V Off-Highway Vehicle Emission Control R&D

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

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Objectives

- Develop analytical tools to enable optimization of the combustion process for both emissions and low fuel consumption.
- Utilize combustion modeling capability to develop in-cylinder solutions to meet the Tier 3 emissions standards while maintaining fuel consumption levels.
- Verify that the Tier 3 engines meet emissions and fuel economy targets through single- and multi-cylinder engine testing.
- Investigate technology options to meet the Tier 4 emissions levels while maintaining fuel consumption levels.

Approach

- Develop analytical modeling capability to facilitate the design and optimization of in-cylinder combustion recipes to meet the Tier 3 emissions levels while maintaining fuel consumption levels.
- Utilize modeling tools to design combustion recipes on multiple engine platforms that meet the Tier 3 emissions targets while minimizing the impact on fuel consumption.
- Demonstrate the combustion recipes in single- or multi-cylinder engine tests and optimize the emissions and performance of the engines.

Accomplishments

- Combustion system design for Tier 3 completed on three engine platforms with fuel consumption close to Tier 2 values.
- Experimental engine validation and optimization completed for Tier 3 combustion system design.
- Improved combustion computational fluid dynamics (CFD) sub-models incorporated and validated.
- Calibration improvement model developed for transient calibrations.
- A new and improved CFD code is under development that will give improved combustion modeling capability for more complex combustion systems.
- Work has been initiated to develop engines to meet the Tier 4 emissions standards. This work has included an investigation into potential technologies to meet these standards as well as work to understand the customers' requirements.

Future Directions

- Complete the validation and optimization of the Tier 3 combustion recipes.
- Continue with combustion tool development.
- Continue with calibration tool development.

- Develop technologies including engine and aftertreatment solutions to meet the Tier 4 emissions levels at Tier 3 fuel consumption levels.
- Analyze the potential Tier 4 technologies' capability to meet the technical requirements of the project.

Introduction

Cummins is a world leader in the development and production of diesel engines for both on-highway and off-highway markets and is committed to the efforts to reduce the emissions of these products. The power range for this project includes 80-750 HP to achieve the Environmental Protection Agency's Tier 3 and 4 emissions levels shown in Figure 1. Cummins' anticipated product offerings regarding this topic include the following: B3.9, QSB6.7, QSC8.3, QSL9, QSM11, QSX15, and QSK19.

Off-highway emissions standards will result in reduced NO_x emissions for Tier 3 off-highway engines and an additional NO_x reduction as well as a reduction in PM for Tier 4 off-highway engines. While these emissions standards lag the on-highway standards, the unique requirements of the off-highway markets make it necessary to consider unique solutions that meet the requirements of these products.

Approach

Cummins' approach to developing next-generation engines to meet the reduced emissions requirements utilizes a customer-led focus as well as an emphasis on analysis-led design. Before the design of the new systems begins, work is completed to clearly understand the customers' requirements and how these impact the technical requirements of the products. An analysis of various technologies and their capabilities to meet these requirements is completed. An analysis-led approach is then utilized to design these future systems, followed by validation through single- and multi-cylinder engine testing and optimization. For Tier 3, an in-cylinder emissions solution was utilized to meet the emissions requirements with minimal impact on fuel consumption, performance, packaging, and cost.

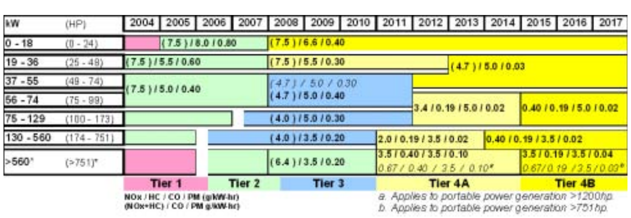

Figure 1. Summary of Tier 3 and 4 Emissions Standards

Results

In-cylinder solutions to achieve the Tier 3 emissions levels have been developed on the QSB6.7, QSC8.3, QSL8.9, QSM11, QSX15, and QSK19 with a minimal impact on fuel consumption. Fuel consumption varies from 2% better to 9 % worse compared to Tier 2, depending on the engine and application. The combustion recipe was first developed utilizing Cummins' combustion CFD modeling tool. This modeling tool has been improved by including new NO_x transport models, an improved spray model, and the ability to model multiple injection events. The combustion recipe was then validated and optimized using experimental single- or multi-cylinder engine testing.

