Advanced Clean Air Technology to treat pollutants and meet Regulatory Norms for Off highway Vehicles

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Abstract

With the off highway vehicle segments moving to CEV 5 emission regulatory norms, faces a very severe control of pollutants. Off highway vehicles offer a minimal space claim and low ownership cost. A high-end technology of After Treatment System (ATS) must be integrated to meet stringent limits of NOx and soot emissions, that requires a catalytic system with huge complexity, size and number of units as well as increased fuel consumption. Selective Catalytic Reduction (SCR) especially with air assisted urea dosing promises a better atomization of urea which improves NOx efficiency and reduces urea consumption in this combined system, while soot filtration is performed by Diesel particulate Filters (DPF) by maintaining Particulate Matter (PM) and Particulate Number (PN) norms. Off-highway vehicle duty cycles vary much from on road automobile applications in terms of exhaust temperature and soot formation. Subsequently DPF regeneration will play a challenging role which requires a specific protection strategy in the after-treatment control system software to protect the DPF for its good functioning. To enhance the exo-thermal efficiency of Diesel Oxidation Catalyst (DOC), HC doser injection or post injection methodologies are adapted. It is important to incorporate DPF fault triggering lamps, temperature warning lamps, automatic regeneration strategy, standstill regen switches to solve DPF related issues instantly. Thus, combination systems are designed for rugged off-highway markets to target clean air environment.

1.Introduction

1.1 Off highway vehicles emission trends

In investigation of current and projected emission control technologies for Construction Equipment Vehicles (CEV) between 130 and 560 kW, the PM and NOx emission rates had transition to more stringent control levels along with the evolution in the engine and emission technologies.

As shown in the Figure1, baseline technology for CEV engines consists of naturally aspirated or turbo charged engines, mechanically controlled conventional fuel injection and muffling system. This engine system is very simple and powerful. However, to meet progressively more stringent emission standards, composite engine design was significantly required. During advancement from CEV III to IV, electronically controlled engine fuel injection was adapted and required to integrate a complex after treatment system of DOC and SCR for treating exhaust gases that increased the vehicle size and fuel consumption. Further moving up to CEV V regulations with lowering PM rates to 0.015 had brought up the necessity to extend the ATS system with additional unit for trapping PM using DPF.

Figure 1. Projected technology for diesel engines used in construction equipment between 130 and 560 kW

1.2 Emission Technology – Evolution of EATS in off highway

Figure 2: Off highway Exhaust After Treatment System evolution

The Figure 2 demonstrate the evolution of EATS from conventional muffling system to the present system in upcoming CEV5 engines in terms of complexity and size. For many off-road applications, because of the limited under-hood space, we need to be creative to fit these new components onto the vehicles and the components need to be more densely packaged. This increased complexity is necessary to meet the ever- tightening emission standards which incorporates more sensors and electrical interfaces in the given package size. Eventually the cost and servicing of the product is way uneconomical and laborious.

1.3 Exhaust After Treatment System Architecture

The After Treatment System is a device for reducing harmful exhaust emissions from the internal combustion engines before allowing it to the environment. The figure 3 demonstrate the complete architecture of Albonair' s Exhaust After Treatment system for diesel engines. This system comprises of four important subcomponents DOC, DPF, SCR and ASC. The DOC aids in the process of oxidation and burns HC and CO followed by the DPF which traps the 90% of the particulate matter in the exhaust gases and passes it to the SCR still with left nitric oxide (NO) and nitrogen dioxide (NO2). In order to reduce the NOx levels a homogeneous distribution of urea-AdBlue is injected at high temperature over the SCR catalyst surface. Albonair' s concept of twin fluid atomizer with external mixing using air conforms uniform decomposition reaction. The contactless design for Diesel Exhaust Fluid (DEF) and air in the dosing system or the injecting nozzle avoids urea crystallization and deposits.

