New Generation of the Liebherr Diesel Engines D934 / D936, Fulfilling Stage IIIB / Tier4i Emission Norms with SCR Technology

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ABSTRACT

Liebherr Machines Bulle SA has developed together with AVL and EMITEC a new family of inline diesel engines for its crane applications to comply with Stage IIIB / Tier4i emission requirements, using SCR technology. Based on technology carried over from the actual Stage IIIA, but using a Common Rail Injection system and sophisticated software functionality, engine performance and engine-out emission levels could be improved significantly.

Development and application of an urea-based SCR system was performed to comply well with the new emission requirements as well as offering a competitive fuel economy of the engines.

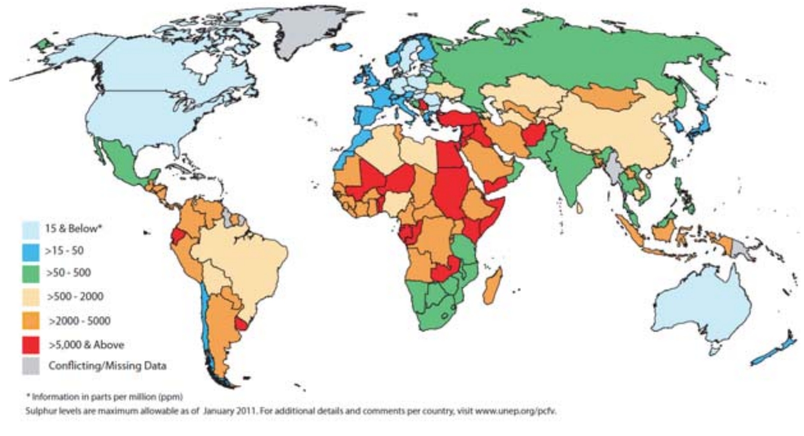


Figure 1 Diesel Fuel Sulfur Levels 2011 **[1]**

INTRODUCTION

Since the beginning of 2011, new Diesel engines for mobile machinery in the power range of 130 – 560 kW have to comply with Stage IIIB / Tier4i emission requirements. It is the first time, that aftertreatment devices will see wide range application in Off-Highway Machinery, with either particulate filters or SCR systems applied to cope with tailpipe emission requirements. Based on market investigations and a collaborative approach with the respective Liebherr sister plants, Liebherr Machines Bulle SA has selected DPF as the main technology path for all Liebherr engines in its earth moving machinery, whilst SCR systems will be applied on the engines powering mobile cranes, crawler cranes, harbour and maritime cranes.

Key driving factor for the EGR / DPF approach for earth moving machinery is the uncertain availability of Diesel emission fluid DEF on each construction site and the compulsory requirement of a particulate filter, if the machinery operates within local emission sensitive areas. On the other hand, SCR technology was chosen for the crane engines, since mobile cranes will be able to use the DEF infrastructure already in place in Europe and the US for On-Highway trucks.

Crawler and harbour cranes see worldwide operation and therefore will be faced with diesel fuels with undoubtedly too high fuel sulfur levels to allow particle filters and EGR systems to survive, **Figure 1**.

COMBUSTION DEVELOPMENT FOR SCR APPLICATION

The Strategy

For the reasons explained above it was decided to apply SCR as the only exhaust after treatment technology for all Liebherr crane engines for all markets requiring EU Stage IIIB or US-EPA Tier4 Interim non-road emission standards, see **Figure 2**.

Product	EAS	Engine	Power [kW]	Cylinder Displacment [L]
Earth Movement 	EGR - DPF	D 834	85 - 120	4.6
		D 934	129 - 175	7.0
		D 936	190 - 270	10.5
		D 946	300 - 390	11.9
		D 9508	345 - 450	16.2
Cranes 	SCR	D 934	129 - 180	7.0
		D 936	250 - 300	10.5
		D 856	350 - 390	12.4
		D 9508	450 - 505	16.2

Figure 2 Liebherr Stage IIIB / T4i engines and applications

An additional boundary for the emission reduction concept was to utilize a modular SCR system using the same key components for all SCR engines. As shown by **Figure 3** in applying SCR for meeting the required NOx and PM standards it is the main challenge of the combustion system to achieve lowest engine-out soot emissions at a NOx target below 8,5 g/kWh in order to prevent an additional diesel particulate filter.

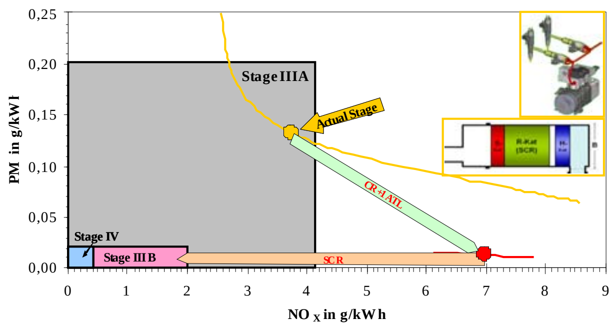


Figure 3 Emission reduction Strategy with SCR

In doing so, the use of a new common rail fuel injection system with high pressure capability was one of the key elements to be introduced. Furthermore, quite a number of additional boundary conditions had to be followed in defining hardware specifications of the D93x CR SCR Base Engine. These refer primarily to parts commonality with Stage IIIA production engine parts as well as with requirements of parallel Stage IIIB/Tier4i DPF engine projects.

Thus, piston and combustion bowl, cylinder head intake swirl, camshafts, turbo-charger (only with different waste gate setting), and intake throttle for thermal exhaust temperature management as well as Common Rail Fuel Injection Equipment (CR FIE) specification had to be maintained, see Figures 4 and **5**.

