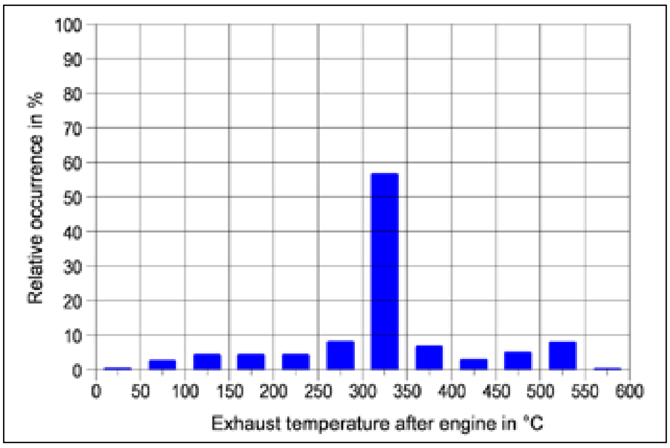

Figure 12: Engine load profile as operating time over exhaust gas temperature.

DPF design and installation

The key criteria for the DPF concept and design were:

- Maximum operational safety, in particular with single engine propulsion;
- Available space in the engine room, considering limitations in case of re-power;
- Fully automatic control and monitoring, therefore no disturbance of captain and crew.

Figure 13 shows the DPF system comprising filter housing with 10 cylindrical filter elements, large service opening and emergency bypass with silencer and spark arrestor. The fuel burner has been designed as a separate unit installed under the DPF owing to the particular installation situation of this repower. The entire unit has been fitted in the space of the originally installed exhaust silencer. The ship control and monitoring system has integrated the DPF parameters to the monitoring of the engine and propulsion unit, which provides the captain with basic information on the DPF status, eg time remaining to next regeneration, emergency bypass status.

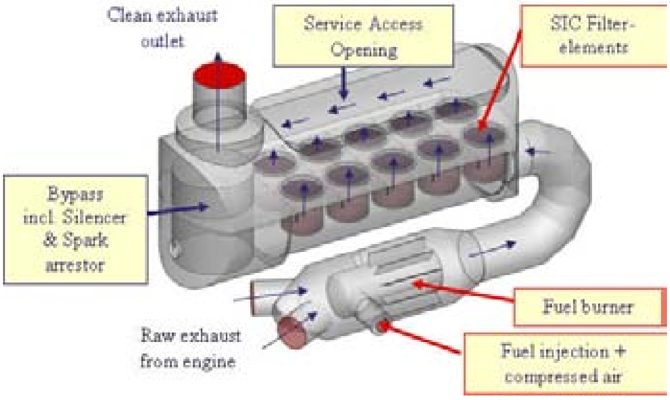

Figure 13: 3-D illustration of the DPF system ***MGS Willi Raab.***

During the field test, the operating and maintenance costs will be tracked and evaluated. Maintenance costs are affected by the burner fuel consumption, slight increase of the engine fuel consumption and electric power for DPF- auxiliaries such as the compressor. Key maintenance tasks are ash removal (designed for annual servicing, approximately 6,000 hours) and burner inspection. Low saps engine lube oil is recommended to minimise the accumulation of ash in the filter elements.

Diesel particle filter with passive regeneration

DPF Systems with passive regeneration might be selected for applications if the operating profile provides regular and sufficiently long periods with high exhaust temperature for continuous oxidation of the soot. Typical applications include ferries or railcars with distinct operating areas and timetable.

"Cleanest Ship" *MV Victoria* with DPF and SCR

MV Victoria, a BP-owned and operated tanker for inland waterways, was chosen as a demonstrator for emission reduction technology. The project was funded by the European Commission. As well as the combined exhaust gas after-treatment system, comprising a DPF and an SCR, the vessel is operated with low sulphur fuel EN 590, with a sulphur content of less than 10 ppm. The ship currently has more than 6,000 operating hours, and the expected emission reductions of particles, NOx, and SOx can be confirmed (see Table 3).

	NOx	PM	Fuel C.	CO2
SCR Selective Catalytic Reduction	-85%	none	none	none
DPF Diesel Particle Filter	none	-95%	+2%	+2%

Table 3: Expected effects on emissions of the components installed on ***MV Victoria****.*

The 8V4000 common rail engine, combined with the low sulphur fuel, already gives low emission levels. The additional installation of such a comprehensive exhaust gas after-treatment system and its integration with the engine's control system yields unprecedented low emissions. So far, the operating experience endorses the design, and will also provide indications for further optimisation of the total system. The close integration of the engine's electronic control, together with the monitoring and control of the exhaust gas after-treatment system, will produce more efficient, compact, user-friendly, economical and ecological propulsion systems.

