

Tier 4 High Efficiency SCR for Agricultural Applications

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ABSTRACT

This paper describes the evolution in diesel engine SCR technology used on tractors >130kW. Details on the SCR technology evolution from Tier 3 to Tier 4 interim are disclosed. Furthermore, this paper demonstrates how state-of-the-art SCR technology can make a non-EGR diesel engine meet Tier 4 final emission limits without using particulate filtration.

Initially, it was assumed that Tier 4 aftertreatment systems would use aftertreatment for NOx and PM, combined with an advanced combustion concept and EGR. However, with this solution, one can expect disadvantages such as: cost, complexity, high heat rejection, large space claim and less than optimal fuel efficiency. Furthermore, active PM filter regeneration is challenging and can be hazardous in certain agricultural applications.

A Tier 4 final engine without PM filtration would require a SCR aftertreatment system with NOx conversion efficiencies in the range of 90-97% on all relevant conditions for the entire life of the engine. With this approach, the base engine technology needs limited alterations from Tier 4 interim. This allows retention of engine robustness, fuel economy and heat rejection.

The feasibility of such a SCR system is demonstrated by means of CFD results, engine dyno data and field test results. This information is used to describe the evolution in SCR aftertreatment mixer design, packaging, NOx reduction performance and deposit formation. Furthermore, an outline is given on how an improved integration of the engine with the aftertreatment can enhance the total system performance (e.g. thermal management, variable raw emissions).

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INTRODUCTION

This paper focuses on SCR aftertreatment for diesel engines, intended for non-road machinery with a power rating of 130-560kW. These diesel engines are popular in large agricultural machinery, such as tractors, combine harvesters, sprayers and many others.

For the majority of these applications, minimizing operation costs is essential. Combine harvester, for example, can consume more than 1000 l of diesel fuel per day in the harvesting season. Hence fuel economy is of high importance for large agricultural machinery.

Exhaust gas emissions of non-road mobile machinery have been regulated already for many years. [Table 1](#) gives an overview of the relevant EU and US legislations for diesel engines (130-560kW).

Table 1. Off-highway emission limit >130kW [g/kWh]

year	Stage	Tier	NOx	PM
2006	3A	3	4.0	0.2
2011	3B	4i	2.0	0.025
2014	4	4f	0.4	0.025

Exhaust aftertreatment comes in different forms. Depending on the strategy chosen, the engine raw emissions and fuel economy can be altered significantly. Furthermore, due to different base engine calibration (injection settings) and engine configuration (cooled EGR, intercooling), the cooling requirements can increase dramatically.

The first off-road engines with exhaust aftertreatment appeared with the T3 emission legislation. The impact of the aftertreatment on the engine and machine is significant.

Aftertreatment systems are often more bulkier than the exhaust mufflers they replace. Furthermore, SCR systems need a separate tank with DEF (AdBlue). These extra/larger components have to be integrated on the machine without negative impact on operator visibility, heat rejection, skin temperatures, fuel capacity and many other factors.

The T3 emission legislation can be achieved without aftertreatment. Compared to previous generations of engines, these T3 engines use mild EGR rates, upgraded injection systems and/or slightly retarded injection settings. As a result, these engines can have less than optimal fuel consumption.

As an alternative approach to reach T3 emission levels, a SCR system can be used. With a SCR system, the engine-out NO_x is relatively high. In the exhaust system, an aqueous solution of urea is injected (DEF, Adblue), this solution partially decomposes to NH₃ and other by-products. These reductants react over a Selective Catalytic Reduction catalyst with NO_x to form harmless H₂O and N₂ [1].

The Massey Fergusson 86-series tractor equipped with the T3 84CWA AGCO SISU power diesel engine was the first off-road tractor available with SCR (Figure 1). This combination allowed the engine to omit EGR, have high engine-out NO_x and use injection parameters optimal for fuel consumption. This contributed to best-in-class fuel economy for the tractor [2]. The high raw NO_x emissions are reduced with a SCR system. The required NO_x conversion of the SCR system is approximately 50%. The T3 emission regulation stipulates a steady state certification cycle, thus cold start and low temperature SCR NO_x are not of high importance. Hence, the minimum dosing temperature is set at a level where deposit formation is no issue. With the above requirements (high minimum dosing temp and 50% conversion), a relatively simple, straightforward and robust SCR aftertreatment was designed.