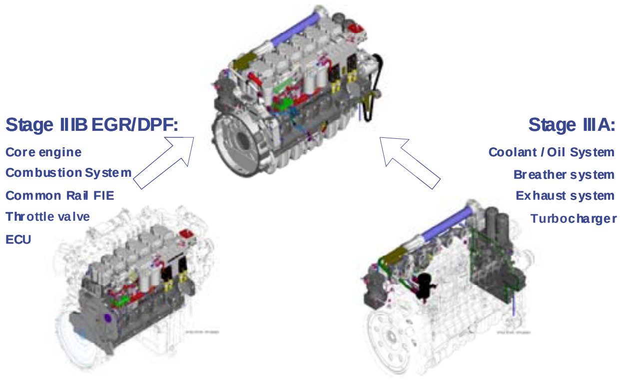


Figure 4 Engine parts commonality with Stage IIIA engine and with Stage IIIB EGR / DPF engine: right engine side

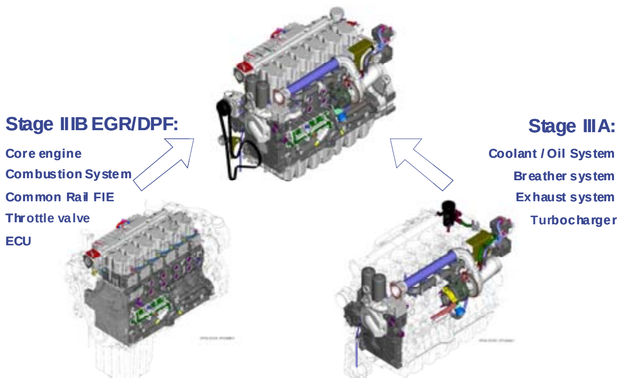


Figure 5 Engine parts commonality with Stage IIIA engine and with Stage IIIB EGR / DPF engine: left engine side

Engine Hardware Specifications and Combustion Achievements

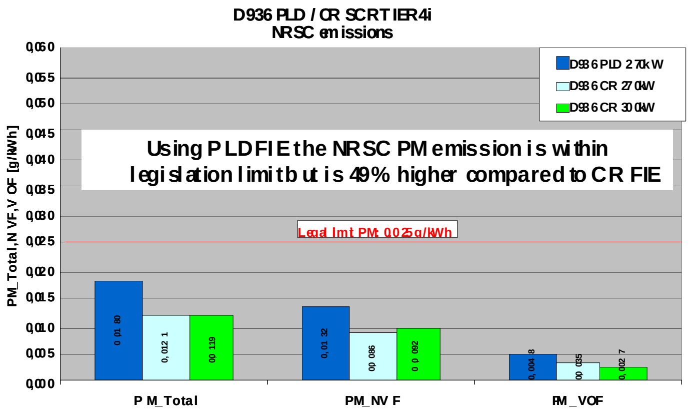
Figure 6 presents a more detailed comparison of the final hardware specifications of Liebherr D934/D936 engines for the Stage IIIA and the new Stage IIIB/ Tier4i engines. It is important to note, that the Stage IIIA engines use a PLD UP20 system with 1800 bar injection pressure capability, whereas the Stage 3B engines use a Solenoid CR system with 2000 bar capability.

D936 Engine HW specification	Stage 3A	Stage 3B / TIER4i
Power	270 kW @ 2000 rpm	300 kW @ 2000 rpm
Turbocharger	K29/3571/14.90	K29/3571/14.90
FIE	Bosch PLD UP20 1800 bar	LMB CR 2000 bar
Nozzle specification	8 x 145° x 840 ml/30 sec	8 x 138° x 650 ml/30 sec
Combustion bowl	Serial bowl	Serial bowl
Compression ratio	17,5:1	17,5:1
Cylinder head swirl	1,2	1,2
Cam shaft	Standard	Standard
EGR system	External EGR	No EGR
SCR after treatment type	No SCR	V2O5 SCR cat

D934 Engine HW specification	Stage 3A	Stage 3B / TIER4i
Power	180 kW @ 2000 rpm	180 kW @ 2000 rpm
Turbocharger	K26/2871/6.81	B2UG/2871/8.81
FIE	Bosch PLD UP20 1800 bar	LMB CR 2000 bar
Nozzle specification	8 x 145° x 840 ml/30 sec	8 x 138° x 650 ml/30 sec
Combustion bowl	Serial bowl	Serial bowl
Compression ratio	17,5:1	17,5:1
Cylinder head swirl	1,2	1,2
Cam shaft	Standard	Standard
EGR system	Internal EGR	No EGR
SCR after treatment type	No SCR	V2O5 SCR cat

Figure 6 Hardware specification of Liebherr D934 and D936 Stage IIIB / T4i SCR engines vs. predecessor engine Stage IIIA

A comparison of PM and NOx emissions achievable with the D936 SCR Tier4i engines (at different power levels) with different FIE, i.e. PLD vs. CR, is shown in **Figure 7** (Non Road Steady State Cycle, NRSC) and **Figure 8** (Non Road Transient Cycle, NRTC).



