Application of Diesel Oxidation Catalyst and Diesel Particulate Filter for Diesel Engine Powered Non-Road Machines

Controlling NOx and PM for US Interim Tier 4 and EU Stage III B emission regulations

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In this paper, applications of the platinum group metal (pgm)-based diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) technologies for John Deere Interim Tier 4 non-road machines are presented. The same criteria apply to EU Stage III B regulations. The design and performance of engine aftertreatment systems are discussed in detail, and a few key performance characteristics of DOC-DPF systems are addressed. Significant passive soot oxidation was observed. Model based controls were found to properly account for passive regenerations of the DPF and could be used to schedule active regenerations automatically. Active regenerations were transparent to operators. Tight DPF inlet temperature control and engine exhaust temperature management were found to be key for successful active DPF regenerations. The average fuel consumption for active regenerations was estimated by a simple energy balance model. The emission performance of a DOC-DPF system under normal and active regenerations is summarised, and ash accumulation and DPF pressure drop impact are analysed.

Introduction

To comply with the US Interim Tier 4 or EU Stage III B emission standards, implementation of either a particulate matter (PM) or a nitrogen oxides (NOx) aftertreatment is recommended. Deployment of aftertreatment enables the engine to extend its power range, altitude capabilities and transient performance characteristics. Both exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) technologies are available for the Interim Tier 4 market. The choice between EGR and SCR for NOx reduction depends on the original equipment manufacturer's (OEM's) production history, technology experience, customer requirements and long term product strategy. Engines with EGR consume only diesel fuel but typically require the fitment of a DPF. DPF active regenerations mean that the maximum skin temperatures of the aftertreatment devices and tailpipe exhaust gases must be limited by the exhaust system design.

US Interim Tier 4 or EU Stage III B standards, shown in **Table I**, have been in effect since 1st January 2011. Besides significant tightening of criteria pollutant limits, a new Non Road Transient Cycle (NRTC) was introduced. Emission compliance on the NRTC is required on top of the existing eight mode steady state test. Speed and torque definitions of NRTC and eight mode tests are displayed in **Figure 1**. Emissions from cold and hot NRTC tests are weighted in a similar way to those for on-highway regulations. Not-to-exceed (NTE) rules equivalent to those for on-highway applications also apply to non-road engines.

NOx and PM criteria pollutant limits for engines above 130 kW are higher than those for 2007 on-highway trucks. However, the NRTC has a higher average load factor and is significantly more transient than the Federal Test Protocol (FTP) heavy-duty cycle. The NOx limit for engines below 130 kW is 3.4 g kW^{-1}. Engines with a power output below 56 kW must comply with a combined NOx + non-methane hydrocarbons (NMHCs) limit of 4.7 g kWh^{-1}. The required emission

Table I

Interim Tier 4 Criteria Pollutant Limits

Pollutant, g kWh^{-1}	Engine rated power, kW <56	56–129	130–560
NOx	–	3.4	2
PM	0.03	0.02	0.02
NMHC [NOx + NMHC]	[4.7]	0.19	0.19
CO	5	5	3.5

useful life is 8000 h for all diesel engines above 37 kW. This requirement differs signficantly from those for on-highway engines (1).

Different factors must be taken into account when designing exhaust aftertreatment systems. Non-road applications are very diversified with a wide range of engine configurations, power bands and machine forms. Some examples are shown in **Figure 2**. Agricultural applications, particularly row-crop tractors (**Figure 2(a)**) and harvesters (**Figure 2(b)**), have high load factors with signficant portions of operating time at full loads and rated speeds. Construction machines (**Figures 2(c)** and **2(d)**) demand highly transient