CONCLUSION

The move towards stricter emission limits owing to regulations, as well as increasing public awareness, requires the application of various new technologies. For economical reasons, the use of engine-internal measures is, as far as possible, essential, and could satisfy actual and potential legislative controls. Nevertheless, to meet further increasing demands from both, future regulatory requirements (as well as stronger commitments by our customers towards improved ecological effects) will inevitably lead to the use of additional exhaust gas after-treatment systems. It is obvious that such systems will increase volume, costs, and complexity of the installations.

Diesel engine manufacturers are being challenged to integrate core competencies in engine development with the exhaust gas after-treatment, thus mitigating these drawbacks as far as possible. Judging from long-term experience with various field test systems in heavy-duty applications, reliable and well-tested cutting edge technology will be available, resulting in minimal environmental effects at competitive rates.

REFERENCES

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[2] *In situ Calibration – High precision Fuel injection for Off-highway Engines*, M Hehle, M Willmann, J Remele, T Ziegler, G Schmidt G, *ATZextra* June 2008.

[3] *From high speed diesel to medium speed HFO engines - L'Orange platform based common rail pumps fulfil future demands*, R Jorach, H Schneider, A Kerckhoff , O Altmann, *Paper Number 80*, CIMAC Congress 2004, Kyoto.

[4] *Die neue Generation der MTU-Motorenbaureihe 4000*, M Kurreck, W Remmels, M Eckstein, O Bücheler, V Wachter, *MTZ 05/2007, volume 68, pp. 356.*

Table 1: MARPOL Annex VI NOx emission limits.

IMO Tier	Date	NOx Limit, g/kWh				NOx limit g/kWh / reduction to Tier 1 (%) **	
		n<130 rpm	130≤ n <2000	n ≥2000 rpm		n = 900 rpm	n =1800 rpm
Tier 1	2000	17,0	45 · n-0.2	9,8		11,54	10,05
Tier 2	2011	14,4	44 · n-0.23	7,7		9,20 (-20%)	7,85 (-22%)
Tier 3 *	2016	3,4	9 · n-0.2	1,96		2,31 (-80%)	2,01 (-80%)
* Only in NOx Emission Control Areas (Tier 2 standards apply outside ECAs). ** Emission limits for typical engine speeds of medium & high speed diesel engines							