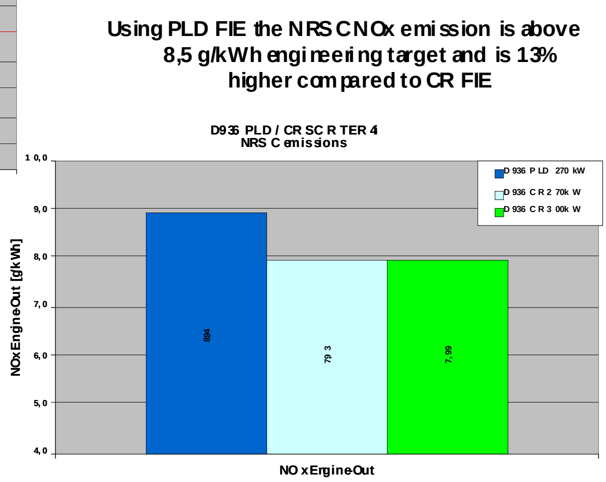


Figure 7 PM and NOx emissions in NRSC, advantage of CR injection system vs. PLD

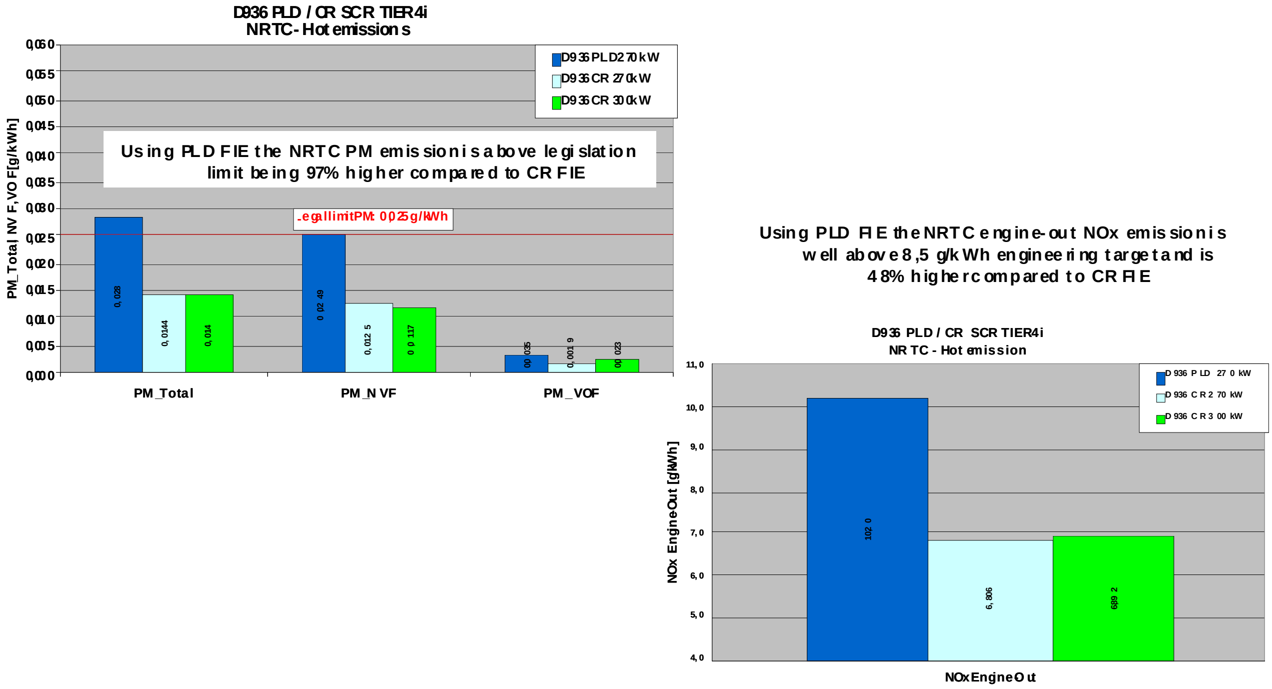


Figure 8 PM and NOx emissions in NRTC, advantage of CR injection system vs. PLD

It is obvious, that at the target NOx-level (8,5 g/kWh in NRSC and NRTC) significantly lower PM emissions are achievable with the CR system in both test cycles. In the NRTC the PLD system yields significantly higher NOx emissions, and PM emissions above the limit. As shown by the injection pressure maps in **Figure 9**, the reason for the higher dynamic soot emissions of the PLD FIE engine is its specific injection pressure characteristic of too low injection pressure at low load over the entire engine speed range. The optimized injection pressure map of the Common Rail FIE (see lower part of Fig. 9) achieves 97 % PM reduction and 48 % NOx reduction in the NRTC compared to the PLD engine. This achievement is of course also a result of the dynamic operation calibration strategy applied to the Liebherr CR system.

