V Off-Highway Engine Efficiency R&D

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V.1 Off-Highway Heavy Vehicle Diesel Efficiency Improvement and Emissions Reduction

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Objectives:

- Evaluate technology options for meeting the Tier 4 Interim emissions requirements for off-highway heavy-duty diesel engines.
- Identify technical solutions best able to meet customer and Tier 4 emissions requirements while maintaining or improving system fuel efficiency.

Approach

- Define the technical and performance requirements of the Tier 4 engine systems.
- Assess the capability of current and future technologies to meet the Tier 4 requirements.
- Use analysis tools including combustion computational fluid dynamics (CFD) and cycle simulation to evaluate the performance of emissions technologies proposed and design an optimal system.

Accomplishments

- Customer requirements understood and translated to critical technical requirements for Cummins' Tier 4 engine systems.
- A number of emissions architectures have been identified for meeting the Tier 4 Interim emissions requirements.
- Potential architectures have been evaluated against the critical technical requirements.
- Combustion CFD and cycle simulation analysis to recommend combustion and air handling hardware for experimental validation.

Future Directions

- Limited experimental confirmation of model results on Cummins QSB engine.
- Key milestones through Q1 2006 include analysis and experimental work leading to the selection of the prime path Tier 4 Interim emission architecture for further optimization.

Introduction

Cummins Inc. is a world leader in the development and production of diesel engines for on-highway vehicles, off-highway industrial machines, and power generation units. Cummins Inc. diesel products cover a 50-3500 Hp range. This project includes engines in the 174-750 Hp range to achieve EPA's Tier 4 emissions levels of 2.0 gm/kW-hr oxides of nitrogen (NOx) and 0.02 gm/kW-hr particulate matter (PM). Cummins' anticipated product offerings for Tier 4 in this range include the following: QSB6.7, QSC8.3, QSL9, QSM11, QSX15, QSK19. (For reference, numerical values indicate engine displacement in liters, letter designations indicate the product model).

Work in past years on this project focused on developing technology to meet the Tier 3 emissions requirements. This work concluded in 2004 with the successful development of an in-cylinder technology that met the emissions requirements while minimizing the impact on original equipment manufacturers (OEMs), providing tolerance to high-sulfur industrial fuels, and minimizing the impact of fuel consumption. During fiscal year 2005, the work was focused on identifying technologies to meet the Tier 4 Interim emissions requirements for the 174 - 751 horsepower category.

Approach

Early work on the Tier 4 technology focused on understanding the technical requirements of our Tier 4 products and identifying technologies that could meet these requirements. In addition to the emissions requirements, customers have a number of requirements that are critical to product success and may change with time as the industry and business environment change. Some time was spent understanding these customer requirements and translating them into technical requirements by which the various candidate emissions technologies could be evaluated. A number of technologies were considered that might be capable of meeting the Tier 4 Interim emissions requirements.

An analysis-led approach was then utilized to evaluate each of the identified technologies. Technologies were first screened based on their capability to meet the Tier 4 Interim emissions requirements and initial cost. The most promising technologies were further analyzed using Cummins' combustion CFD and cycle simulation analysis tools. Figure 1 describes the design and validation process that is utilized for optimizing the combustion system. More detailed performance estimates were completed and recommendations made for combustion and air handling hardware to be utilized in the experimental validation and optimization of these emissions architectures.

Results

A number of customers were interviewed to better understand the technical requirements of our Tier 4 products. These included Cummins employees, equipment manufacturers, and end users. Several Six Sigma tools were utilized to facilitate the process of conducting interviews and translating the input into meaningful technical requirements. This process is summarized in Figure 2. These technical requirements or critical parameters and target values for each are utilized to evaluate each of the potential emissions technology approaches.

A number of emissions control technologies have been identified as candidates for meeting the Tier 4 emissions requirements.