A number of techniques have been employed to reduce the emissions levels while maintaining fuel consumption levels. A transient calibration technique (multivariable local regression, or MLR) has been developed which allows the calibration of the engine to be completed in one-half to one-third of the time needed for the conventional technique and results in a more optimized calibration. This technique improves the ability to prevent emissions overshoots and reduce fuel consumption during transient operation. Figure 2 shows a comparison of MLR's predicted NO_x and particulate emissions and actual emissions recorded over the first 900 seconds of the Federal Test Procedure (FTP) transient cycle.

Additional work is underway to further optimize the calibration of the Tier 3 engines and to complete mechanical verification of these engines.

As the Tier 3 work wraps up, the focus has shifted to meeting the Tier 4 emissions standards while continuing to maintain fuel economy and meet customer requirements. The Technology Development for Six Sigma approach will be utilized in developing technology for Tier 4. This consists of

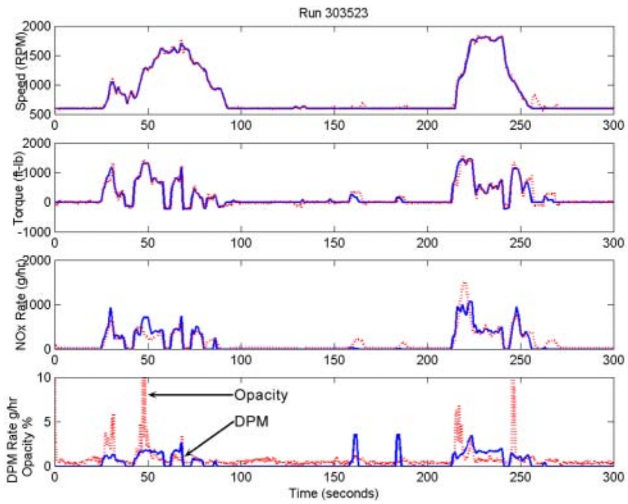

Figure 2. MLR Predicted Emissions for ISX '04 FTP Cycle Compared to Experimental Data

four phases of development as shown in Figure 3: Invent and Innovate, Develop, Optimize, and Certify. This process introduces a rigorous approach to technology development which emphasizes the relationship between the customer requirements and the technical solution and the development of a robust and tunable technology.

Currently, further improvements are being made to the combustion modeling tools to enable the design of these combustion systems. Work has been initiated to understand the customer requirements for Tier 4 products and to evaluate potential technologies, including in-cylinder and aftertreatment approaches, to meet these emissions standards.

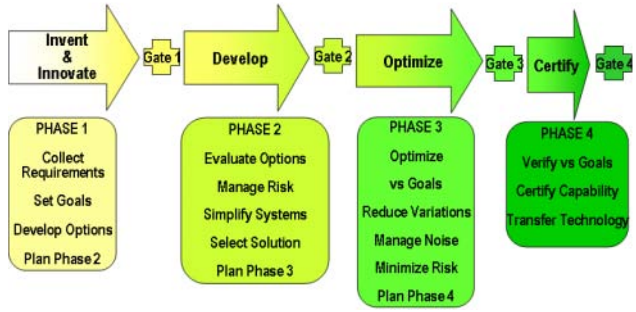

Figure 3. Tier 4 Technology Development Cycle

Conclusions

The design and optimization of Tier 3 compliant off-highway engines is nearing completion. Advances in the combustion CFD tool's capability to model and predict combustion recipe performance was a key enabler in the design of these solutions. An in-cylinder solution which does not require the use of cooled exhaust gas recirculation has been successfully employed across Cummins' off-highway engine product line (QSB6.7, QSC8.3, QSL8.9, QSM11, QSX15, and QSK19). A slight fuel consumption penalty has resulted for some engine platforms.

Work is now underway to develop the customer and technical requirements and understand the technology capabilities as we begin to investigate solutions to meet the Tier 4 emissions standards.

V.2 Exhaust Aftertreatment and Low-Pressure Loop EGR Applied to an Off-Highway Engine

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Objectives

- Demonstrate that 4 g/kWh NO_x + HC (hydrocarbon) and 0.02 g/kWh particulate matter (PM) emission levels can be achieved over the ISO 8178 test cycle using cooled low-pressure loop exhaust gas recirculation (EGR) and a continuously regenerating diesel particle filter (CR-DPF). This will require optimizing the EGR strategy for NO_x reduction and also optimizing the engine for best brake specific fuel consumption (BSFC).
- Collect particle size distribution data and loading curve data for the CR-DPF that can then be used to verify the Michigan Technological University (MTU) aftertreatment model.
- Develop an aftertreatment model incorporating exhaust flow, filtration, heat transfer, reaction kinetics, and regeneration characteristics, including an NO_2-assisted oxidation sub-model and an "in the wall" sub-model to predict the regeneration behavior of a CR-DPF.