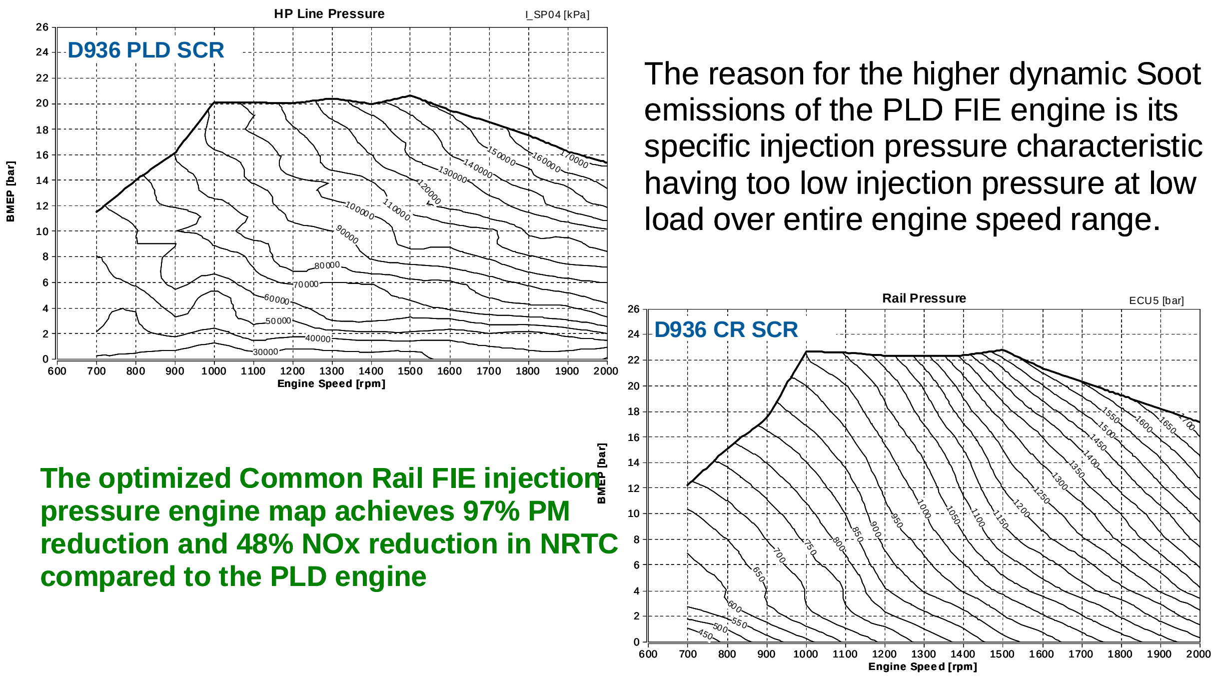


Figure 9 Injection pressure maps of Stage IIIB engine (Common Rail) vs. Stage IIIA engine (PLD)

Calibration strategy for lowest possible PM emission

Besides optimized steady state injection pressure map calibration, following additional dynamic operation strategies were used for achieving the best transient operation NOx / PM trade-off and invisible smoke in vehicle dynamic operation:

- **Dynamic operation rail pressure increase** – during highly dynamic operation, the rail pressure at part load is raised to full load level, so that even at an air excess ratio as low as 1,05 combustion is without visible smoke thus allowing very fast dynamic torque increase
- **Dynamic operation timing retard** – during highly dynamic operation, the start of main injection is retarded up to 3°CA depending on load and engine speed, in order to compensate the higher dynamic operation NOx emission due to the dynamic rail pressure increase
- **Smoke puff limiter over intake manifold pressure signal** was selected due to its flexibility and high effectiveness

It is interesting to note, that due to the dynamic injection pressure and injection timing flexibility of the Common Rail system nearly invisible smoke (less than 6% Opacity) at full load acceleration can be achieved at dynamic air excess ratios as low as 1,05. As a result, the same vehicle acceleration performance is achieved with the Stage 3B engine as with the earlier Stage 3A engine, see **Figure 10**.

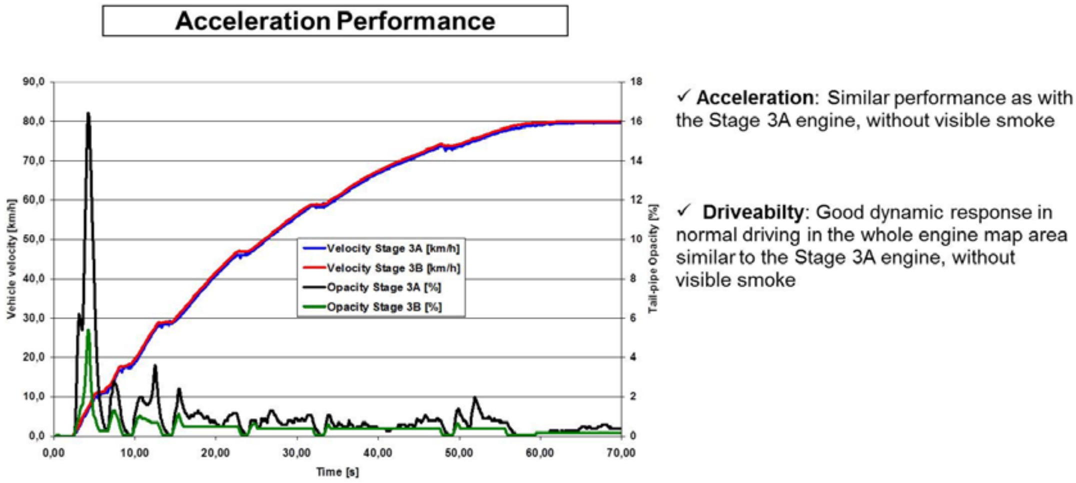


Figure 10 Vehicle acceleration performance and transient smoke emission: Stage IIIB SCR engine vs. predecessor

The dynamic response of the Stage 3B Crane Drive engine (D934 CR SCR TIER4i) is significantly improved compared to the Stage 3A engine, see **Figure 11**. The latter shows the available engine torque improvement 1 second after dip-in of the Stage 3B engine compared to that of the Stage 3A engine.