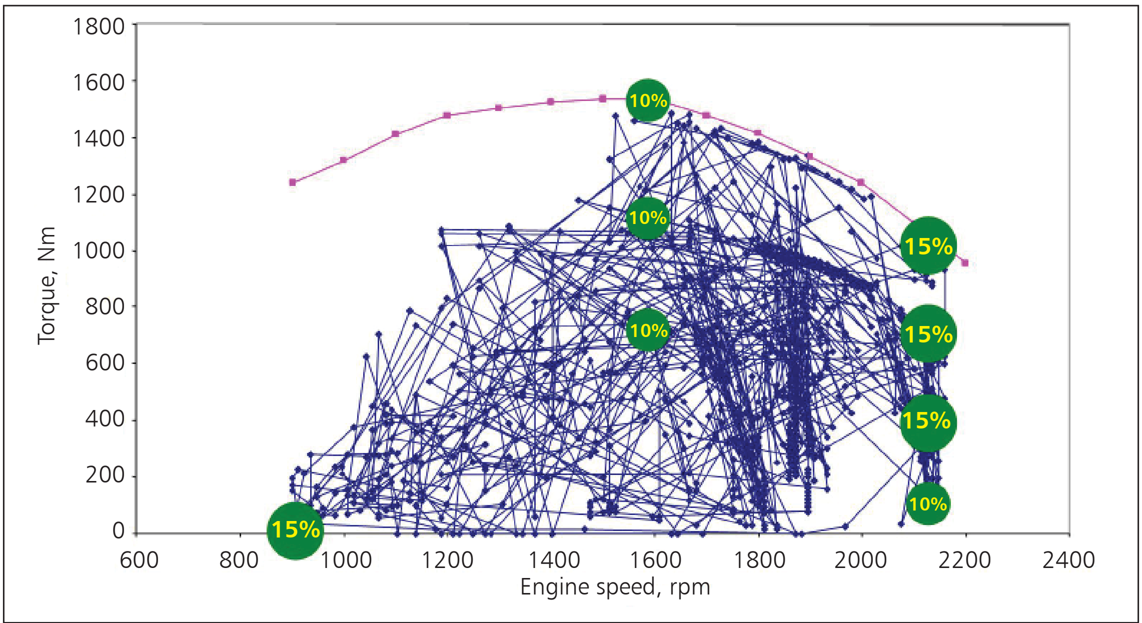

Fig. 1. Non-Road Transient Cycle (NRTC) and eight mode test cycles. Circle points are eight mode; % represents emission weighing factor per point

engine performance, altitude capabilities and longevity. Utility tractors (**Figure 2(e)**) and small construction machines (**Figure 2(f)**) can operate persistently at light loads with extended idle time. Their usage profiles are sporadic. This market segment is very sensitive to cost, especially the initial machine purchase price.

Most non-road machines are used for commercial purposes, therefore reliability and uptime are premium for the equipment owners and operators. Modern large scale agriculture and construction operations require a fleet of machines to work together. If one piece of equipment goes down, the whole operation may be jeopardised. Further, production volumes for the equipment vary drastically. High volume equipment is manufactured in tens of thousands of units annually, while specialty machines may be made at a rate of a handful a year. And non-road machines often have to perform at extreme ambient temperatures, high altitudes and off-level positions. Some machines operate in remote areas, in harsh terrains and under unique environmental conditions.

System Design for Interim Tier 4

Three types of system designs are available for Interim Tier 4 compliant machines. For engines with power output above 130 kW, both cooled EGR (cEGR) and SCR are offered by different manufacturers. For engines under 130 kW, cEGR with a DPF is currently the most popular system, although some cEGR engine applications with a narrow power range below 130 kW will not use particulate filters. Engines have been designed and calibrated to meet the PM standards with or without a DOC (2). This product strategy becomes technically feasible when permitted NOx output levels are 3.4 g kWh^{-1}. Several OEMs offer both cEGR and SCR technologies depending on machine applications (3).

At John Deere, externally cooled EGR technologies had been successfully implemented on Tier 3 engines, offering fuel economy advantages over the alternative approach of internal EGR and fuel injection timing retards. John Deere's global product strategy for Interim Tier 4 is cEGR technology with a DPF. Due to the variability of the applications, only a high efficiency wall flow DPF was considered, although it would be technically feasible to meet the PM standards with a partial flow filter or a DOC. To be fully robust towards all applications and operating conditions, active DPF regenerations were enabled for each engine.

Implementation of any aftertreatment technology must overcome its respective challenges for non-road applications. The following discussions will focus on design and performance development of EGR with DOC-DPF solutions for John Deere Interim Tier 4 products. How engine and aftertreatment systems were integrated and optimised to ensure quality, reliability, performance and emission compliance will be reviewed, and perspectives on design trade-offs will be provided.

Engine and DOC-DPF Designs

Five engine families are offered from John Deere for the Tier 4 market. The engine line up is summarised in **Table II**.

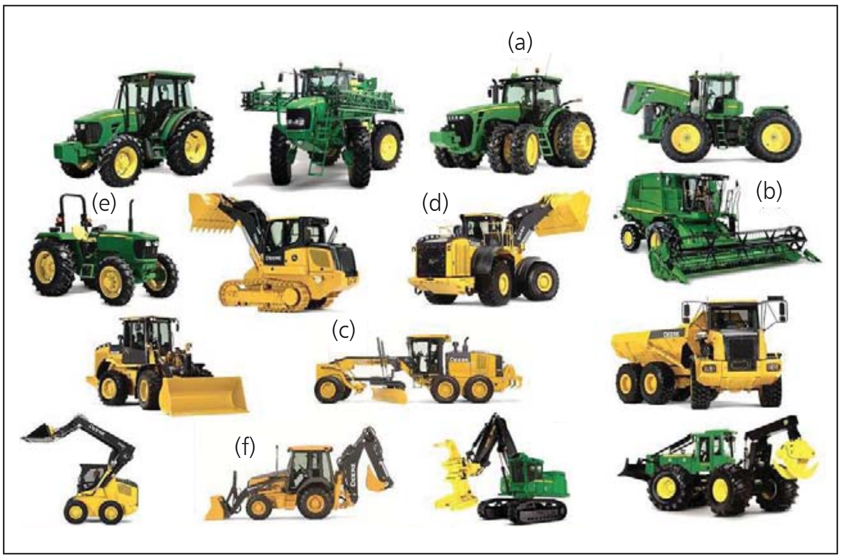

Fig. 2. Examples of non-road machines produced by John Deere, including: (a) row-crop tractor; (b) harvester; (c) and (d) construction machines; (e) utility tractor; (f) a small construction machine (Images © copyright John Deere)

Interim Tier 4 engines were based on Tier 3 engines using cEGR technology, re-optimised to meet the new NOx standards and to facilitate active DPF regenerations. Precise control of EGR rates and combustion events under transient operations was achieved by a redesigned engine control unit (ECU) with a new software package. A single ECU manages both engine operations and aftertreatment performance.