Approach

- Collect gaseous and particulate data over the ISO 8178 steady-state test cycle with and without exhaust aftertreatment.
- Measure the exhaust particle size distributions with and without the EGR/DPF emission control system over several engine-operating conditions.
- Determine DPF loading curves for various conditions.
- Modify the MTU aftertreatment model to include the NO-to-NO_2 conversion across the diesel oxidation catalyst and also the NO_2-assisted regeneration across the DPF.
- Use the engine and emission data collected to verify the MTU aftertreatment model.

Accomplishments

- The low-pressure loop EGR system has been optimized, and the goal of less than 4 g/kWh NO_x and less than 0.02 g/kWh PM over the ISO 8178 eight-mode test was achieved.
- All the engine emission data has been collected.
- The MTU aftertreatment model has been completed and calibrated with the collected data. The model determines the NO-to-NO_2 conversion across the diesel oxidation catalyst and predicts the NO_2-assisted and thermal regeneration across the CR-DPF as well as the pressure drop across the aftertreatment system.

Future Directions

- The plan is to switch to a 6.8-liter, more advanced diesel engine and reduce the NO_x from 4 to 2 g/kWh to meet the interim Tier 4 (2011) off-highway emission standards. The exhaust aftertreatment will be upgraded to the latest technology for better performance.
- MTU will add new subroutines to their computer code to model the new aftertreatment technology.

Introduction

This project evaluates the feasibility of using a low-pressure loop EGR system in combination with a high-efficiency CR-DPF to reduce both NO_x and PM. By removing the EGR downstream of the DPF, it 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. With this emission control strategy, the overall engine efficiency is greater than if a high-pressure loop EGR system was incorporated. A study by Moser et.al., 2001, indicated that the low-pressure loop EGR system with a DPF resulted in a BSFC that was 3.5% percent better than that of a high-pressure loop system with a DPF.

The major driving force for the research is to meet the future off-road diesel emission standards. The Off-Road Tier 3 standards take effect in 2006, and the Tier 4 standards begin in 2011. The technology gained from this project will contribute to meeting both the Tier 3 and Tier 4 standards with improved fuel economy.

Approach

A John Deere 6081H 175-kW engine has been used for this research. The engine's displacement is 8.1 liters and is turbocharged and intercooled. It incorporates a high-pressure common rail fuel injection system and is fully electronic. A CR-DPF was placed downstream of the turbocharger, and downstream of the CR-DPF a portion of the exhaust gas is routed back to the intake system. A cooler is incorporated to cool the EGR, which maximizes reduction of NO_x.

The test project consisted of obtaining baseline data with no aftertreatment or EGR over the ISO 8178 test cycle. An EGR strategy was determined, and additional tests were conducted with EGR and the CR-DPF. Several additional operating conditions were identified that were used for loading the DPF without regenerating. These conditions were necessary so that when the DPF was installed, the steady-state loading curves could be obtained. The data was used to validate the MTU model.

Results

The initial data was collected over the ISO 8178 eight-mode test cycle. Table 1 compares the results between the baseline data and the low-pressure loop EGR with the CR-DPF. The low-pressure loop EGR system reduced the NO_x emissions by an average of 28%. The CR-DPF reduced the PM and HC emissions by over 94%. The NO_x plus HC standard for Tier 3 is 4.0 g/kWh for this power engine, and the values obtained provide an acceptable margin for meeting the standards. The data also indicates that brake-specific fuel consumption (BSFC) improved slightly over the baseline data.

Table 1. Summary of the ISO 8178 Data

Data in g/kWh	NO_x	HC	NO_x + HC	PM	BSFC at FLRS[1]
Baseline, no EGR	5.22	.51	5.73	.132	211.9
With EGR/ CR-DPF	3.74	.03	3.77	.008	208.9

[1]Full Load Rated Speed

The DPF loading curve data was collected as shown in Figure 1. First, the data was collected with only the DPF portion of the exhaust aftertreatment. During this loading, the diesel oxidation catalyst was not installed and, therefore, there was no NO_2-assisted regeneration. This is evident because the pressure drop curves continue to increase as a function of time (see DPF 100%, DPF 75%, DPF 50% and DPF 25% curves). When the diesel oxidation catalyst was installed upstream of the DPF,