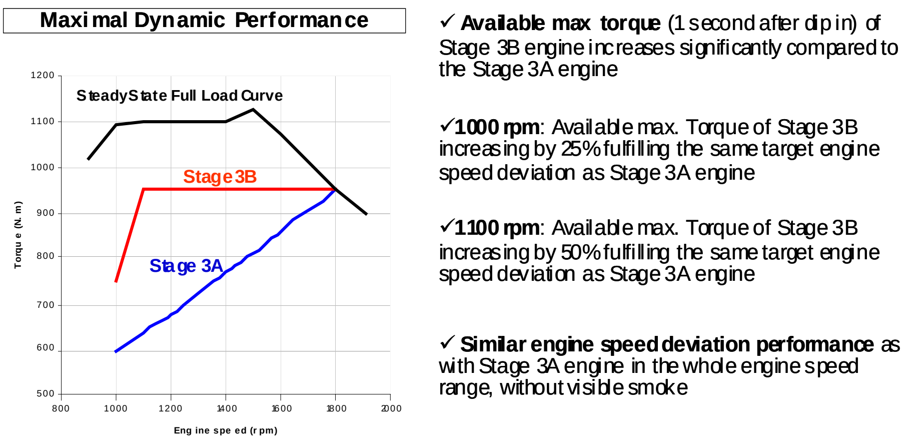


Figure 11 Dynamic behavior of Crane Drive engine: Comparison of Stage IIIB SCR engine vs. predecessor

Exhaust Temperature Management

Once Stage 3B/Tier4i engine-out emission targets have been achieved and successfully demonstrated (see previous Figures 8 and 9) as a prerequisite for the application of SCR systems, it is important to manage dynamic exhaust temperatures to the levels required by the SCR system for sufficient NOx conversion, especially after the engine start at cold engine conditions and at low load conditions, as they typically occur during the last third of the NRTC.

The most effective measure to immediately increase exhaust temperatures is to throttle the air flow.

Figure 12 demonstrates the influence of throttling on exhaust temperatures upstream and downstream of the SCR catalyst during the first time phase of the Cold Start NRTC. By use of the intake throttle valve the exhaust gas and SCR catalyst average temperature are reached and maintained above the target 280°C being required for efficient NOx conversion from the 260th second up to the end of the Cold NRTC.

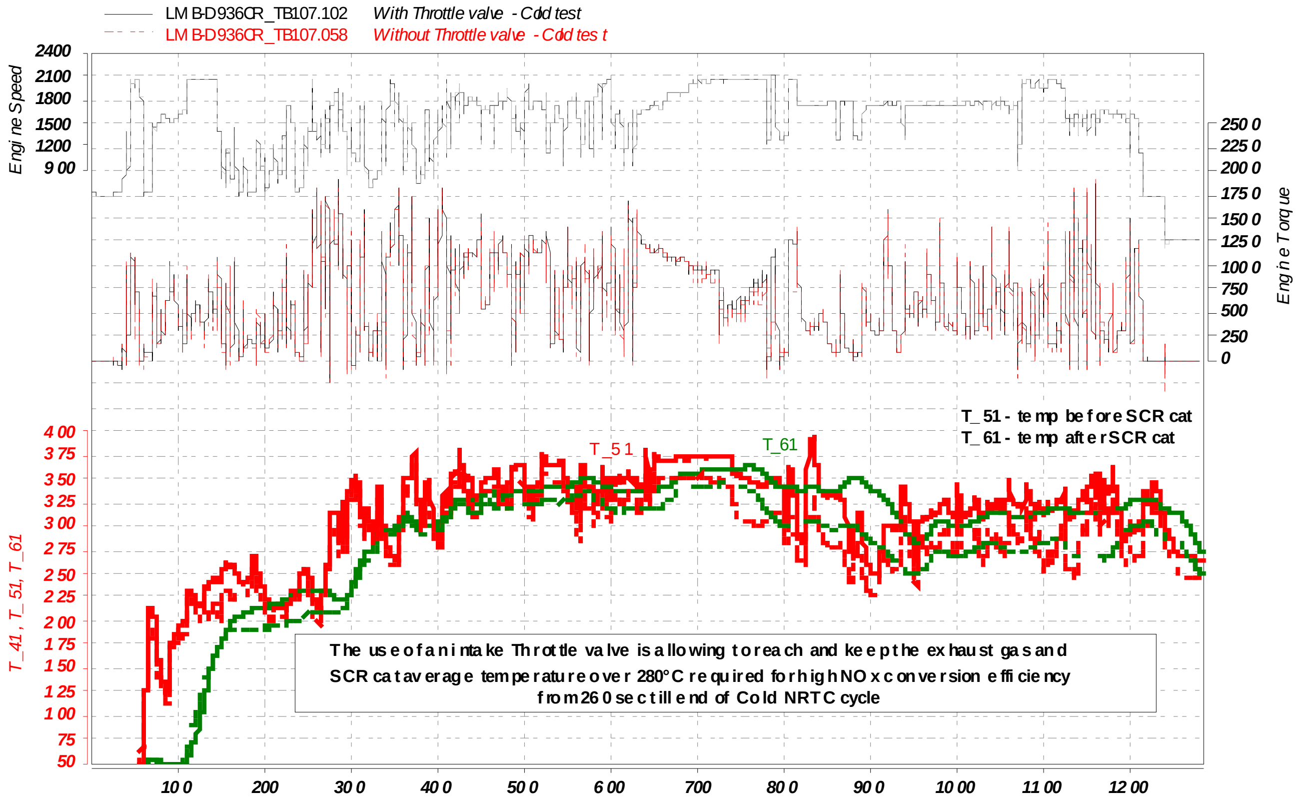


Figure 12 Effect of intake throttling on exhaust system temperatures during cold NRTC

Figure 13 compares the influence of air throttling for the same engine during Cold NRTC and Hot NRTC. It can be seen that by throttling the target 280°C exhaust temperature level is achieved approx. 100 seconds earlier during the hot start test cycle than during the cold start NRTC test.