Engine out PM and NOx predictive models were used to calculate DPF soot loadings. New engine combustion modes enabled the engine to raise exhaust gas temperatures when DPF active regenerations were required. This was accomplished by increasing engine fuelling and reducing exhaust flow through an air intake throttle or an exhaust brake. Exhaust temperature management is critical to ensure the completion of an active DPF regeneration event when the exhaust temperature can fall below the pgm catalyst light-off temperature in a normal combustion mode. Capable engine hardware and calibration strategies eliminated the need for an exhaust diesel burner.

The DOC and DPF were sized according to exhaust flow rates, which correlated well with engine power outputs if EGR rates and air to fuel ratios were similar. A total of seven DOC-DPF sizes were designed and released for the five engine families ranging from 37 kW to 460 kW. The DPF dimensions are summarised in **Table III**. Each design also features ash serviceability, inlet/outlet rotatability, three temperature sensors and one delta pressure sensor. Round filters with a larger diameter and shorter length were preferred for vehicle installations as they provide lower DPF pressure drop, higher volumetric soot loading and active regeneration robustness. Filters made of 200 cells per squre inch (cpsi) cordierite and 300 cpsi silicon carbide (SiC) materials were applied to engines above 130 kW and under 130 kW, respectively. DOC substrates were sized to have the same diameters and approximately half the volume of the filters.

DPF designs must consider the worst case pressure drop when loaded with ash and soot. The ash cleaning service requirement is 4500 h for engines above 130 kW and 3000 h for engines under 130 kW. A 200 cpsi cell structure is more tolerant towards ash accumulations, and is therefore preferred for applications above 130 kW. For engines under 130 kW, a higher volumetric soot limit and smaller volume filters favour 300 cpsi cell structures. A 300 cpsi filter offers lower pressure drop in a soot loaded state due to its higher geometric surface area and a thinner soot layer. In addition, smaller SiC filters fit better into compact vehicles.

A DOC was designed to convert nitrogen monoxide (NO) to nitrogen dioxide (NO_2) for passive regenerations and to provide high hydrocarbon (HC) oxidation activity for active DPF regenerations. PGM loading was selected to provide adequate residual conversion efficiencies of NO to NO_2 as well as sufficient HC light-off performance beyond 8000 h. A catalysed DPF with a low pgm loading was highly effective to prevent HC emissions during active DPF

Table II

Tier 4 Engines Made by John Deere

Criteria	Displacement, l				
	2.9	4.5	6.8	9	13.5
Number of cylinders	3	4	6	6	6
Max power rating, kW	56	129	224	317	460
Fuel system	Common rail	Common rail	Common rail	Common rail	Electronic unit injector
Turbos	Single	Single	Dual	Dual	Dual
Cooled EGR	No	Yes	Yes	Yes	Yes

Table III

DPF Sizes Available for Different Engines

	Size 2	Size 3	Size 4	Size 5	Size 6	Size 7	Size 8
DPF diameter, inches	7.5	9	9.5	9.5	10.5	12	13
DPF length, inches	6	6	8	9	11	11	12.5

regenerations. The catalyst on the DPF was highly active for HC oxidations during active regeneration because of high reaction temperatures and an abundance of oxygen. NO_2 generated by the DPF catalyst also promoted more passive regenerations. Design and function relationships are summarised in **Table IV**.

The DOC, DPF and exhaust gas sensors were packaged and integrated into a converter assembly, shown in **Figure 3**. An integrated DOC-DPF design was preferred over separated DOC and DPF converters as it required less space and had higher efficiency. This system design eliminated the need for two additional end cones and reduced heat loss and pressure drop. To accommodate diversified vehicle installations, the inlet and outlet cones were made fully rotatable. Two serviceable flanges, one on each side of the DPF, allowed the DPF to be removed for ash cleaning. Cylindrical converters with two service flanges provided flexibility in the installation of aftertreatment sensors and the positioning of wire routings. Each DOC-DPF converter contained three temperature sensors and one delta pressure sensor across the DPF. The DOC inlet temperature sensor (T1) was used to initiate HC dosing for active regenerations; the DOC outlet sensor (T2) was used primarily for temperature control; and the DPF outlet sensor (T3) was used for temperature diagnostics.

The DOC-DPF converters were heavily insulated, including areas around the sensor ports, to keep converter skin temperatures below the required limits even during active DPF regenerations. The design assumed no air flow around the converters. Under normal engine operating conditions, which accounted for over 97% of the total time, the DOC-DPF converter skin temperature was lower than that typically found for a traditional muffler. Since the DOC-DPF converters were internally insulated with a stainless steel sheet metal surface, any external air flow would effectively reduce skin temperatures further.