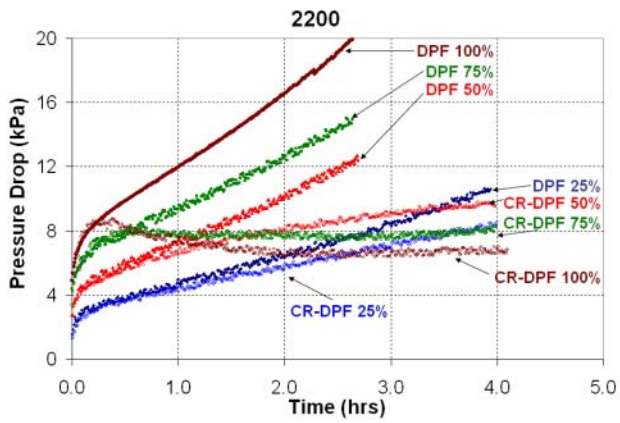

Figure 1. Pressure Drop Data Collected Over Time at 2,200 RPM and Various Percent Engine Loads for Both the DPF (diesel particle filter) and the CR-DPF (continuously regenerating diesel particle filter)

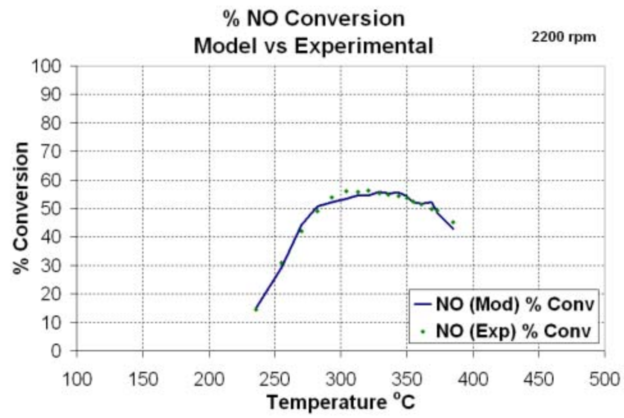

Figure 2. Oxides of Nitrogen Percent Conversion at 2,200 RPM, Model Versus Experimental

the pressure drop initially increased but then decreased and leveled off for the 100% and 75% load CR-DPF conditions. This indicates that the amount of soot being deposited within the DPF is equal to the amount being burned. For the CR-DPF 25% and 50% load conditions, the pressure drop continues to slowly build but at a much slower rate than with the DPF only. At these lower exhaust temperatures, there is NO_2-assisted regeneration occurring, but the amount of soot being deposited is greater than the amount being consumed. The amount of soot regenerated during these tests was determined by weighing the DPF before and after each loading test. By comparing the amount of mass collected within the DPF to the amount that entered, one can determine the amount that was regenerated. This information was used in the MTU model to verify the NO_2-assisted regeneration model.

The amount of NO_2-assisted regeneration is naturally dependent on the amount of NO_2 present. Therefore, it was necessary to determine the conversion rate of NO to NO_2 across the diesel oxidation catalyst. This data was obtained by operating the engine at several speeds and various loads to vary the exhaust temperatures. The data for 2200 rpm is shown in Figure 2 along with the MTU model results. The model results agree well with the experimental results. Similar results were obtained at 1400 rpm. Antonio (et.al.) reported these results in an earlier SAE publication.

In order to more accurately predict the pressure drop across the DPF, it is necessary to know the size distribution of the particles entering the DPF. Figure 3 shows the upstream and downstream distributions at 2200 rpm and 100% load. The solid line is the MTU model results and the open symbols are the experimental data. Similar results were obtained at 1400 rpm.

Figure 4 shows the modeled pressure drop results at 1400 rpm and 50% load. Again, the open symbols are the experimental results and the solid lines are the modeled results. The difference between the DPF and the CR-DPF pressure drop results is due to the NO_2-assisted regeneration. The slopes on the CR-DPF curves are still positive, indicating that there is still some soot being deposited. This is due to the fact that the NO_2-to-PM ratio is only 2.7:1. Theoretically, a ratio of 8:1 is needed to have sufficient NO_2 to react with all the soot.

The 8.1-liter engine was not designed for low-pressure loop EGR, and when the EGR was added, the NO_x emissions were reduced but the PM emissions increased. This corresponds to the well-known NO_x-to-PM relationship in which if the NO_x is reduced, the PM emissions increase. In order for this technology to be successful on this engine family, the engine-out PM emissions must be decreased. This could be done with an improved fuel injection system, optimized combustion system and a rematch on the turbo charger.