NOx Reduction

- Diffusion burn with cooled exhaust gas recirculation (EGR)
- Diffusion burn with oxygen membrane for charge nitrogen enrichment
- Combustion hardware optimization through piston, nozzle, and swirl modifications
- Selective catalytic reduction – hydrocarbon or urea-based
- NOx adsorber
- Premixed combustion

Particulate Reduction

- Particulate filter
- Oxidation catalyst
- Partial filter
- Combustion hardware optimization through piston, nozzle, and swirl modifications
- Increased injection pressure
- Premixed combustion

An initial down-selection of technologies was based on the ability of each to meet the Tier 4 Interim emissions requirements and the projected initial cost. More detailed analysis was completed of the remaining candidates. This analysis included

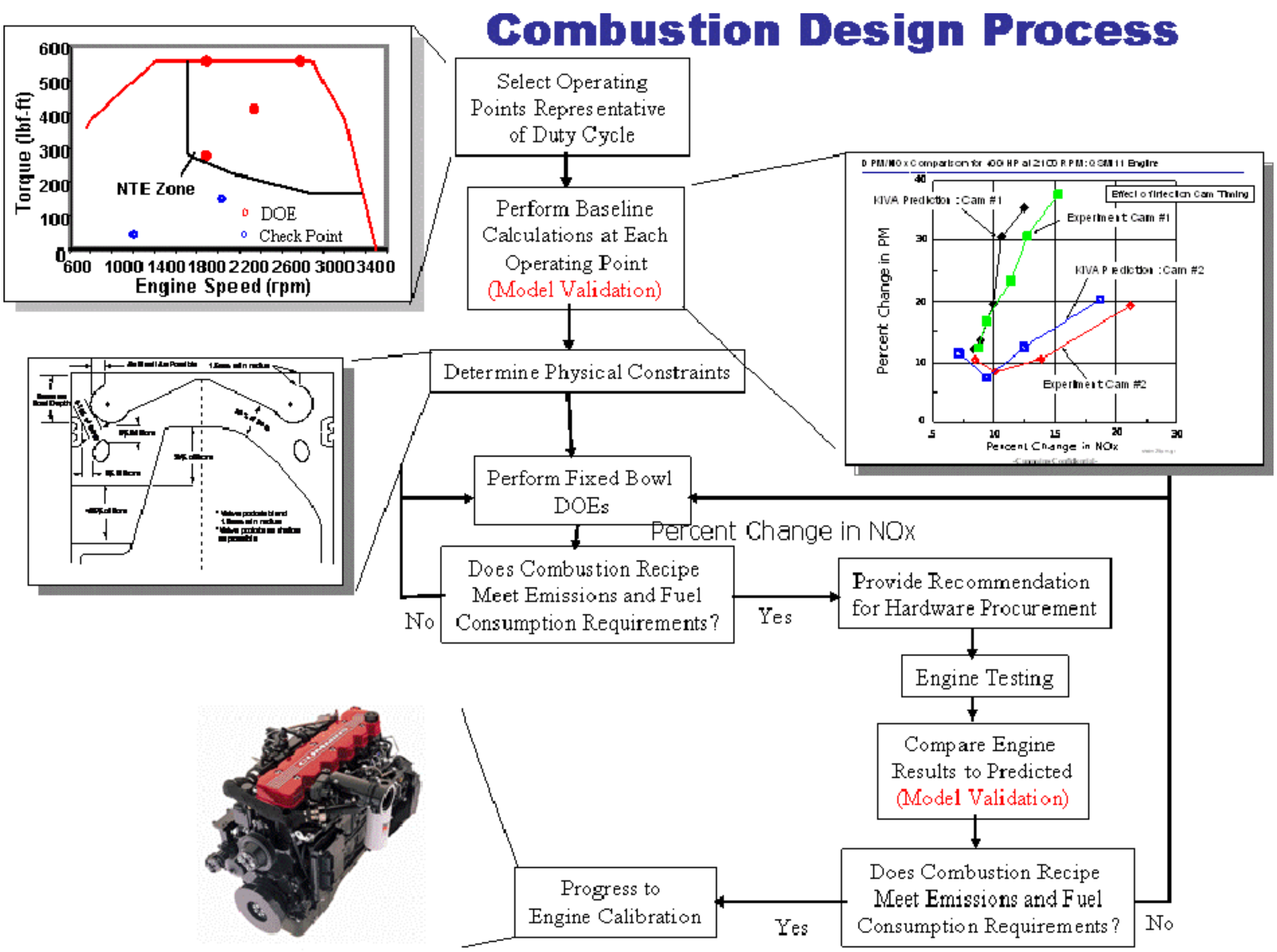

Figure 1. Combustion Design Process

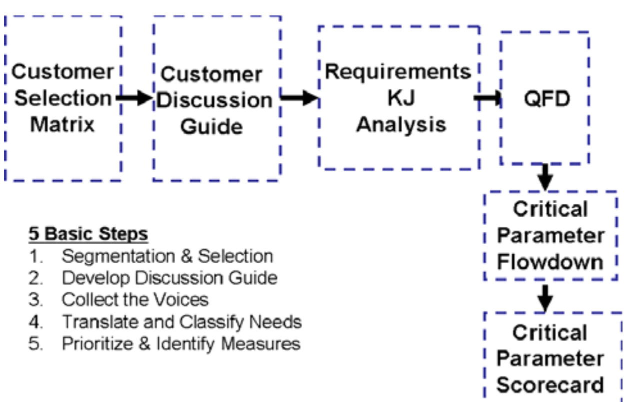

Figure 2. Technical Requirements Identification Process

combustion CFD modeling to assess in-cylinder emissions capability and define the optimal combustion system for each emissions architecture. The analysis approach was to do a model-based Design of Experiments (DOE) on the combustion system using the KIVA model. The combustion system elements considered in the DOE analysis are listed below.

- Injector spray angle
- Injector cup flow
- Rail pressure
- Number of injections/injection timing
- Cylinder head swirl
- Piston bowl geometry

A sample result from this DOE analysis for one emissions architecture is shown in Figure 3.

In addition to the detailed combustion analysis, cycle simulation analysis was completed to assess the overall fuel economy, altitude capability, and other performance characteristics. Results indicate that several emissions architectures present the opportunity to maintain or improve fuel economy