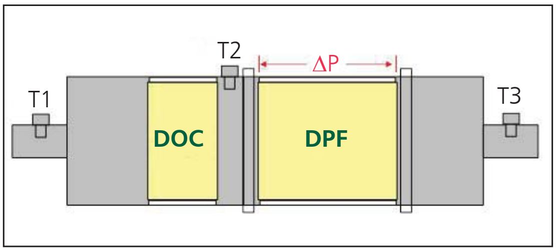

Fig. 3. Integrated DOC-DPF converter schematic. T1, T2, T3 = temperature sensors; ΔP = delta pressure

For engines above 130 kW, HC was delivered to the DOC through an airless exhaust fuel doser, as shown in **Figure 4**. A tip coking resistant design was selected. No air purging or tip cleaning service was necessary. Late post injections were used for engines under 130 kW.

The exhaust fuel doser was mounted next to the engine turbocharger to maximise fuel evaporation and mixing. For engines with two-stage turbochargers, a fuel doser was placed between the two turbines. The second stage turbine served as an active mixer. Uniform HC distributions maximised DOC catalytic efficiencies and exhaust temperature homogeneities for DPF regenerations. Perfect HC mixing avoided hot spots on the DOC and reduced its degradation rate.

Diesel Oxidation Catalyst-Diesel Particulate Filter Performance

Wall flow DPFs were selected due to their high PM trapping efficiencies and their robustness towards diversified applications and engine operating conditions. Measured PM trapping efficiencies on

Table IV

DOC-DPF Design-Function Matrix

Design criteria	Function criteria	
	DOC	**DPF**
Volume	HC slip, NO to NO_2 conversion, ΔP[a]	Soot and ash loading, ΔP
Platinum group metal loadings	NO to NO_2 conversion, HC quench temperature	HC slip clean up, secondary NO_2
Cell structure	ΔP	Ash loading, ΔP
Length/diameter ratio	DOC retention, vehicle package	Soot limit, DPF retention, ΔP
Material	Reliability, cost	Soot loading

[a] *ΔP = delta pressure*

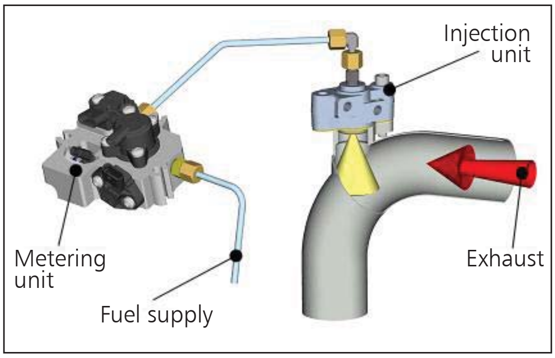

Fig. 4. An exhaust fuel hydrocarbon dosing system schematic

a 9 l engine are summarised in **Table V**. The results demonstrated a filtration efficency of over 95% with a brand new DPF. The PM trapping efficiency well exceeded 99% when the ramped modal tests were repeated and a soot layer had been established on the DPF. Similar performance data for a DPF after 5000 h field usage showed efficiencies greater than 99% both before and after an ash cleaning service.

The full benefits of passive regenerations were achieved with a DOC and a catalysed DPF (4). The DOC oxidised NO to NO_2 under normal engine operating conditions. A production design DOC, after accelerated ageing to simulate 8000 h field usage, was capable of providing NO to NO_2 conversion efficiencies of over 50%, as shown in **Figure 5**. Each data point in **Figure 5** represents an engine operating condition. The bubble size signifies the actual engine out NOx ppm level. To fully benefit from passive soot oxidations, the DPF soot predictive models must account for the soot and NO_2 reaction rates, and adjust for catalyst degradation over time.

Due to a higher NOx limit of 3.4 g kWh^{-1}, engines for applications under 130 kW produce less PM. **Table VI** compares the NOx:PM ratios of an engine running at 2 g kWh^{-1} *vs.* 3.4 g kWh^{-1} permitted NOx output levels. A higher NOx:PM ratio provided a greater opportunity for passive regenerations. In principle, active regeneration is only required when an engine operates persistently at low loads with low exhaust temperatures. Under low load conditions, the engines produced little soot and the DPF soot loading rates were low. Infrequent active regenerations for engines under 130 kW enabled HC to be delivered by late post injections without oil dilutions or compromises in engine durability.

Table V

Measured DPF PM Trapping Efficiencies

Ramped modal cycle	Trapping efficiency, %
DPF first test (brand new DPF)	96.6
DPF second test	99.9
DPF third test	100

At 2 g kWh^{-1} NOx for engines above 130 kW, active regenerations were more frequent. But significant passive regenerations were also observed. Engines for applications above 130 kW tended to operate at higher average loads with temperatures over 250ºC, which are more favourable for passive regenerations. High speed and low load engine operations tended to produce more PM and lower exhaust temperatures, and therefore required more frequent active regenerations than other operating conditions.