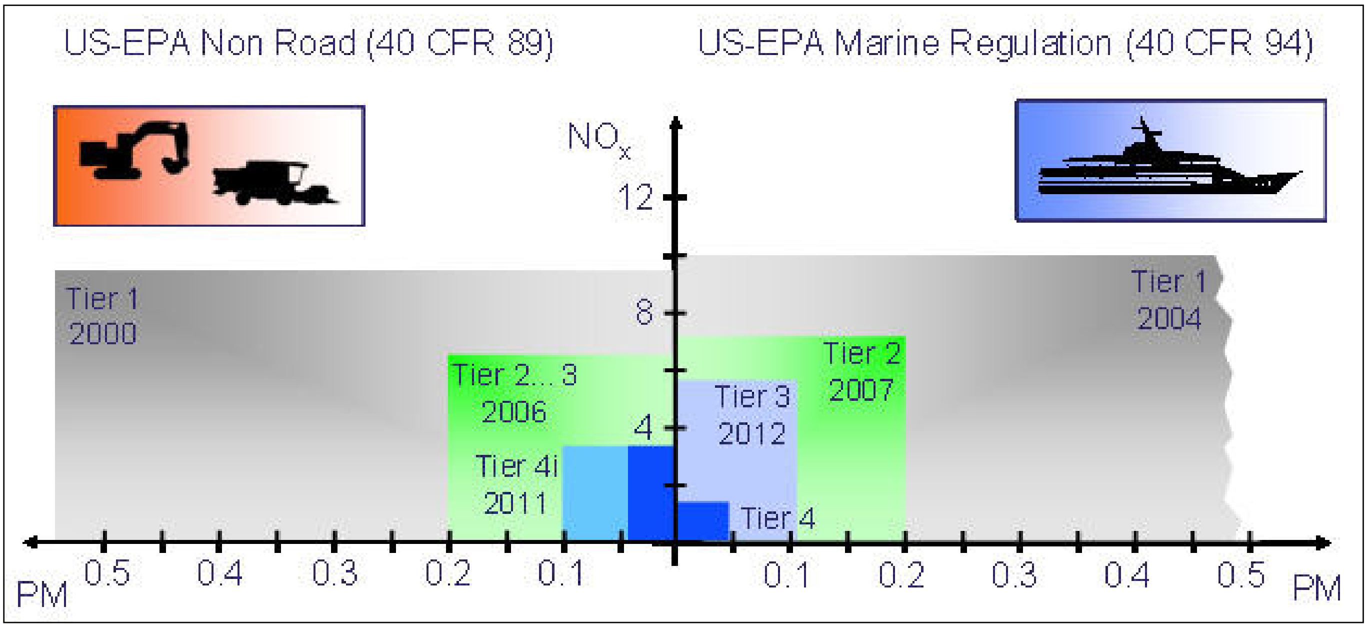

Figure 1: Comparison of EPA emission regulations for non-road vehicles and marine applications, in the case of an engine of category C1- 4 l/cyl, standard power density, P >560 kW.

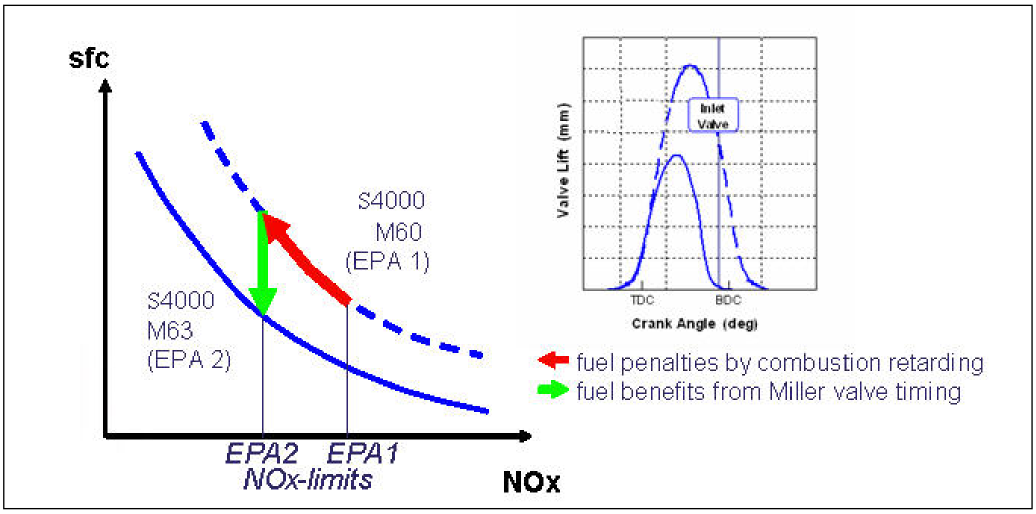

Figure 4: Trade-off NOx/sfc, effect of Miller valve timing on specific fuel consumption (sfc).