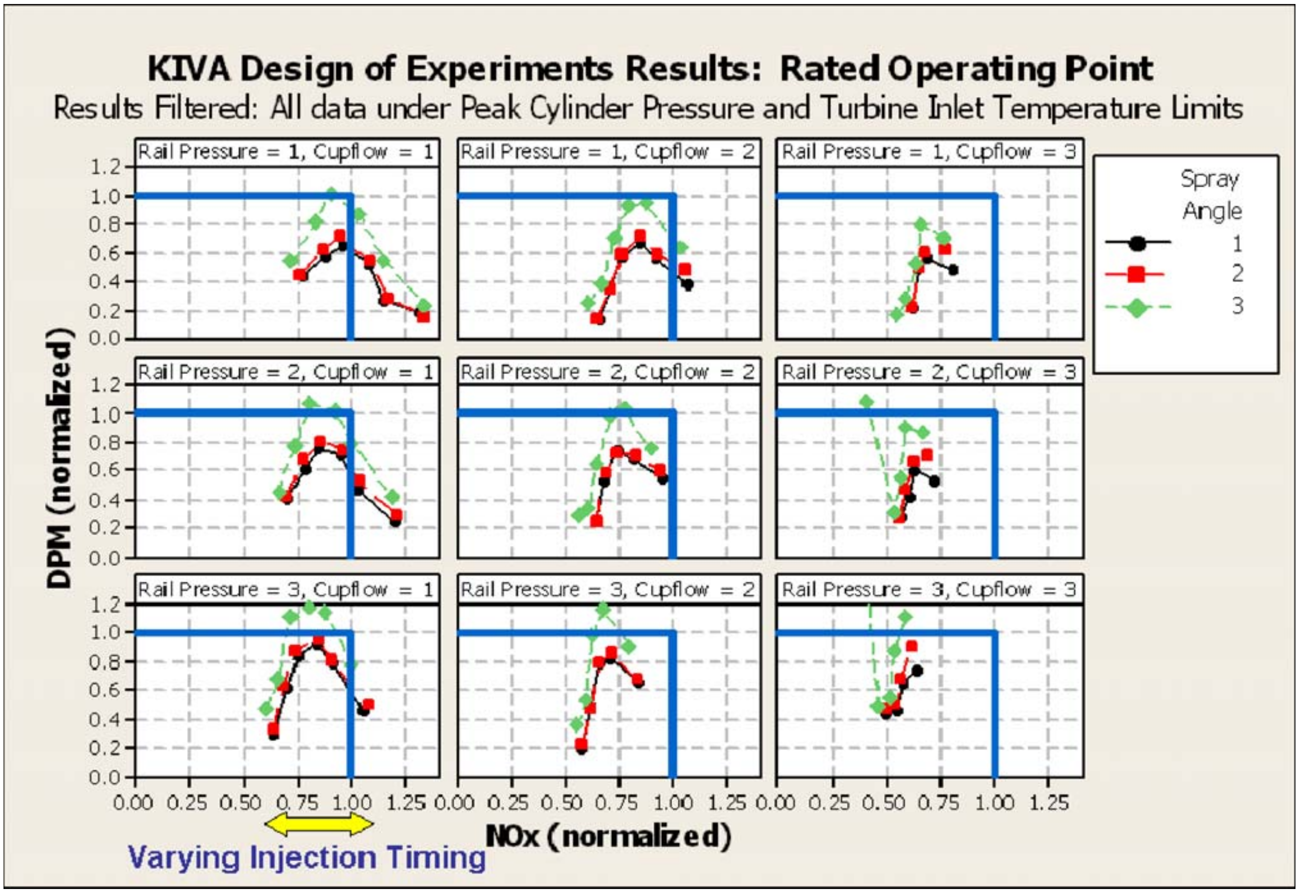

Figure 3. Example Design of Experiments Data for One Emissions Architecture

over Tier 3. Life-cycle cost modeling for several key industrial applications was completed to compare the impact of each of the emissions architectures on annual operating cost. All of this information will be utilized in selecting the best emissions technology for meeting the Tier 4 Interim emissions requirements.

Conclusions

The development of Cummins' Tier 4 Interim technology is well underway. Tier 4 customer and technical requirements have been defined and documented. Candidate emissions technologies for Tier 4 Interim have been identified. An initial down-selection has been completed based on emissions capability and initial cost. An analysis-led assessment of remaining emissions technologies and the recommendation of optimal hardware for experimental validation and optimization is underway.

FY 2005 Publications/Presentations

1. Q4 2004 Progress Report
2. Q1 2005 Progress Report
3. May 2005 DOE Technical Update in Columbus, Indiana
4. Q2 2005 Progress Report
5. Q3 2005 Progress Report
6. 2005 DEER Conference Poster Presentation

V.2 21st Century Locomotive Technology: Advanced Fuel Injection

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Objective

- Demonstrate advanced fuel injection systems on a large-bore, medium-speed, single-cylinder diesel engine that provide the desired injection characteristics for optimized specific fuel consumption and emissions.

Approach

- Implement advanced fuel injection system on single-cylinder locomotive engine.
- Determine optimized fuel injection parameters via experiments, using model predictions as a guide.
- Develop combustion model for locomotive engine and verify model via test data.
- Use combustion model and single-cylinder engine experiments to optimize fuel injection strategy.

Accomplishments

- Evaluated common rail fuel system performance on an EMI 2 flow meter (commercial device that measures individual injection quantities; made by Moehwald GmBH). Measurements were conducted to compare two generations of Bosch common rail hardware and included injection quantities representative of Notch 1 (N1) to Notch 8 (N8) of locomotive operation.
- Implemented latest generation of Bosch common rail hardware on the single-cylinder engine. This hardware delivers more consistent fueling cycle-to-cycle and features enhanced safety.