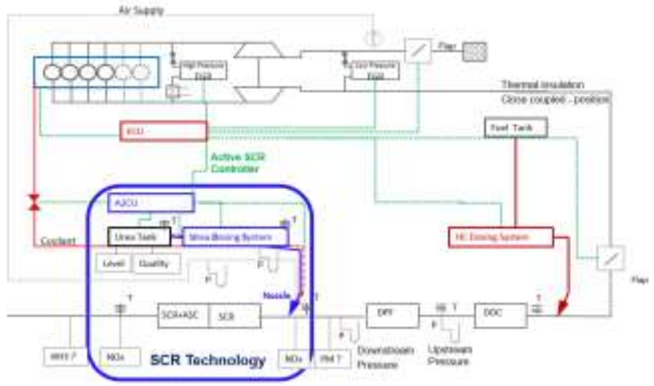

Figure 3: Proposed Architecture of EATS for Off-road vehicles

2. SCR challenges and protection Features

This paper elaborates built-in controller software features for two major segments of EATS, SCR and DPF to confirm these components are functioning properly. While designing an ATS, considering the product point of view both the system must be more prominent in such a way that all the hardware and software features needs to address the customer challenges at field and maintain the product quality to ensure the performance of the system. These features are customer specific and are not common among the OEMs.

2.1 Key Features of SCR

The four major features that impacts the performance of the SCR system are

- ❖ Urea injection design.
- ❖ Catalyst design.
- ❖ ATS mixer design.
- ❖ NOx control strategy.

The above listed are the component level challenges for an rigid SCR design. Urea deposition is the most common failure in the SCR system that affects the system functioning. Deposition of urea on the hydrolysis pipe, tailpipe or on the SCR chamber and SCR catalyst face plug has an effect on increased back pressure, white smoke, higher tail pipe NOx and catalyst poisoning. And also, high deposition of sand or mud on the ATS surface, damage of SCR catalyst and urea contamination reduces the SCR conversion efficiency and risk of integral part removal in the field. These failures are very common in case of off highway vehicles running at low duty cycle and in low load conditions. Equivalent software methodologies are to be proposed to avoid SCR failures in field.

Figure 4: Customer field issues on SCR components a) sand/mud deposition b) SCR catalyst damage c)Urea deposition d)SCR face plug.

2.2 SCR Protection features

To protect the hardware from failure, an equivalent software methodology has to be proposed for smooth functioning

- **SCR bed temperature software model**- Efficient urea dosing at right catalyst bed temperature avoids urea deposition. The temperature difference at the inlet of SCR and its bed differs about 30°C. Dosing at undefined temperature leads to efficiency loss and goes as a slip or deposits which in turn creates a high back pressure and reduce vehicle performance. To estimate the right SCR bed temperature needs a modelling using values of both the temperature sensors integrated at inlet and outlet.

- **NH3 ammonia slip estimation software model**- The performance of the SCR improves in a closed loop condition than in an open loop. Integrating a sensor to measure the NH3 slip at the tail pipe is expensive, instead an efficient closed loop control is built-in to prevent excessive dosing and ammonia slip using the measured inlet and outlet NOx.

- **Reactive Regeneration:** In the off-highway sector, with more vehicle applications running at different load conditions, for a SCR system with low temperature less than 250°C there is a high possibility of urea deposition at the catalyst. Removing and cleaning DPF always encounters a safety measure that must be taken in order to prevent potential incidents from happening as there are no standard procedure followed. In that case a suitable controller mechanism should trigger the reactive regeneration in order to increase the temperature above 500℃ to flush out the urea deposition at the SCR surface.

- **Desox**: Sulphur poisoning on the base metal or zeolite SCR catalyst in the diesel engine application is well known. A way to estimate the sulphur tolerance on the SCR catalyst and to control the sulphur poisoning, a proposed deSOx strategy avoids sulphation effect by promoting regeneration to increase temperature typically in excess of 550℃ to maintain high NOx efficiency of these catalyst even when ultra-low sulfur diesel is used. With much reduced sulphur content in BS6 fuel compared to BS4, there are still prevailing field cases of customers using adulterated fuel which is the severe cause for SCR poisoning.

3. DPF challenges and protection Features

As particulate matter is the main emission pollutant of diesel engine, it is highly harmful to the human health. Diesel particulate filter is designed to trap the particulate matter in the exhaust gases, and it is required to be cleaned and emptied on a regular basis so that there is space to continue trapping more particulate matter. To achieve reduction in PM emission norms from CEV4 to CEV5, DPF technology is introduced into this integration system of DOC and SCR.

As there are more variants in off highway sector, the operating conditions are also very high. Vehicles run in low load conditions with low temperature where the soot accumulation is abrupt. To have a proper estimate of the soot and to improve the accuracy of the regeneration, an equivalent circuit model is designed for DPF soot model estimation and DPF regeneration in the software logics that always ensures to achieve a clean and safe DPF.