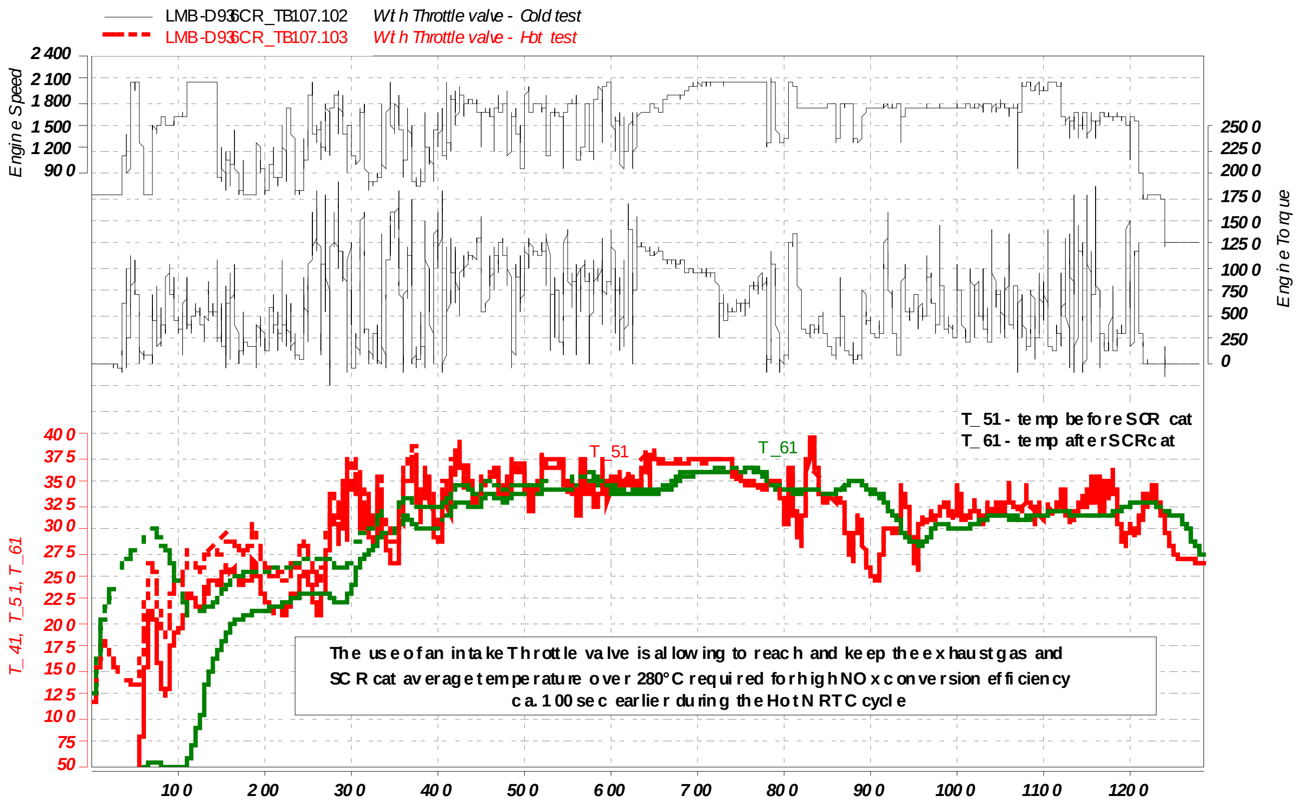


Figure 13 Influence of air throttling in cold and hot NRTC on exhaust system temperatures

SCR AFTERTREATMENT SYSTEM

Components of the Exhaust Aftertreatment System

As described before, a common approach for all Liebherr Stage III-B engines intended to be equipped with a SCR system should be used. A modular system could be achieved using the same urea dosing unit and the same urea injector for all four engines from four to eight cylinders. Two catalyst systems - using an existing canning from the Stage III-B DPF systems - reduce the variety of parts for Liebherr.

UREA DOSING UNIT

It was decided to use an airless dosing system, as the engines will be used in applications where pressurized air is not available. The Emitec NoNOx urea dosing system, **Figure 14**, is designed to deliver a precise amount of urea in form of a volumetric flow rate into the diesel exhaust systems. The required quantity is calculated by an algorithm in the integrated controller, considering the used catalyst performance under varying conditions like exhaust gas mass flow, temperature and NO_x concentration.

A self-diagnostic procedure is included, communicating with the ECU via the CAN bus. The system is connected to the engine coolant for defrosting.

Figure 14 Emitec NoNOx Urea Dosing Unit

REDUCTANT DELIVERY UNIT (UREA INJECTOR)

The injector used, **Figure 15**, is based on a robust gasoline injector which is in high volume production for gasoline engines. This gives advantages in respect of robustness, cost and flexibility in adaption for different requirements. To meet the demanding off road requirements an injector cooling system was added, which is connected to the engine coolant.

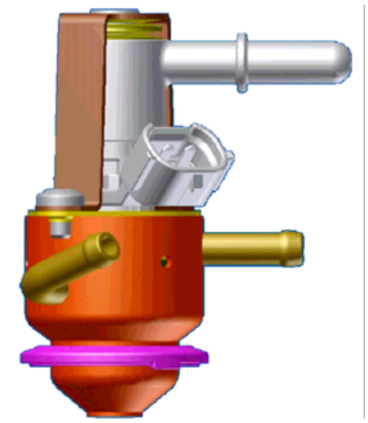


Figure 15 Reductant Delivery Unit with water cooling

CATALYST SYSTEM

To fulfil the emission requirements of 4 engines in more than 45 installations from 129 kW up to 505 kW power, two system sizes have been defined:

- Low Power System (LPS) up to 300 kW,
- High Power system (HPS) for the power range above.

The catalyst volume was adapted to the higher exhaust mass flow for the HPS by increasing the diameter.