- Compared engine performance with “fast” and “slow” needle lift response and quantified the impact of response on fuel consumption and emissions. Variations in needle lift response were accomplished by changing injector orifice plate.
- Performed optimization studies at N4 and N8 with the latest generation high-pressure common rail (HPCR) system. The variables explored include injection timing, rail pressure, needle lift response, and multiple injection strategies.
- Established an improved method to compare the brake performance of the single-cylinder engine (SCE) operation with the HPCR and the production unit pump system (UPS) fuel system.
- Collected baseline engine performance data with the production UPS fuel system at N4 and N8.
- Quantified fuel savings and emissions of the HPCR system at N4 and N8.

Future Directions

- Evaluate the performance of other hardware modifications to the common rail system. Possibilities include nozzle, orifice plate and injector accumulator volume changes.
- Continue optimization studies at N4 and N8.

- Expand testing at lower notches.
- Explore advanced combustion strategies for future emissions regulations.

Introduction

The goals and objectives of the Department of Energy and GE's 21st Century Locomotive Program are to develop freight locomotive engine technology and locomotive system technologies to address emissions standards while maximizing fuel efficiency. In 2005, Tier 2 freight locomotive emissions regulations took effect in the U.S. GE's response to the emissions regulations was to develop a completely new locomotive. Looking ahead, GE is working to reduce fuel consumption while continuing to meet Tier 2 emissions regulations and explore combustion systems to meet future emissions regulations. Future regulations will likely drastically reduce allowable NOx and PM emissions. Traditional methods to reduce emissions in diesel engines come at a cost of increased fuel consumption.

GE is committed to bringing technology to the locomotive industry to achieve both low emissions and low fuel consumption. Over the past year, GE has worked to advance the technology at both the diesel engine and locomotive system level. This document describes the technology development at the diesel engine level, which involves improving the brake-specific fuel consumption by development of advanced fuel injection.