The next task of the project is to design a low-pressure loop EGR system to meet the interim Tier 4

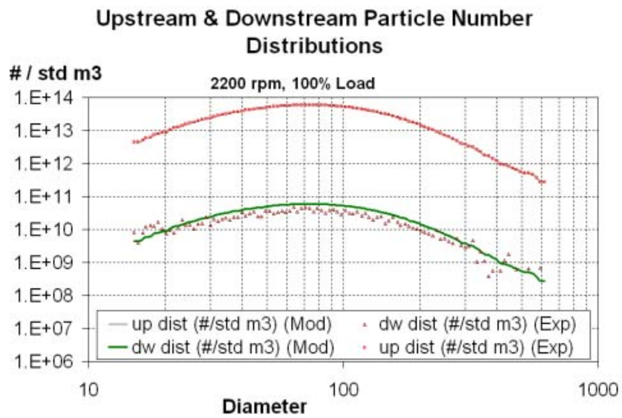

Figure 3. Particle Size Distributions Upstream and Downstream of the DPF at 100% Load and 2,200 RPM

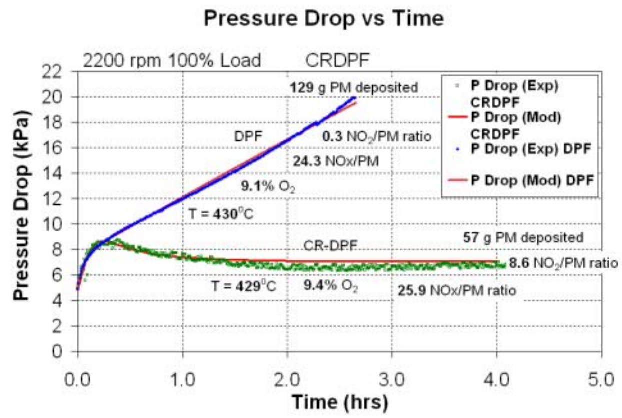

Figure 4. MTU Modeled Pressure Drop for Both the DPF and CR-DPF Conditions at 1,400 RPM and 50% Load

off-highway standards. This will require larger quantities of EGR and will require a more advanced engine. The engine will be 6.8 liters with a more advanced high-pressure common rail fuel system and a better-matched turbocharger. The exhaust aftertreatment will also be changed to the latest technology that incorporates a diesel oxidation catalyst and a catalyzed DPF. By adding catalytic material to both the diesel oxidation catalyst and the DPF, the theory is that more NO_2 will be available to react with the collected soot.

Conclusions

- The low-pressure loop EGR and CR-DPF system reduced NO_x emissions 28%, HC emissions 94% and PM emissions by 94%.
- The MTU model was able to incorporate the thermal and NO_2-assisted regeneration for the CR-DPF technology.
- The MTU model also properly predicted the pressure drop across the CR-DPF technology.

Presentations

1. Simulation of a Coupled Diesel Oxidation Catalyst and a Diesel Particulate Filter Model. Antonio Triana. Michigan Tech University. Presented at the June 16th, 2004 CLEERS Workshop in Detroit, Michigan.

References

1. Moser F., Sams T., Cartellieri W. Impact of Future Exhaust Gas Emission Legislation on the Heavy Duty Truck Engine. SAE 2001-01-0186.
2. Antonio P., Triana A.P., Johnson J.H., Yang S.L., Baumgard K.J. An Experimental and Numerical Study of the Performance Characteristics of the Diesel Oxidation Catalyst in a Continuously Regenerating Particulate Filter. SAE 2003-01-3176.

V.3 Advanced Fuel-Injection System Development to Meet EPA Emissions Standards for Locomotive Diesel Engines

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Major Technical Objectives of Phase I of the Project

- Demonstrate, via emissions modeling and engine testing, Tier 2 emissions-compliance potential utilizing an advanced fuel-injection system.
- Design and build a prototype advanced fuel-injection system suitable for a single-cylinder locomotive diesel engine.
- Conduct demonstration tests on a single-cylinder locomotive diesel engine to validate the new fuel-injection system design and injection strategies along with re-optimized engine hardware and operating conditions.