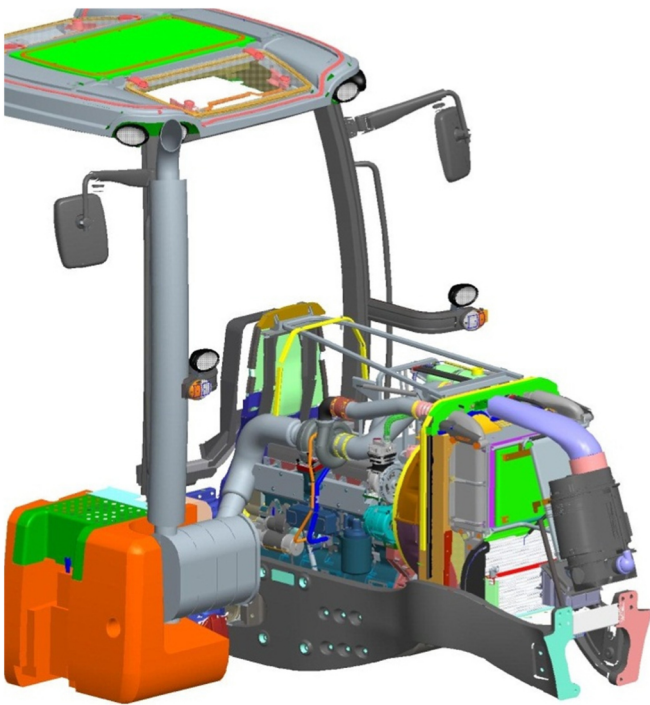


Figure 1. T3 SCR tractor

This system is depicted in Figure 1, it has following components:

- AdBlue/DEF tank with pump unit

- An exhaust tube which connect the turbo with the SCR box
- An airless doser/injector mounted on the tube
- The SCR packaging itself, located at the bottom of the cabin
- An A-post muffler with integrated venturi for air cleaner dust aspiration

As can be seen in Figure 1, this exhaust line does not have any AdBlue/DEF mixer. In fact, to meet the NO_x conversion target no mixer is needed. Furthermore, the minimum dosing temperature is set high enough to avoid deposit formation.

From T3 to T4i, the PM limit reduces by an order of magnitude, while the NO_x limit goes down from 4.0 to 2.0 g/kWh. This can be achieved with two different strategies (see also Figure 2).

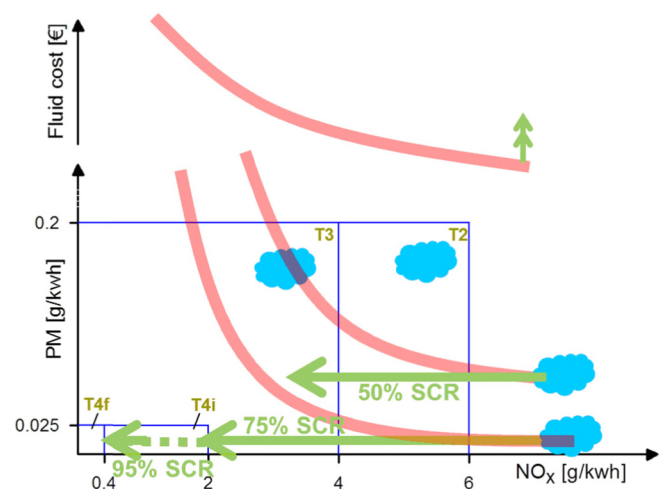


Figure 2. Emission trade off and SCR efficiencies

One approach is using EGR to reduce the oxygen concentration of the intake charge. A lower O₂ concentration leads to a lower adiabatic flame temperature in the combustion front which lowers NO_x formation. EGR reduces the O₂ concentration and the total quantity of O₂ (unless compensated by higher boost pressure), this leads to more formation of Particulate Matter [3, 4, 5]. Typically, an EGR engine emits less NO_x, but more PM. The PM is then trapped in a diesel particulate filter. The quantity of PM in this filter is limited by passive regeneration (based on NO₂) and active regeneration (high temperature reaction with O₂). These active regenerations involve very high exhaust temperatures for short periods. The high temperatures can be a fire hazard in agricultural environments. To make full advantage of the EGR, these recirculated exhaust gasses need to be cooled by an EGR cooler. To compensate for the fresh intake air that is replaced by the EGR, a higher boost pressure can be used, which in turn, demands a larger intercooler. Both the EGR cooler and intercooler put an additional strain on the cooling package. T4i EGR engines typically need approximately 25% more cooling capacity than non-EGR T4i engines.