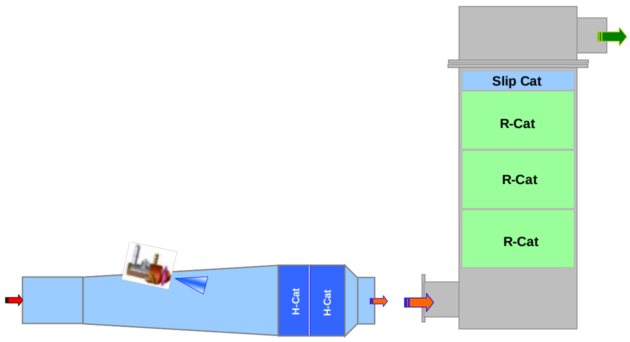


Figure 16 Catalyst system (sketch)

The catalyst system, **Figure 16**, consists of a mixing pipe with hydrolyses catalysts and a reduction catalyst assembly with a slip catalyst incorporated.

The goal of the hydrolyses catalyst (H-Cat) is to ensure the evaporation of the injected urea and enhance the ammonia formation, as the tubing between the mixing pipe and the reduction catalyst assembly can vary for different applications. For the H-Cat a metallic catalyst support with MX structured foil design (see **Figure 18**) is used with an adequate coating. Ammonia distribution measurements confirm an enhanced NH_3 and also HNCO formation - showing an improved urea conversion - compared to a system without the H-Cat.

Extensive simulation and testing was performed to optimize the system layout in order to avoid deposits. Unacceptable urea deposit can occur (see **Figure 17**) if the injector position and spray is not well adapted to the exhaust gas flow and temperature.

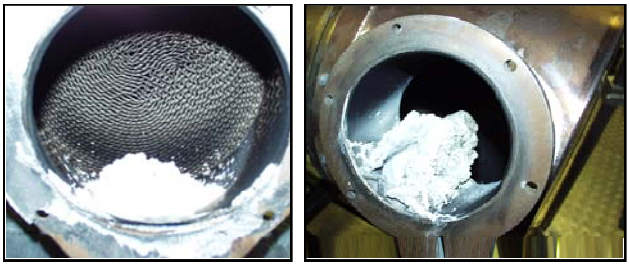


Figure 17 Unacceptable urea deposit (left with H-Cat; right without H-Cat)

For the reduction catalysts also structured metallic foils are used: LS- and LS/PE structure. This results in higher catalyst efficiency due to the generated „turbulence like flow“ in the channels compared to a catalyst with „laminar“ channels at the same catalyst dimensions.

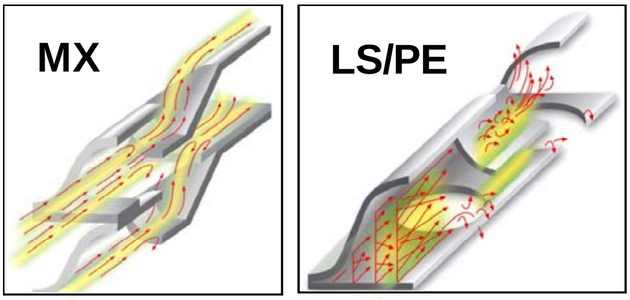


Figure 18 Structured foils used for H-Cat (MX) and R-Cat (LS/PE and LS)

To avoid ammonia slip under all conditions a slip catalyst was added using a 50.8 mm short metallic substrate with adapted coating.

SYSTEM VALIDATION

Besides meeting the emission targets, avoiding of urea deposit - as described above - is a major challenge in application of an airless SCR system. The goal was achieved by optimizing all relevant parameters such as

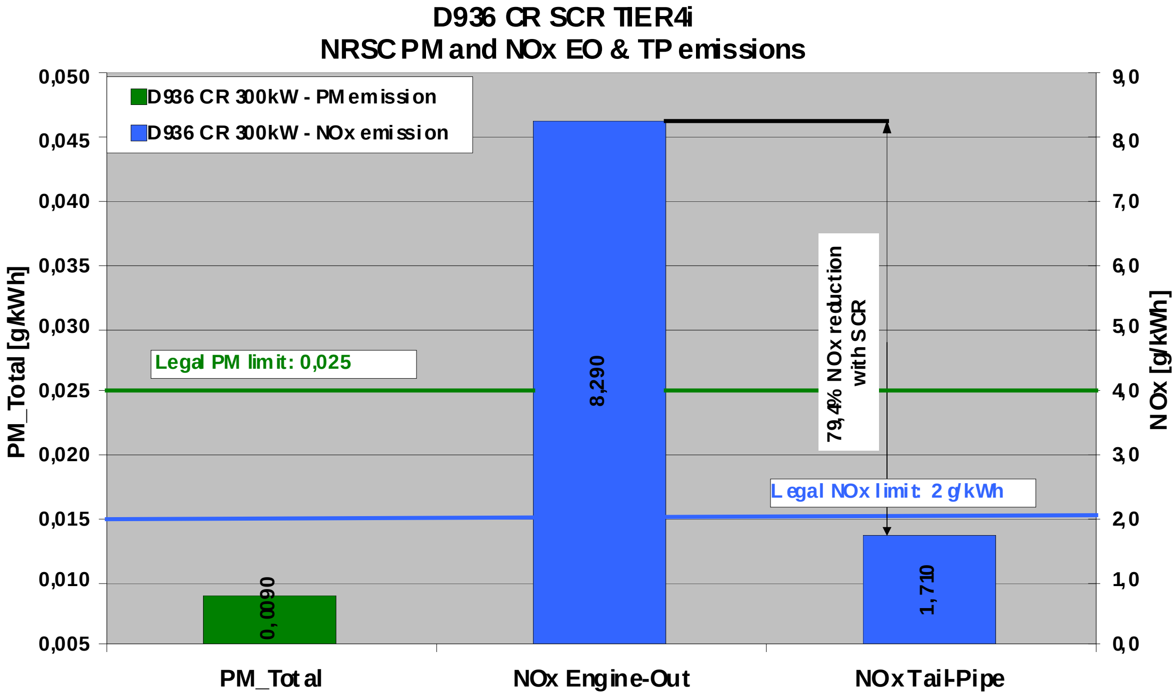
- injector spray and orientation,
- injector position
- position and design of the H-Cat.