Approach

- Set up appropriate analytical (engine and combustion) models and conduct parametric studies to analyze the effects of various injection strategies.
- Develop conceptual designs of the injection system, system layout, and the electronic control strategy.
- Choose and build designs based on analytical predictions and structural and hydraulic analyses of selected hardware components.
- Test the new injection system along with various hardware engine upgrades in a single-cylinder locomotive diesel engine and obtain performance and emissions characteristics.
- Study fuel spray behavior and cavitation phenomena using appropriate analytical tools and optical methods.

Accomplishments

- Developed design concepts for key hardware components and system layout of the new fuel-injection system.
- Built prototype injectors and tested them in the hydraulic bench. The designs were iteratively improved based on the testing and operational observations.
- The final versions of the prototype injector and high-pressure pump (electric-motor driven) that were developed in this project were integrated with the single-cylinder test facility, and extensive engine testing was conducted. Performance and emissions data were gathered guided by the computational fluid dynamics (CFD) modeling results.

- Engine test results show that the new fuel-injection system has the potential to meet Tier 2 emissions goals with favorable NO_x-BSFC-PM (oxides of nitrogen – brake specific fuel consumption – particulate matter) tradeoff characteristics.

Future Directions

We plan to complete the remaining single-cylinder engine tests and spray imaging experiments at Argonne National Laboratory, and CFD studies on cavitation at Wayne State University during the first quarter of FY 2005. We plan to prepare a final report from our Phase I studies and submit to DOE during the second quarter of FY 2005. Further, the continuation of this collaborative work (Phase II, demonstration of the technology and hardware on a multi-cylinder locomotive diesel engine) will be explored in discussions with DOE.

Introduction

As a result of the railroad and locomotive technology roadmap workshop, a cooperative agreement was reached between the U.S. Department of Energy and the Electro-Motive Division (EMD) of General Motors Corporation in October 2002. The first phase of this cooperative R&D effort involves developing advanced fuel-injection technology and demonstrating its potential benefits towards meeting fuel savings goals and the EPA Tier 2 emissions standards using a single-cylinder research engine platform. The details of technical tasks involving engine modeling and parametric studies were reported in the FY 2003 annual report. The technical progress that we have made during FY 2004 (October 1, 2003 through September 31, 2004) is reported here.

Approach

The major activities pursued in FY 2004 include a series of single-cylinder engine tests with the new prototype fuel-injection system. Efforts were also directed at examining the fuel spray characteristics on the bench using a high-speed imaging technique. Our defined tasks to pursue in FY 2004 are as follows: (1) Task # 3 – bench-test component evaluations as well as an investigation of fuel spray characteristics using established optical diagnostic techniques, and (2) Task # 4 – implementation and testing of the prototype injection system in a single-cylinder engine. Analytical results that were previously obtained in FY 2003 were used to guide the engine testing. EMD's research facilities at Argonne National Laboratory were utilized in conducting single-cylinder engine testing and fuel spray imaging work. These efforts were carried out in close cooperation with our subcontractors, Argonne National Laboratory and Wayne State University. Our fuel-injection equipment supplier, Robert Bosch AG, supported the development of prototype injection hardware, testing on the hydraulic test bench, and development of control system software.

Features of Advanced Fuel-Injection System Applied for Locomotive Diesel Engines

Our advanced fuel-injection system, also known as Modular Common Rail System (MCRS), is a new and improved version of conventional Common Rail System (CRS). A system-level comparison between conventional CRS and MCRS is presented in Table 1;

Table 1. A System-Level Comparison between Common Rail Injection System (CRS) and Modular Common Rail Injection System (MCRS)

parameter/ system	CRS	MCRS
max. press. peaks	>+20 MPa	>+20 MPa
multiple injection	- limited (influence of pipe inner diameter/length)	- pilot/main/post injection lag > 0,4 ms (control valve/ nozzle dynamic)
retrofit	- problem area: rail(s) integration - system tests for different engine configuration (L6 - V18)	- simple retrofit - only components tests (no influence of engine configuration)
safety	- shielded rail(s)/ pipes	- shielded pipes (smaller pipe size needle than for CRS)
cost	- base	- ~ - 30 %