Passive Regenerations

To assess the passive regenerations, a 4.5 l Interim Tier 4 engine was programmed to repeat a tractor cycle on an engine dynamometer. Engine out soot was measured by an AVL List GmbH smoke meter. The DPF was periodically weighed to determine the soot loading levels. The results are shown in **Figure 6**. DPF soot levels reached a balanced point below the soot limit of the DPF material, and an increasing percentage of soot was oxidised passively over time. Approximately 80% of engine out soot was oxidised passively in 50 h, 85% in 100 h and 90% in 150 h. In theory, no active regenerations were required for this drive

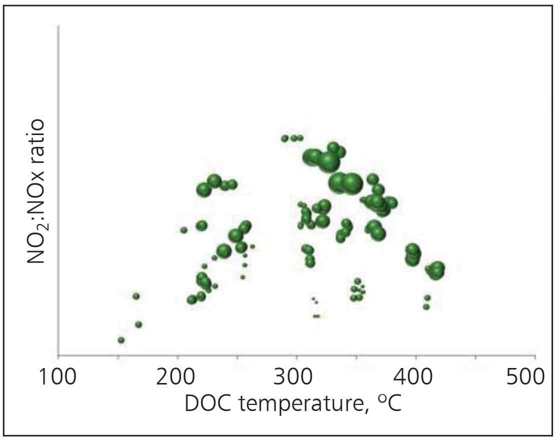

Fig. 5. NO_2:NOx ratio at a DOC outlet

Table VI

Comparison of NOx:PM Ratios for Engines Above and Below 130 kW

Pollutant	Engine rated power, kW	
	<130	>130
NOx, g kWh^{-1}	3.4	2
PM, g kWh^{-1}	0.05	0.08
NOx:PM ratio	68	25

cycle, but in practice active DPF regenerations were necessary as they allowed the soot predictive models to reset and system performances to recover from slow sulfur poisoning. Furthermore, an active regeneration can effectively allow the system to recover from misfueling with high sulfur fuels.

Figure 7 displays the passive regenerations of a DOC-DPF system on a John Deere 744K wheel loader powered by a 220 kW 9 l Interim Tier 4 engine. The 744K loader was operated to perform real world truck loading routines. Soot on the DPF was determined by weighing the DPF module periodically. Over a span of 50 h, soot on the DPF reached a balance point far below the soot mass limit of the DPF material. The truck loading cycle is one of the most transient operations for non-road applications.

An alternative to the passive regeneration DOC-DPF system is to use a burner-DPF combination to enable active regenerations. However this has the disadvantage of greater mechanical complexity. In practice a DOC is recommended even if a full capacity burner is used to benefit from passive regenerations.

Active Regenerations

During an active regeneration, the engine switches to an exhaust temperature management mode to ensure the exhaust gas temperature stays above 275ºC at the DOC inlet. HC from an exhaust doser or from late post injections enters the downstream DOC. Released fuel energy from oxidation reactions heats the exhaust gas before it reaches the DPF. An energy balance model calculates the required fuel quantity based on temperature rise demands and exhaust flow rates. The T2 sensor, at the DOC outlet, provides feedbacks for closed loop controls. A fast response control system ensures the DOC outlet temperature stays on target while engine operations vary considerably. To verify the tight DPF inlet temperature control, an active regeneration was enabled during a NRTC test. The results are shown in **Figure 8**. Despite large fluctuations of engine speeds and torques, the DOC outlet temperature was maintained around 600ºC and the active regeneration was sustained for the whole NRTC.

A DOC offers a cost effective means to actively regenerate a DPF while providing the full benefit of passive regenerations. A DOC oxidises nearly all the injected HC under most conditions, except near peak exhaust flows. The small amount of slipped

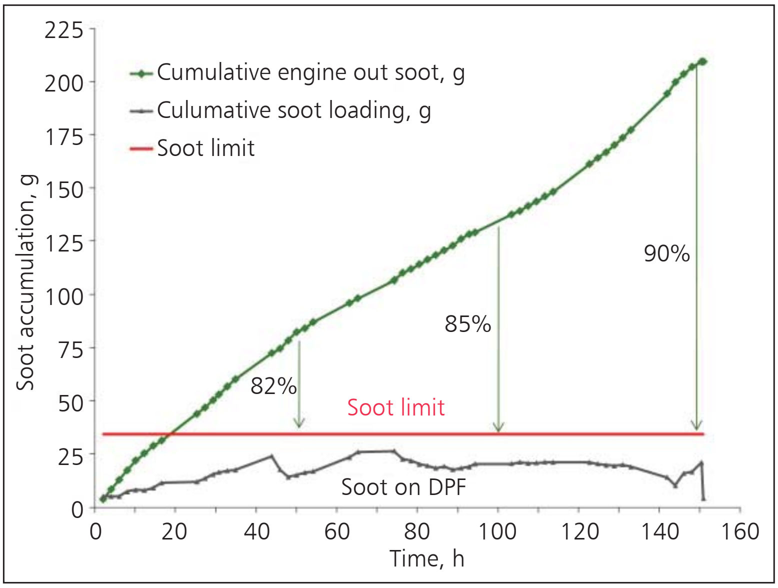

Fig. 6. Passive regeneration test on DPF for a 129 kW rated 4.5 l engine

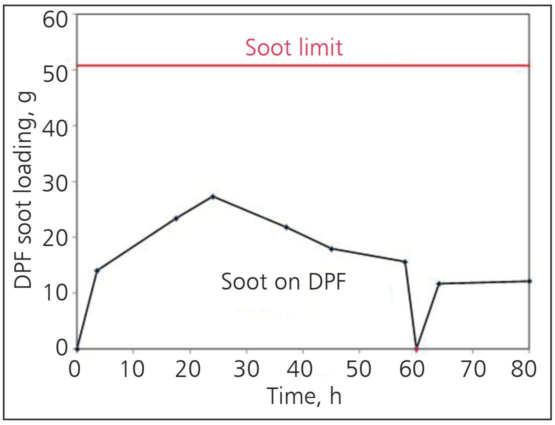

Fig. 7. Passive regeneration test for a DOC-DPF system on a John Deere 744K wheel loader with a 9 l engine