3.1 DPF Soot Model Estimation

DPF model estimation for heavy truck diesel engines is carried out in two ways

3.1.1 Engine soot model estimation

This method estimates the accuracy of the soot load under engine transient operating conditions. A mathematical model is established that calculates the engine out soot based on the fuel flow rate, EGR flow rate, air flow rate, coolant temperature, boost temperature, atmospheric pressure, air inlet temperature, exhaust mass flow and exhaust gas temperature.

3.1.2 DP sensor-based soot estimation

The relationship between the pressure drops in the DPF inlet and outlet measures the amount of soot accumulated. These measured values of the differential pressure sensor were obtained from the pressure drop under exhaust mass flow resistances due to the soot. Although the accuracy of the soot estimation deteriorates seriously at the lower exhaust mass flow. The figure 5 explains the modelled soot value and the measured value from the sensor falls on the same range.

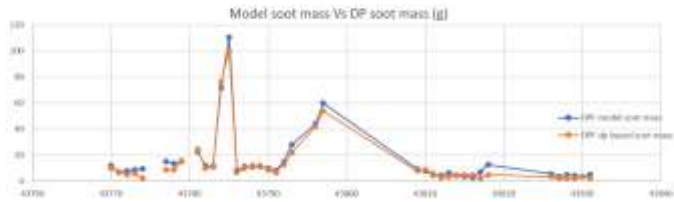

Figure 5: Results showing Model soot mass Vs DP soot mass

Both the devised methods are calibrated for the application variants, and it is extensively validated in the vehicle with different operating conditions and duty cycles. As seen in the figure 6, the accuracy of the weighed actual soot and the estimated model soot lies less than 10%. These results shows that the defined methodologies overcome the difficulty of accurately measuring the soot load.

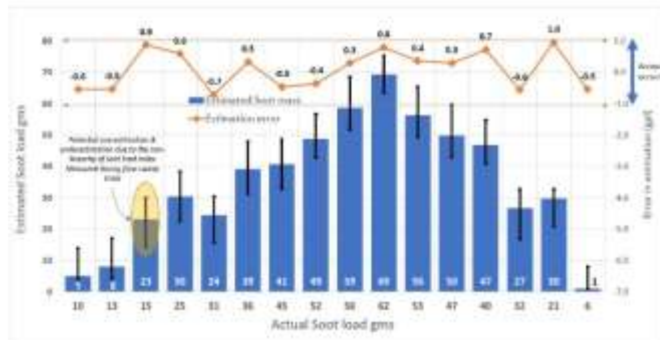

Figure 6: Results showing DP soot mass estimation vs actual soot

3.2. DPF Regeneration

Triggering a DPF regeneration at the right timing is a challenging task that requires an accurate estimation of the soot load. If the regeneration frequency is too high, the fuel economy of the engine will be worsened and the lifespan of the DPF will be reduced. If the regeneration frequency is too low, there will be too much soot particle accumulation in the DPF, which will result in poor engine performance.

However, with the gradual accumulation of PM in the DPF, the exhaust back pressure of the engine gradually increases, which reduces engine efficiency, and increases fuel consumption. As a result, it is necessary to remove PM periodically or continuously. With the increasing tailpipe temperature and NO2 concentration, passive regeneration is accelerated. This regeneration will happen once the exhaust temperature is higher than 300℃ and that will burn soot even under low soot mass. But the soot burn rate depends on the soot accumulation, exhaust temperature and duration of vehicle run time. There is no specific target temperature of the passive regeneration by the controller, but in general, a higher exhaust temperature and higher exhaust mass flow is required. In contrast, active regeneration interval is defined in the software accordingly.

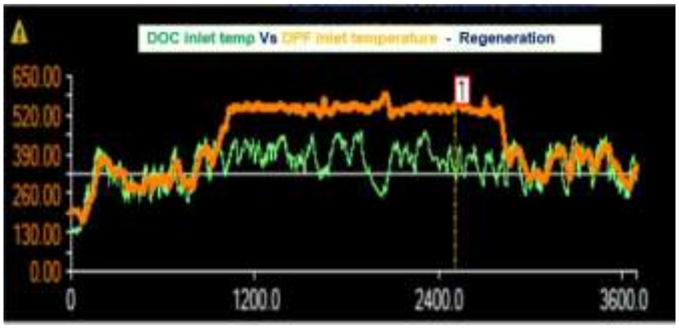

Figure 7: Results of rise in DPF temperature during regeneration process

3.2.1 Model based regeneration

Active regeneration is triggered when the exhaust back pressure across the DPF is sensed to have reached a first critical point or the model soot mass value exceed the threshold calculated based on the catalyst volume and design. As soon as the temperature reaches 250℃ the HC is injected upstream, or post injection process is initiated which results in the sudden increase of temperature inside the DPF above 500℃ to burn the soot. It is also set not to go beyond 600℃ during regen considering the safety factor.