Table 2. A System-Level Comparison between Common Rail Injection System and Traditional Injection Systems, UIS/UPS

parameter	UIS/UPS	CRS
max. inj. pressure	< 200 MPa(cam size and driven limits)	< 180 MPa
max. press. peaks	< + 10 MPa	> 20 MPa
inj. press. control	- no	- yes
injection rate shaping	- triangle type shape - potential for press. modulated shaping w/ 2 stage closing of solenoid valve	- square type shape - limited potential by needle lift control
retrofit potential	- limited by original design	- limited by original design but w/ higher potential than cam driven systems
cost	- base	- higher espec with "double wall" rail and pipes

the advantages of MCRS over CRS are evident. A system-level comparison between existing cam-driven injection systems and CRS injection system is presented in Table 2 to illustrate the progression of injection system technology in locomotive diesel engines. The cam-driven injection systems include unit injector system (UIS) and unit pump system (UPS), which are currently being used in our 2-cycle and 4-cycle locomotive diesel engines, respectively. The conventional CRS system (with a rail-pipe injector) commonly used in passenger-car diesel engines has limited potential for use in large diesel engines because of high-pressure pulsations in the pipes and injectors. The higher costs of high-pressure piping further limit its use in large diesel engines. On the other hand, MCRS eliminates some of the technical shortcomings of conventional CRS. More importantly, MCRS minimizes the high-pressure pulsations that are generated on the pump

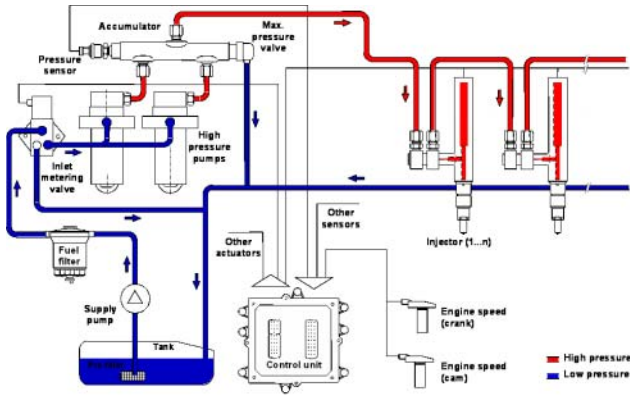

Figure 1. A Schematic Layout of Modular Common Rail Injection System for Large-Bore Medium-Speed Diesel Engines

side with two-stage damping volumes, a high-pressure accumulator (1) on the top of high-pressure pump and (2) integrated within the injector. Figure 1 shows the schematic layout of MCRS for large medium-speed diesel engines. The rail volume is split up and integrated both in the first-stage accumulator and second-stage accumulator within the injectors. This reduction of the distance between fuel accumulator and nozzle reduces the pressure pulsation in the injector significantly. High-pressure hard pipes with inner diameters between 3 and 4.5 mm connect the high-pressure pump, accumulator and injectors. An inlet orifice in the injector prevents any remaining pulsation from propagating through the fuel system. Each injector has a damping volume about 50 to 70 times larger than the maximum injection quantity. The minimized pressure pulsations in the connection pipe from the pump to the injectors permit the integration of the pressure relief valve and the pressure sensor in the accumulator of the high-pressure pump.

Figure 2 shows the cross-section of the MCRS injector design. The integration of control valves, which are currently being developed for future truck diesel engines, will allow the design and development of injectors with an integrated fuel accumulator. There are several advantages of having the control valve close to the needle. For example, it provides optimized packaging and fast response time, and it is pressure-balanced using hydraulic forces (rather than mechanical spring forces). It is fitted with close proximity to the nozzle to minimize