HC is oxidised over the downstream platinum-palladium (Pt-Pd) catalysed DPF, as shown in **Figure 9**. The black bar represents the HC concentration before the DOC and is above 2000 ppm (off the scale of measurement). The blue bar represents the measured HC level at the DOC outlet, or HC slip. Only low ppm levels of HC were detectable at the DPF outlet, represented by the green bar. Despite a light pgm loading, the catalysed DPF was very efficient for HC oxidations during active regenerations due to its large volume and high reaction temperatures. At lower flow conditions, DOC HC oxidation efficiency was nearly 100%.

The DOC ensured a good energy balance for temperature controls with little waste. Even after full useful life of 8000 h, the HC oxidation efficiency of the DOC for active regenerations was hardly changed.

The DOC was also effective at oxidising HC under normal operating conditions. **Figure 10** shows the performance of a DOC for reducing engine out HC during a NRTC test. The cumulative engine out total HC is shown as the black line which, in this case, already meets the emission standard of 0.19 g kWh^{-1} (shown as the green line). The DOC reduced an additional 95% of the engine out HC, as shown by the blue line. The red curve represents the tailpipe HC when an active regeneration was enabled with DOC.

Although a DOC is not required for HC emission compliance, removing HC is beneficial for extending DPF active regeneration intervals. The DOC oxidises the soluble organic fraction of PM and extends the soot loading limit by eliminating the excess exotherm associated with HC oxidation during an active regeneration. Active regeneration is an efficient way to oxidise soot. During an active regeneration, the fuel consumption is increased, but this is necessary for DPF applications.

Assisted Passive Regenerations

An alternative approach is to raise the exhaust temperature to 300ºC to promote passive soot oxidation by NO_2. This is sometimes refered to as assisted passive regeneration.

A simple energy model was used to compare the fuel consumptions of an active regeneration *vs.* an assisted passive regeneration. Assumptions used for the calculations are summarised in **Table VII**. The base exhaust temperature was kept at 150ºC. An