The alternative approach avoids EGR and calibrates the engine for optimal fuel efficiency. This type of diesel combustion is characterized by very low PM, high NO_x emission and low heat rejection. The high NO_x is then reduced in a SCR aftertreatment system. Such a SCR system typically needs an efficiency of 75 % for the T4i legislation (e.g. from 8.0 g/kWh raw to 2.0 g/kWh tailpipe). The cooling requirements of such a non-EGR engine are often very similar (or lower) than for a T3 engine, thus the cooling package does not need to be altered.

EXPERIMENTAL INSTALLATION

The data and information shown in this paper has been acquired by state of the art test equipment.

Aftertreatment performance is evaluated in a diesel engine test installation, consisting of a 600 kW AC dyno, using conditioned air (23degC-50% humidity) for the engine air supply. The engine exhaust mass flow is calculated from intake air flow (hot film sensor) and a wide range exhaust gas O₂ sensor. Gaseous emissions are measured with a Horiba MEXA 7000-series analyzer (chemiluminescence for NO_x). In addition commercially available Smart NO_x Sensors are used to measure NO_x and to control DEF dosing. NH₃ is measured with a Horiba 6000 FTIR analyzer and a NEO LaserGas based on a tunable laser diode for optical absorption spectroscopy.

All results presented in this paper are obtained with an *AGCO SISU power* diesel engine. Specifically, an 8.4dm³-276kW engine is used which was updated/replaced over time to be representative of the latest emission legislation (from T3 to T4f prototype status). This state-of-the art six cylinder engine uses turbocharging, common rail injection and 4 valves per cylinder.

In addition to the engine test results, some data is obtained on a natural gas burner. This gas burner is designed in-house and is able to replicate the transient exhaust flow and temperature of a 350 kW diesel engine. Flow is generated by a 30 kW electric roots blower with a frequency controller, this air flow is heated by a 300kW natural gas burner. This equipment is used for accelerated thermal aging of full size aftertreatment systems.

Furthermore, this burner is used to evaluate long term effects of DEF spraying in exhaust systems. With this hardware it is cost-efficient to run DEF deposit formation tests for hundreds of hours. The burner is switched off at predetermined intervals for inspections of the exhaust systems (and deposits) using a digital camera and a digital flexible boroscope.

DEF MIXER STUDY

The previously described T3 SCR system does not have any specific mixer elements to enhance DEF atomization, evaporation and distribution. One of the design targets of the T4i SCR system is improving mixing performance.

In laboratory SCR systems, the exhaust line is often simplified and uses only straight tube sections and round bodies. However, real vehicle exhaust systems can incorporate bends, large inlet volumes (e.g. SCR inlet), and perforated tubes and baffles. Furthermore, SCR systems sometimes include specific mixing elements on which the DEF is sprayed on [6]. One can assume that all these elements in the exhaust system do have an influence on the DEF mixing and evaporation. To quantify these effects, a specific mixer study is set up; following configurations are evaluated:

1. In-tube DEF injection, 850 mm upstream of SCR (Ø100mm tube)
2. As in 1, with 2 * 45deg bends
3. As in 1, with 2 * 90deg bends
4. As in 1, spraying on a wire mesh mixer (in tube)
5. As in 1, enlarging the inlet section of the SCR (larger volume, larger residence time)
6. As in 5, including a perforated tube at the SCR inlet
7. As in 1, using an annular shaped DOC (donut)
8. As in 7, adding an swirl component to the flow
9. As in 8, increasing the swirl

These different exhaust configurations were evaluated with a T3 engine. The exhaust system consists of a DOC (generates NO₂) and a vanadium SCR (volume≈ 1.5* engine displacement). The airless DEF injector is located in-between the DOC and SCR. The DEF mixing performance is evaluated by quantifying the maximum SCR performance. In this case, the Non Road Transient Cycle (NRTC) is used in both high power (100%) and low power (70%) version. A typical result from the above study is plotted in [Figure 3](#). A fixed NH₃/NO_x (alpha) ratio is used for the entire NRTC. The first NRTC starts with a low NH₃/NO_x ratio. For every new NRTC cycle, the NH₃/NO_x ratio is increased up to the point where the average NH₃ slip over the entire NRTC cycle exceeds 10ppm. In the postprocessing, the cycle average NO_x conversion efficiency at 10 ppm NH₃ slip is interpolated from the test data. This cycle average NO_x conversion is then used as a measure to quantify the DEF mixing quality.