Approach

Fuel injection has a significant effect on a diesel engine's performance since the combustion is controlled by the rate of mixing and the fuel atomization. To explore the opportunity for performance and emissions improvements by advanced fuel injection, a flexible HPCR system has been installed on a locomotive single-cylinder research engine. The system, which is provided by Bosch, is capable of up to four injection events per cycle and produces injection pressures above 1800 bar.

The HPCR system allows real-time adjustment of fuel pressure and injection schedule. Hardware changes include orifice plate, nozzle configuration, and other details regarding the injector design. GE has executed experiments to understand the role of each of these parameters on engine performance and emissions. In addition, computational fluid dynamics (CFD) analysis using the KIVA code was performed in collaboration with the University of Wisconsin – Madison. The KIVA modeling work provides input and guidance for the experimental study on the SCE.

Results

Major accomplishments pertaining to the advanced fuel injection are new hardware integration and experimental optimization on the SCE. The latest generation fuel injection hardware provides lower variation in fuel injection parameters. The new features on the fuel injection hardware include a high-pressure accumulator integrated into the fuel injector, an orifice between the injector accumulator and the larger "common rail" accumulator, and a check valve between the aforementioned accumulators. Testing on an EMI 2 measurement device showed a decrease of cycle-to-cycle variability in rail pressure, rate of injection profile, and injected quantity (Figure 1). Lower variation in

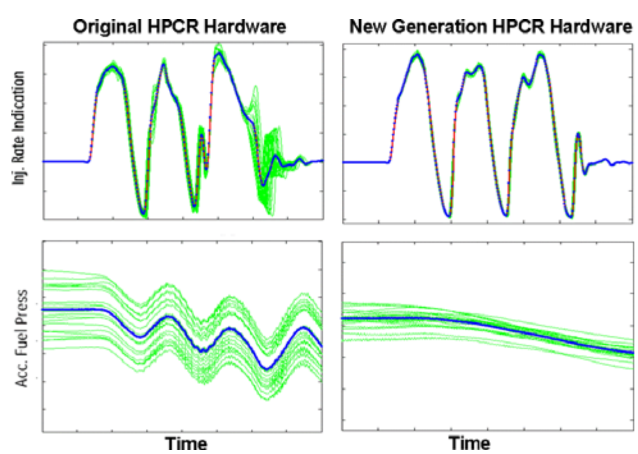

Figure 1. Injection Rate Shape and Fuel Rail Pressure for 20 Consecutive Cycles and Their Average [Left] Original fuel injection hardware shows significant variation in injection rate and fuel pressure. [Right] New generation fuel injection hardware has lower variation in both fuel pressure and injection rate.

the fuel injection parameters allows for more precise control of the engine.

The experimental efforts have been focused on performance mapping of the HPCR system on a single-cylinder locomotive engine at N4 (part-load) and N8 (high-load) operating conditions. The variables explored include rail pressure, overall injection timing, multiple injection/stroke (where variables include number of injections, relative size of injection, and relative spacing of injections), and injection rate shape (distinguished by "fast" and "slow" needle response). By changing control hardware internal to the common rail fuel injector, we have tailored the fuel injection rate shape and explored its effect on engine performance. With the data collected over the last annual period, we determined which type of injection rate is preferred.

The effects of multiple injection strategies versus single injection strategies were quantified for both the fast and slow needle lift variations, as depicted in Figure 2. The multiple injection strategies were determined via screening tests in which split, pilot, and post injection strategies were considered.

A friction adjustment was performed to compare the brake-specific fuel consumption of the HPCR to that of the UPS. The engine camshaft drives the fuel pump for the UPS, while the fuel pump for the prototype HPCR system is driven electrically. The horsepower required to drive the HPCR pump was calculated (given assumed efficiencies of the pump) and deducted from the horsepower generated by the engine. Given this adjustment, the brake-specific fuel consumption values for the UPS and the HPCR are calculated with consistent auxiliary loads.