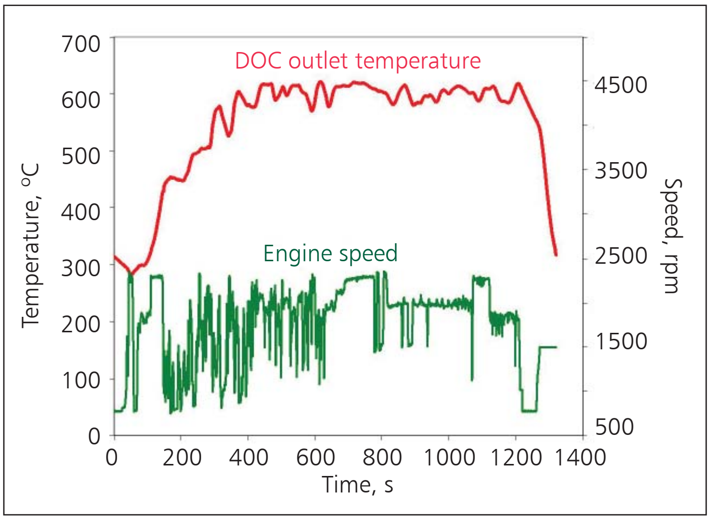

Fig. 8. DOC outlet temperature during a NRTC with active regeneration

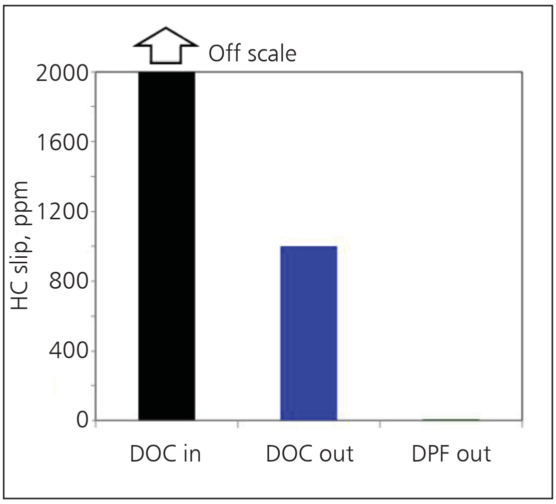

Fig. 9. HC emission during an active regeneration of a DPF

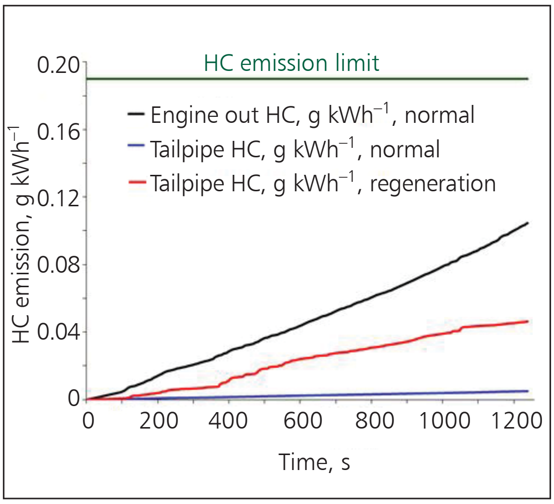

Fig. 10. NRTC HC emission with and without DPF active regenerations

active regeneration raised the exhaust temperature by 450ºC with a total regeneration time of 30 minutes. An assisted passive regeneration had a lower temperature increase and was assumed to take 2 h to oxidise the same amount of soot.

The fuel consumption was time averaged between normal and regeneration events. The results are shown in **Figure 11**. This conservative simulation revealed a 1.5% fuel consumption increase with an active regeneration interval of 10 h. As the regeneration interval increased, the average fuel consumption decreased. With a 50 h regeneration interval, the average fuel consumption increase was less than 0.5%. These estimates are consistent with previously published results (5). It may be concluded that an active regeneration is more fuel efficient than an assisted passive regeneration.

Steady State Tests

Steady state eight mode emission results of a fully aged engine aftertreatment system for a 9 l engine are shown in **Figure 12**. The blue bars represent the US Interim Tier 4 or EU Stage III B standards for CO, HC, NOx and PM. The engine out NOx emission is under the limit with a reasonable engineering margin. HC, CO and PM criteria pollutants are far below the regulatory limits.

Ash Residues

A DPF traps not only engine out soot particles, but also metal containing particles in the form of ash residues. Ash accumulation on a DPF is primarily due to engine oil consumption. Engine oils with a maximum of 1% sulfated ash are required for Interim Tier 4 engines. Ash accumulation on a DPF can be estimated by the oil consumption and an empirically measured ash trapping efficiency (6).

The impact of ash loading on the DPF pressure drop was calculated using an in-house model based on the method published by Konstandopoulos (7). The model was first calibrated using production DPF hardware. The results, shown in **Figure 13**, assume the use of CJ-4 oil with an ash content of 1% and an empirical ash retaining efficiency for the DPF of 60%. The ash loading on the DPF increased over time, leading to a higher pressure drop. The solid blue line represents the DPF pressure drop at a soot loading of 3 g l^{-1} at rated power with the maximum exhaust flow rate and the highest normal operating temperature. The dotted blue line represents a soot loading of 0 g l^{-1} at rated power. The green lines represent the DPF pressure drops at an average exhaust flow rate and an average exhaust temperature calculated from a NRTC test.

Table VII

Assumptions Used for Fuel Consumption Calculations of Regenerations

Parameter	Assisted passive regeneration	Active regeneration
Temperature increase, ºC	150	450
Time, min	120	30

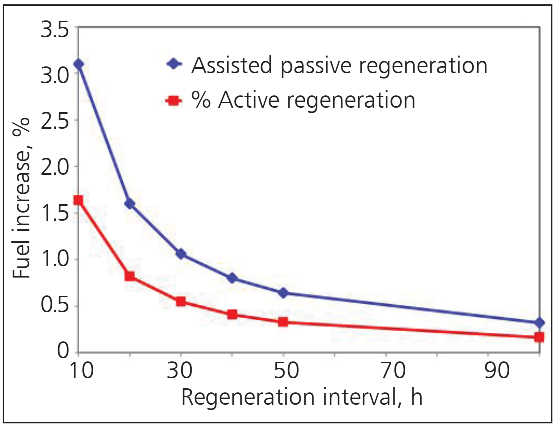

Fig. 11. Time averaged fuel consumptions of active vs. assisted passive regenerations of a DPF

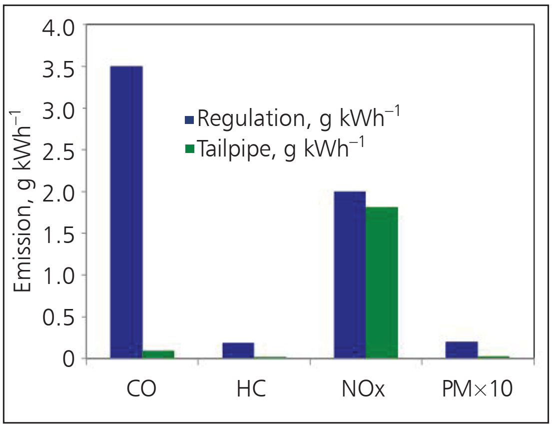

Fig. 12. Eight mode emission results for a 9 l non-road engine at 8000 h

These results illustrate low average DPF pressure drops although the instantaneous DPF pressure drop could spike to high values when engine exhaust flow rates suddenly increased. This high pressure drop condition disappeared over time if the engine was operated near peak power. The DPF pressure drop returned to the dotted blue line over time due to passive regenerations.