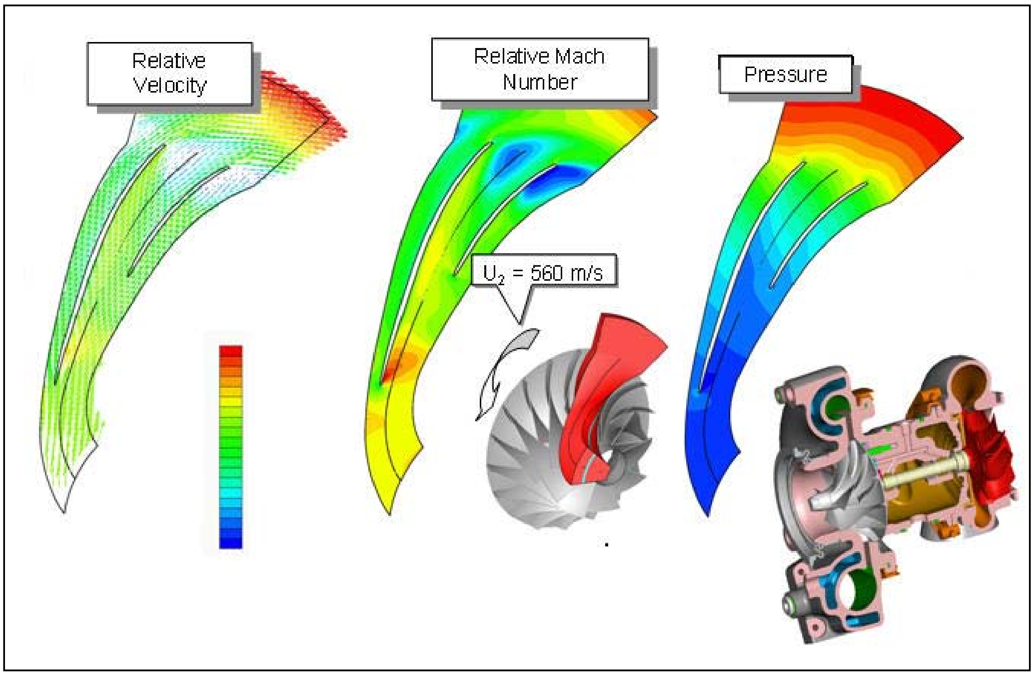

Figure 7: Optimising a compressor wheel by computational fluid dynamics (CFD).

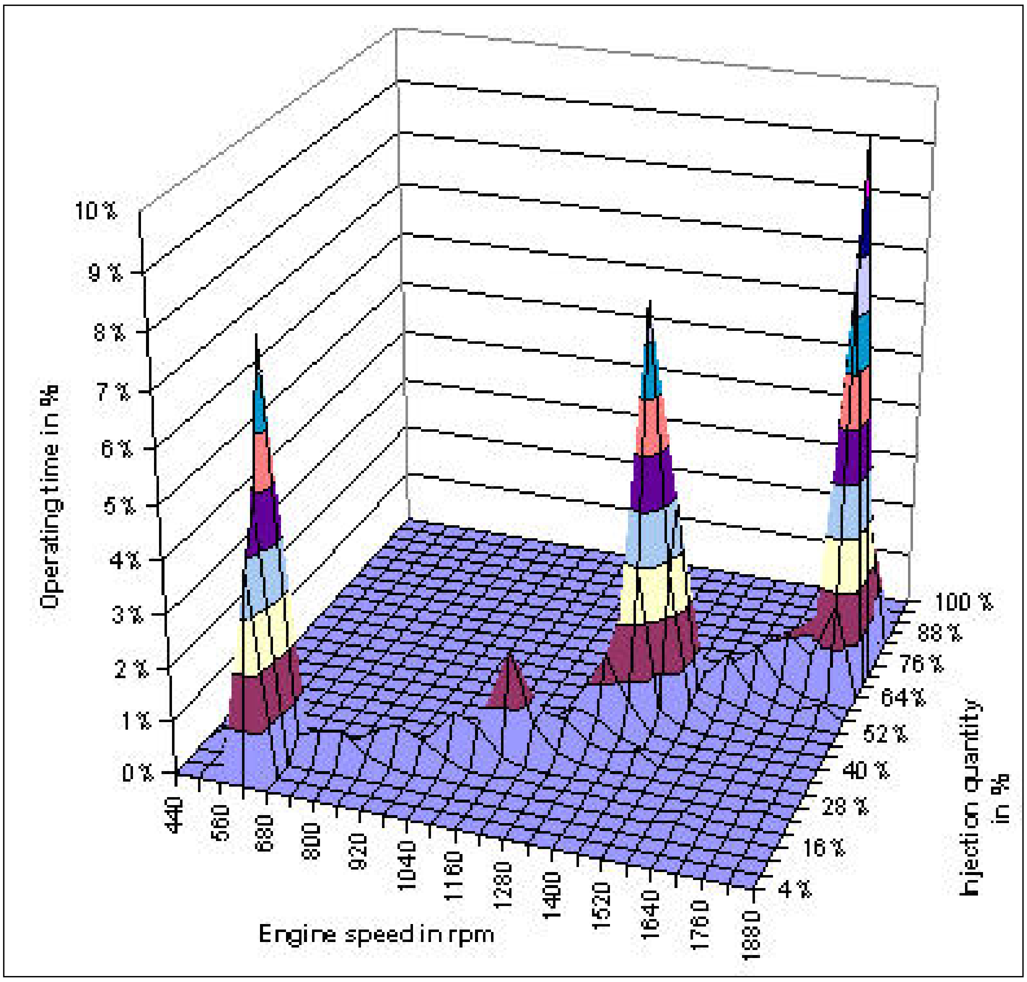

Figure 11: Load profile main propulsion engine of ***MGS Willi ++****, total 1,800 hours up to November 2008.*