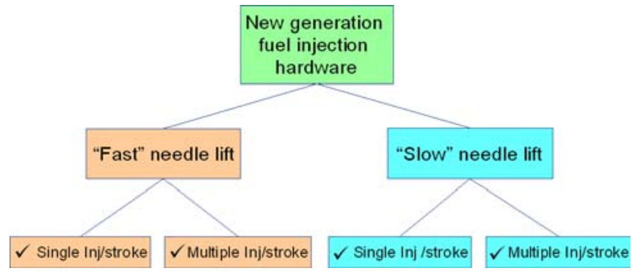

Figure 2. Tree Depicting the Types of Experiments that Were Performed in the Last Quarter on the GE Global Research Single-Cylinder Engine with a High-Pressure Common Rail Fuel System

Conclusions

- The HPCR fuel system provides greater opportunity to reduce NOx and PM emissions without increasing brake-specific fuel consumption, due to its flexibility in fuel injection.
- Additional experiments, hardware refinements, and lower notch investigations are required to determine the optimum HPCR strategy over the range of locomotive operation and to determine duty cycle improvement.
- Further work is needed to quantify the impact of cycle-to-cycle variability of the fuel rail pressure on the emissions and performance tradeoff.

Special Recognitions & Awards

1. GE Rail Technology Leadership for Innovation Award – January 2005

V.3 Exhaust Aftertreatment and Low Pressure Loop EGR Applied to an Off-Highway Engine

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Objectives

The overall goal of the project is to demonstrate that low pressure loop exhaust gas recirculation (EGR) incorporating a diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF) can be applied to an off-highway engine to meet Tier 3 (Task I) and interim Tier 4 (Task II) off-road emissions standards. Task I was completed in 2004 and Task II was completed in 2005. Task II objectives were as follows:

- Optimize a 6.8 liter, 4 valve engine with an advanced high-pressure common rail fuel injection system using EGR and an advanced combustion system to minimize brake-specific fuel consumption (BSFC) and still meet the emissions standards of 2 g/kWh NOx and 0.02 g/kWh particulate matter (PM).
- Collect particle size distribution data and DPF loading data for the continuously regenerating catalyzed diesel particulate filter (CR-CDPF) that can then be used to verify the MTU aftertreatment model.
- Identify optimum regeneration control strategies.

Approach

- Collect gaseous and particulate matter data over the ISO 8178 steady-state test cycle with and without the exhaust aftertreatment
- Measure the exhaust particle size distributions for both the baseline engine and for the engine with the EGR/CR-CDPF emission control system over several engine operating conditions.
- Determine DPF loading curves for various conditions to calibrate the MTU aftertreatment model.
- Use cylinder deactivation to increase exhaust temperatures at light loads to enable passive regeneration.

Accomplishments

- The low pressure loop EGR system has been optimized and the goal of less than 2 g/kWh NOx and less than 0.02 g/kWh PM over the ISO 8178 eight-mode test was achieved.
- All the aftertreatment loading data has been collected and provided to MTU for their aftertreatment model development.
- The cylinder deactivation tests have been completed, and by operating the engine on 3 of the 6 cylinders, the exhaust temperatures under most light load conditions are above 275°C, which will enable passive regeneration.

Future Directions

- MTU will add new subroutines to their computer code to model the new aftertreatment technology.
- The data collection portion of the project has been completed. The final DOE report will be prepared early in 2006.

Introduction

This project evaluates the feasibility of using an EGR system in combination with a high-efficiency diesel particulate filter to reduce both oxides of nitrogen (NOx) and particulate emissions. By removing the EGR gas downstream of the DPF, the clean gas can be routed to the upstream side of the turbocharger, and because the exhaust is free of particles, there is no abrasive wear on the turbo compressor wheel or fouling of the engine's intercooler. The major driving force for this work was to meet the future 2011 Tier 4 off-road diesel emissions standards with improved fuel economy over alternative technologies for meeting Tier 4.

This project was divided into two tasks. Results from Task I were reported in 2004. This report covers the results from Task II and will also make important comparisons to results from Task I.

Approach

A John Deere 6081H-175 kW engine was used for Task I, and an advanced John Deere 6068H-187 kW engine was used for Task II. Table 1 compares the engine specifications for the two engines. The main difference is that the 6068 engine had a modified fuel injection system that enabled higher fuel injection pressures. This was required in order to minimize the PM emissions as the EGR percentage was increased to obtain NOx levels of less than 2 g/kWh. The aftertreatment for Task I incorporated a diesel oxidation catalytic converter (DOC) with an uncatalyzed continuously regenerating DPF (CR-DPF), and Task II incorporated a DOC plus a catalyzed DPF (CR-CDPF). Both DPFs used the Corning DuraTrap CO cordierite material with 200 cells/in^2 (cpsi).