As a result a system without any deposit at different load points could be demonstrated while meeting the emission requirements with a safety margin, **Figure 19**.

Figure 19 H-Cat: no deposit after 10 h @ A 25 load point

FINAL EMISSION RESULTS OF D936 CR SCR STAGE 3B/TIER4I ENGINE

Figure 20 demonstrates emission results over the NRSC and the NRTC, respectively. Thanks to the layout of the combustion system, the SCR system and the exhaust temperature management applied a SCR NOx conversion efficiency of 79% could be achieved to meet the Stage IIIB / Tier4i emission standards with sufficient margin against catalyst ageing.



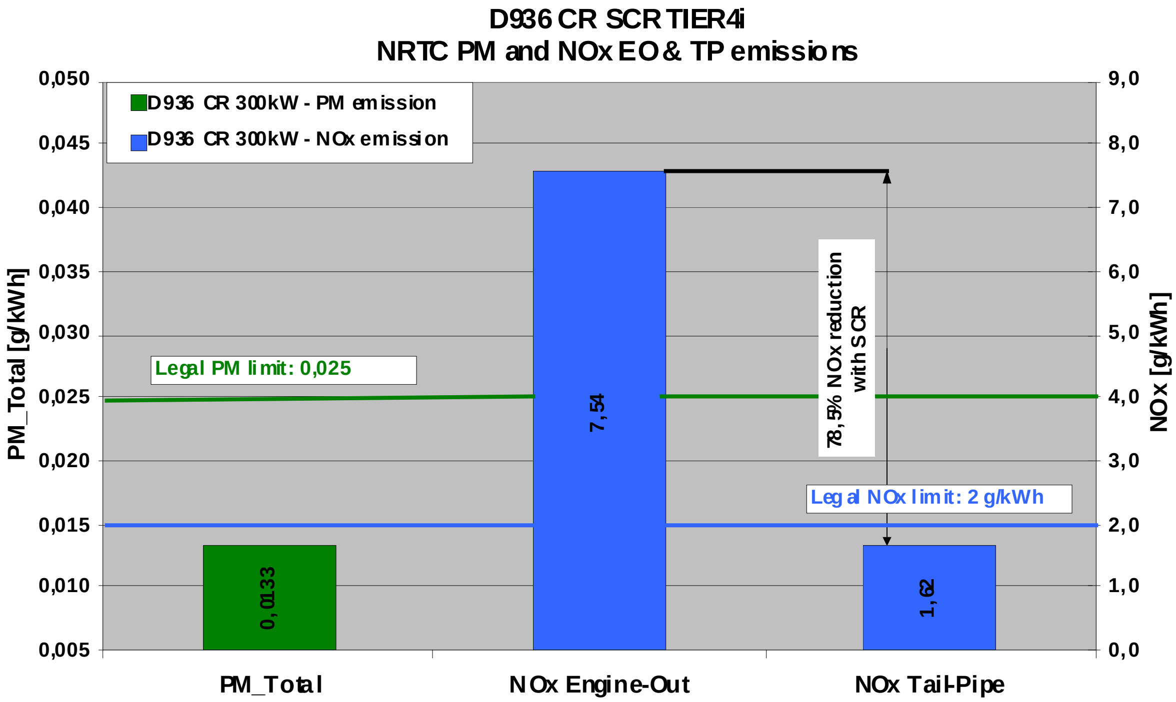


Figure 20 NRSC (top) and NRTC engine-out and tailpipe emissions of D936 Stage IIIB SCR engine

CONCLUSION

To comply with the specific requirements of Stage IIIB / Tier4i engines in crane applications, an airless SCR approach was chosen in favor of the mainstream technology EGR / DPF.

First investigations based on the Stage IIIA engine configuration pointed out, that applying the Stage IIIA PLD injection system, falls short of meeting the soot emission limits especially under transient conditions. The additional degrees of flexibility of the Common Rail system were favorably used to achieve lowest dynamic soot emission, low combustion noise and a significantly improved cold start performance of the engine even with the high drive resistance of the hydraulic pump drive engaged. The application of an intake throttle valve allowed to increase the exhaust temperature level at engine part load significantly to improve – or even enable – sustainable NOx conversion ratios with the SCR system without causing deposits of the injected ammonia.

As outlined in this paper, a robust engine and aftertreatment system configuration could be established, satisfying both, emission, transient performance and fuel consumption requirements.

REFERENCES

[1] UNEP: Diesel Fuel Sulfur Levels Global Status, January 2011, www.unep.org/pcfv

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CR	Common Rail Injection System
DEF	Diesel emission fluid
DPF	Diesel Particle Filter
EGR	Exhaust Gas Recirculation
FIE	Fuel Injection Equipment
H-Cat	Hydrolyses Catalyst
HPS	High Power System
LPS	Low Power System
PLD	Pump-Line-Nozzle Injection System
NRSC	Non-Road Stationary Cycle
NRTC	NON-Road Transient Cycle