3.2.2 Time based regeneration

After every defined engine operation time, regeneration is triggered automatically. The time is fixed based on the system application and the vehicle operating condition. Regeneration takes place for every 105 hours in continuous emission strategy as per the BS6 emission requirement.

3.2.3 Mileage based regeneration.

With respect to the application, vehicle operation and soot behavior during running, a scheduler accelerates the regeneration in the vehicle after a fixed mileage. This method of regeneration management is commissioned mostly for on-road vehicles rather than the off-highway sectors where the vehicle operation is determined in terms of engine running hours instead of mileage accumulation.

3.2.4 Standstill regeneration

In operating conditions where the temperature in the DPF remains too low to initiate an automatic regeneration under low load conditions, often accompanied by a high soot output. There will be no conditions to make active regeneration (driving only in extremely short trips). In that case the driver may have to start a regeneration manually called forced regeneration or standstill regeneration. The driver has to stop the vehicle aside in a safe place and initiate a forced stationary regeneration. The vehicle must be driven for a short period at a steady accelerated speed without turning off the engines.

3.3 DPF protection strategy

DPF filters needs service to maximize its efficiency. Improper maintenance of DPF leads to heavy soot deposition, DPF damage, DPF leak or DPF crack which has an impact on engine back pressure, power loss and vehicle pick up. Major cause of failures is due to sudden accumulation of soot due to engine operating issue and high temperature in the DPF during regeneration event. Figure 8 shows the DPF failure cases in the field.

Figure 8: DPF field issues a) DPF clogged b) soot accumulation c)DPF crack or damage

The DPF safety features adhered in the controller software to maintain the performance and life of the DPF. This section covers overall algorithm built-in to protect DPF from failure. The two significant factors that drives the safety of the component is proper or accurate estimation of soot accumulation strategies for instance model based /DP based to trigger regeneration effectively to clean the DPF. The second is intimation to the driver or display of soot information in the cluster will help in servicing. Vehicle torque limitation inducement with respect to the enormous soot alerts the driver to initiate regeneration and clear the soot. High temperature warning lamp in the cluster will indicate driver the regeneration is in progress and to move the vehicle away from the hazardous areas like gas stations. Service regeneration is performed only in the workshop when the DPF loading reach 100 % and incase the automatic regeneration has not happened in some of the vehicle application due to low temperature operation.

Benefits

1. The major drawback of the off-road vehicle is the timely Maintenace of the vehicle which result in severe damage if it is not properly maintained. Advancing to the most salient software features for the ATS avoids DPF /SCR failures from field vehicles and life of the components.

2. Fault management and OBD advancement in off highway sector creates awareness to driver before the critical failures happen.

3.Inducement with respect to the DPF soot and automatic regeneration features reduces the downtime of vehicle and the servicing cost and effort of the technician.

Summary

As the emission trends for off highway keeps progressing from CEV4 to CEV5, it is must to integrate a complex after treatment system of DOC, DPF and SCR into the vehicle. The major challenge of off highway vehicle is the space constraint for packaging. Incorporating such huge system will be highly challengeable. Off highway vehicle would require a high protection strategy to prevent SCR and DPF faults in field vehicles. This paper gives a clear idea about the software control features which is required to avoid DPF and SCR failures in field. As like the other automotive sectors or on-road applications, off highway vehicles like dumper, paver, excavators, wheel loaders etc. have different operating conditions and runs in high mud areas would always require a periodic maintenance and service. Warning lamps and fault codes creates a technical awareness and indicates the drivers to take precautionary actions and address SCR and DPF related faults in prior and benefits the customers. All the hardware and software features mentioned in this paper gives better working of SCR and DPF systems in turn improves the efficiency of the system performance and reduce failures in field.

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Definitions/Abbreviations

CEV	Construction Equipment Vehicle
SCR	Selective Catalyst Reduction
EATS	Exhaust After Treatment System
ATS	After Treatment System
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ASC	Ammonia Slip Catalyst
OBD	On Board Diagnosis
DEF	Diesel Exhaust Fluid
OEM	Original Equipment Manufacturer
HC	Hydro Carbons
NH3	Ammonia
PM	Particulate Matter
PN	Particulate Number
NOx	Nitrous oxide