The test program was initiated by obtaining baseline data with no aftertreatment or EGR over the ISO 8178 test cycle. An EGR strategy was then determined, and additional tests were conducted with EGR and the CR-CDPF. Several additional operating conditions were identified that were used for loading the DPF without regenerating. Particle size distributions were obtained using a TSI Scanning Mobility Particle Size Analyzer (SMPS). In order to only measure the solid particle size distributions, the sample was passed through a thermal denuder to remove the volatile portion of the particles and then diluted and passed to the SMPS.

Table 1. Engine Specifications for the 6081 and 6068 John Deere Engines

	Task 1	Task 2
Model	Tier 2 John Deere 6081H	Tier 2 John Deere 6068H
Type	4 stroke 2 valve	4 stroke 4 valve
Cylinder	6, in-line	6, in-line
Aspiration	Turbocharged, Aftercooled	Turbocharged, Aftercooled
Displacement	8.1 liters	6.8 liters
Rated Power	175 kW @ 2200 rpm	187 kW @ 2200 rpm
Peak Torque	1060 N-m @ 1400 rpm	1000 N-m @ 1650 rpm
Timing	Variable (Electronic Control Unit)	Variable (Electronic Control Unit)
Injection System	Standard HPCR	Advanced HPCR
EGR System	Cooled LPL EGR	Cooled LPL EGR with increased quantities

For Task II using the CR-CDPF technology, passive regeneration can occur at temperatures around 275°C. Cylinder deactivation was evaluated to increase the exhaust temperatures at the light load conditions. This was accomplished by removing the lifters from cylinders 4, 5 and 6, and then only firing cylinders 1, 2 and 3. This caused the load to double in the firing cylinders and the exhaust temperatures to increase.

Results

Figure 1 shows the 8-mode NOx and PM results for both engines (Task I and II). The large box represents the Tier 3 standards and the smaller box the interim Tier 4 standards. For Task 1 with the 8.1 L engine, the 8-mode data indicated 0.006 g/kWh PM and 3.6 g/kWh NOx. By changing to the 6.8 L engine, adding additional EGR and using higher fuel injection pressure, the 8-mode data were improved to

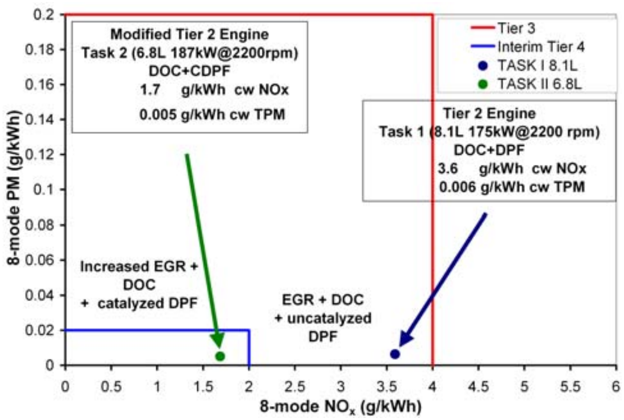

Figure 1. ISO 8178 Test Cycle Results for Task I and Task II

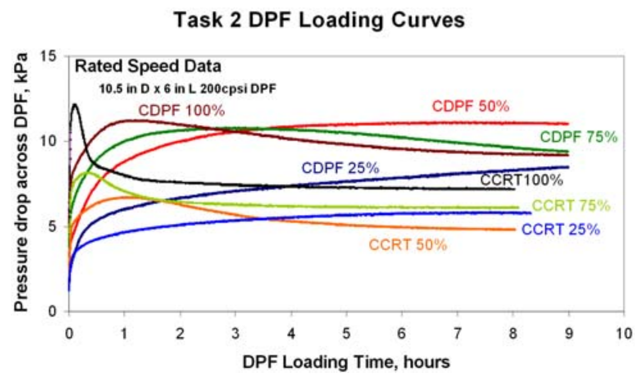

Figure 3. Particulate Loadings at Rated Speed and Various Percent Loads for the CDPF and the CR-DPF Aftertreatment Devices