Field data have shown the real world 'apparent' ash trapping efficiency of the DPF is approximately half of the intial 60% assumption. A number of hypotheses could explain this observation: (a) engine oil sulfated ash content may be less than the specification limit of 1%; (b) not all consumed oil may be converted into sulfated ash and transported to the DPF; and (c) sulfated ash may decompose to metal oxides of lower mass during active regenerations. In practice, the ash cleaning interval is expected to be much longer than the initial assessment.

Conclusion

Cooled EGR, DOC and DPF are proven technologies for meeting the US Interim Tier 4 and EU Stage III B emission control standards for non-road diesel applications. High trapping efficiency wall flow filters enable flexibility in engine design, broad engine applications and wide operating windows. The platinum-palladium based DOC is cost effective and robust and provides the benefit of passive regenerations through NO_2 and soot reactions. The DOC oxidises HC and the soluble organic fraction of PM and heats the exhaust gas for active DPF regenerations under a wide range of exhaust flow, O_2 level and inlet temperature conditions. The robust HC performance and thermal inertia of a DOC are beneficial for precise control of the DPF inlet temperature for active regenerations.

For non-road applications, passive soot regeneration occurred extensively in the DOC-DPF system. The aftertreament control alogrithm within the engine management system was designed to take advantage of this. The DOC-DPF system is less complex than the burner-DPF alternative. A key enabler was a new engine exhaust temperature management mode to ensure exhaust gas temperatures are above the DOC light-off temperature. Active regenerations are recommended for wall flow DPF applications to provide a reliable and robust system for diversified

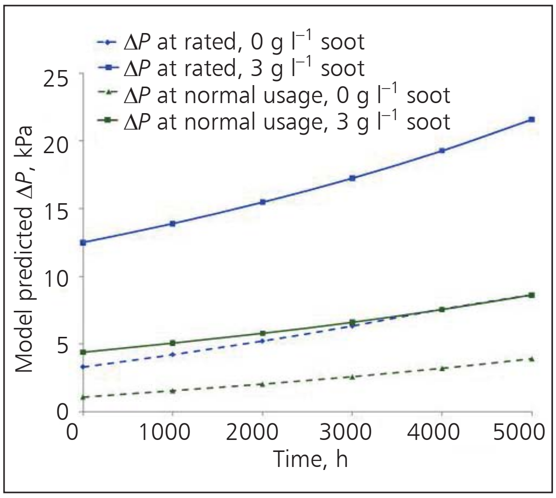

Fig. 13. Calculated DPF pressure drop over time with and without soot

non-road applications. Uniform HC distributions and precise DPF inlet temperature controls are critical for reliable active DPF regenerations. Additional vehicle level integrations are required to effectively manage the DOC-DPF converter skin and exit gas temperatures. Overall, the EGR and DOC-DPF solution offers the best in class engine and emission performance as well as being cost effective.

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References

1 X. Gui, D. Dou and R. Winsor, 'Non-Road Diesel Emissions and Technology Options for Meeting Them', 2010 Agricultural Equipment Technology Conference, Orlando, Florida, USA, 10th–13th January, 2010, American Society of Agricultural and Biological Engineers, St. Joseph, Michigan, USA, 2010, pp. 1–24

2 F. Conicella, 'Low Particulate Combustion Development of a Medium Duty Engine for Off-Highway Applications', Heavy Duty-, On-/Off-Highway Engines, MTZ-Konferenz, Friedrichshafen, Germany, 17th–18th November, 2009

3 H. Bülte, H.-J. Schiffgens, P. Broll and S. Schraml, 'Exhaust Aftertreatment Concepts for Engines in Mobile Machinery According the Legislation of US Tier 4 and EU Step IV. Technologies and Applications',18th Aachen Colloquium "Automobile and Engine Technology", Aachen, Germany, 5th–7th October, 2009

4 R. Allansson, P. G. Blakeman, B. J. Cooper, H. Hess, P. J. Silcock and A. P. Walker, 'Optimising the Low Temperature Performance and Regeneration Efficiency of the Continuously Regenerating Diesel Particulate Filter (CR-DPF) System', SAE Paper 2002-01-0428, SAE World Congress and Exhibition, Detroit, MI, USA, 2002

5 N. Khadiya, 'Exhaust Thermal Management Using Fuel Burners', 3rd International Conference, Vehicle Emission Reduction Technologies – Criteria Pollutants and CO_2, Car Training Institute (CTI), Detroit, USA, 16th–20th May, 2011

6 W. A. Givens, W. H. Buck, A. Jackson, A. Kaldor, A. Hertzberg, W. Moehrmann, S. Mueller-Lunz, N. Pelz and G. Wenninger, 'Lube Formulation Effects on Transfer of Elements to Exhaust After-Treatment System Components', SAE Paper 2003-01-3109, SAE Powertrain & Fluid Systems Conference & Exhibition, Pittsburgh, PA, USA, October, 2003

7 A. G. Konstandopoulos, E. Skaperdas and M. Masoudi, 'Microstructural Properties of Soot Deposits in Diesel Particulate Traps', SAE Paper 2002-01-1015, SAE World Congress and Exhibition, Detroit, MI, USA, March, 2002

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