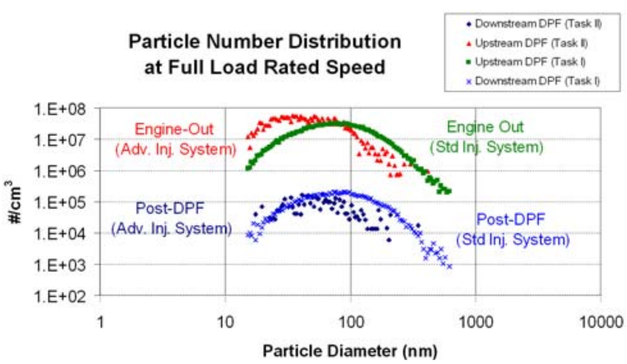

Figure 2. Particle Number Distributions Measured at Pre and Post Aftertreatment Locations

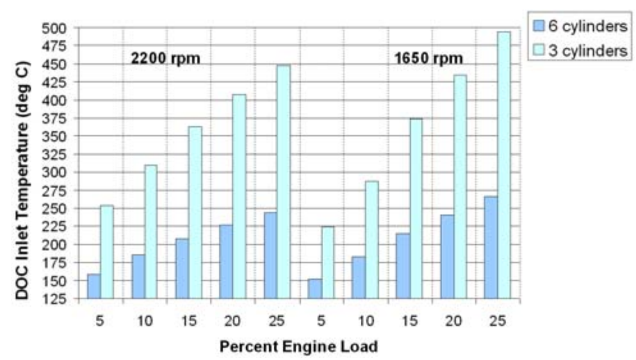

Figure 4. Results from the Cylinder Deactivation Tests

0.005 g/kWh PM and 1.7 g/kWh NOx. These values are comfortably within the Tier 4 standards.

Figure 2 shows the particle number distribution at full load rated speed for both engines. The particle concentrations for both engines were similar; however, the 6.8 L engine with the advanced fuel system indicated slightly smaller particles. Similar results were obtained post DPF. Even though the particle concentrations were similar, the 6.8 L engine had considerably less mass emissions engine-out than the 8.1 L engine. In fact, the 6.8 L engine with EGR had 67% less engine-out PM than the 8.1 L engine with no EGR. The 6.8 L engine also had NOx/PM ratios greater than 40:1 for ISO 8178 modes 1, 2, 3, 5 and 6, while the 8.1 L engine had NOx/PM ratios of only 9-10 for the same modes. The aftertreatment supplier recommends NOx/PM ratios greater than 20 for passive regeneration.

Figure 3 shows the loading curves at rated speed and various percent loads for Task II. Because the CR-CDPF has catalyst on both the DOC and the DPF, loading data had to be collected for both the CDPF and the CR-CDPF to enable proper modeling of the aftertreatment system. The upper curves have higher pressure drop because there is less passive regeneration occurring. The lower curves with the CR-CDPF technology (labeled CCRT) indicate that for the 50, 75 and 100% loads, the pressure drop increases, then decreases and stabilizes, indicating that passive regeneration is occurring. Only the 25% load indicates that the pressure drop is still increasing. This condition had exhaust temperatures around 250°C.

Figure 4 shows the results from the cylinder deactivation tests for 2200 and 1650 rpm conditions. Passive regeneration occurs at about 275°C when the NOx/PM ratio is greater than 20 to 1. The intent is for the engine to switch to 3-cylinder operation at the lighter load conditions, causing the exhaust temperature to increase above 275°C and passive regeneration to occur. For these two speeds, 275°C exhaust temperature was obtained for loads above 10%. When switching from 6 cylinders to 3, the engine was still balanced, and there was very little difference in the audible sound of the engine. One could not distinguish between operating on either 3 or 6 cylinders.

Conclusions

- The low pressure loop EGR and CR-CDPF system using the advanced 6068 engine reduced the NOx emissions to 1.7 g/kWh and the PM to 0.005 g/kWh.
- The particle size distributions shifted to smaller particles when using higher fuel injection pressures, but the overall mass was reduced more than 67%.
- Aftertreatment loading data was collected and will be used by MTU to further calibrate their aftertreatment model.
- Cylinder deactivation can be used at the light load conditions to increase the exhaust temperature and enable passive regeneration.

FY 2005 Presentations

1. Baumgard K.J. Exhaust Aftertreatment and Low-Pressure Loop EGR Applied to an Off-Highway Diesel Engine. Presented at the 11th Diesel Engine Emission Reduction (DEER) Conference in Chicago, IL, August 21-25, 2005.

References

1. Triana A.T., Johnson J.H., Yang S.L. and K.J. Baumgard. An Experimental and Computational Study of the Pressure Drop and Regeneration Characteristics of a Diesel Oxidation Catalyst and a Particulate Filter. SAE Paper No. 2006-01-0266.