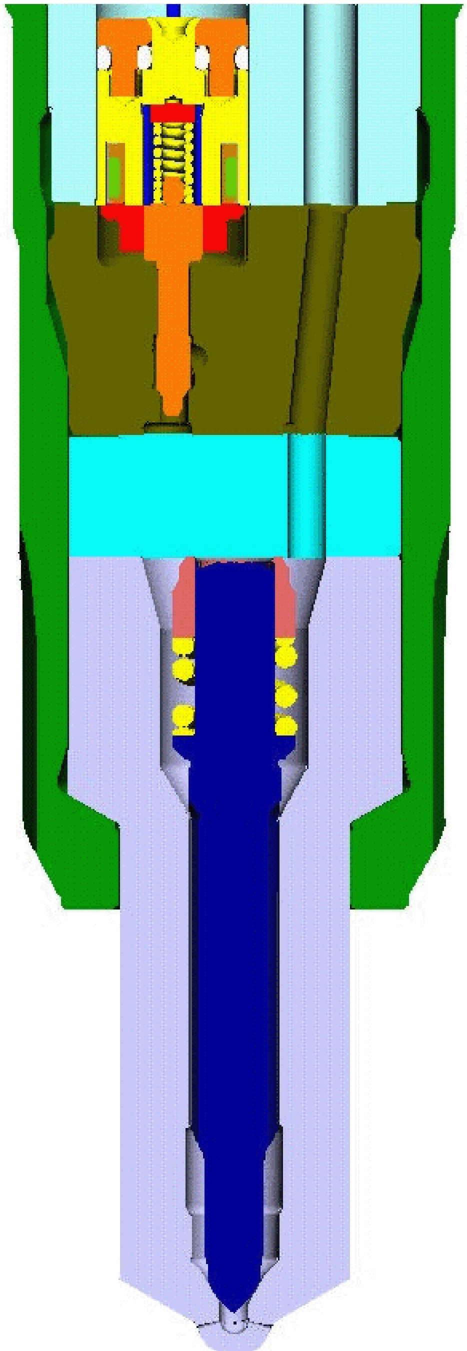

Figure 2. Cross-Section of MCRS Injector Design

the influence of hydraulic and pressure pulsations on the switching behavior of the nozzle. The opposite side of the needle seat is designed as a pressure-controlled chamber with inlet and outlet orifices integrated in the plate between solenoid valve and nozzle. The solenoid valve controls opening and closing of the needle and thus each injection event. The solenoid valve technology is currently being applied for three different sizes, from high-speed to medium-speed diesel engines with fuel injection quantities ranging from 500 to 3,000 mm^3 per stroke. The wider usage of this solenoid technology in different engine platforms helps to bring the cost down and improve component reliability.

Results

Component Evaluations – Needle Movement and Pressure Pulsations

The needle movement, nozzle and sac-hole injection pressure/injection rate characteristics were studied using a calibrated 1-D hydraulic model (a modified version of AMESim software). A comparison of injection rates and pressure pulsations between CRS and MCRS with single (main only) injection is shown in Figures 3 and 4, respectively. Similarly, the injection rates and pressure pulsation between CRS and MCRS were studied using a split injection (main and post injection). These results are presented in Figures 5 and 6. The advantages of MCRS, in particular pressure pulsations in the injector and injection rate, are quite evident from these results.

The shorter distance from the injector and integrated accumulator to the nozzle of the MCRS influences the injection rate in the first phase of the injection. The layout of inlet and outlet orifices allows an adaptation of the injection rate for reduced rate of cylinder pressure rise during the premixed phase of the combustion cycle. The MCRS also allows multiple injections for further reduced cylinder pressure gradients. In the case of CRS, the pipe inner diameter and pipe length strongly influence the injection rate and pressure pulsations. On the other hand, with MCRS the decrease in fuel pressure at the end of the injection depends primarily on the injector volume and the inlet orifice. Hydraulic analysis followed by bench tests (verification tests) show the excellent dynamic behavior of the MCRS for both single and multiple injection events, which results in great potential for engine optimizations with respect to performance, noise and emissions control.

Engine Tests

The prototype MCRS has been adopted for testing in the singe-cylinder locomotive diesel

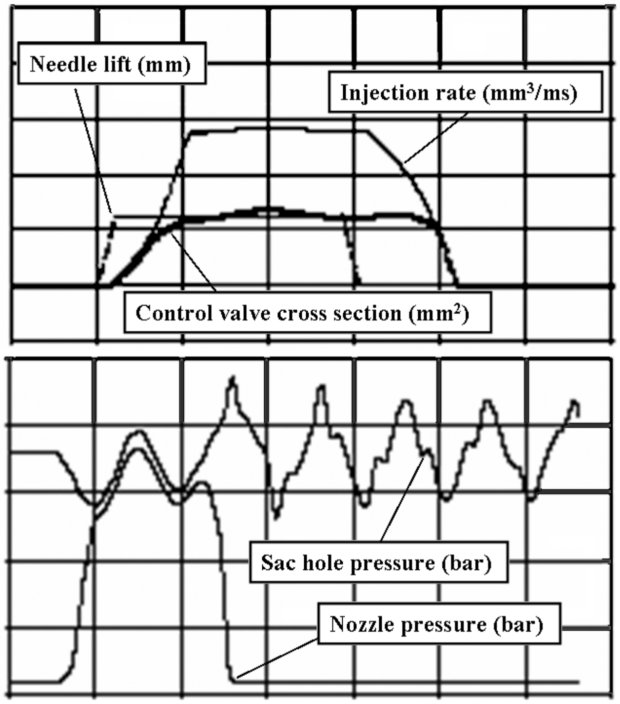

Figure 3. Needle and Injection Behavior Using CRS Single Injection

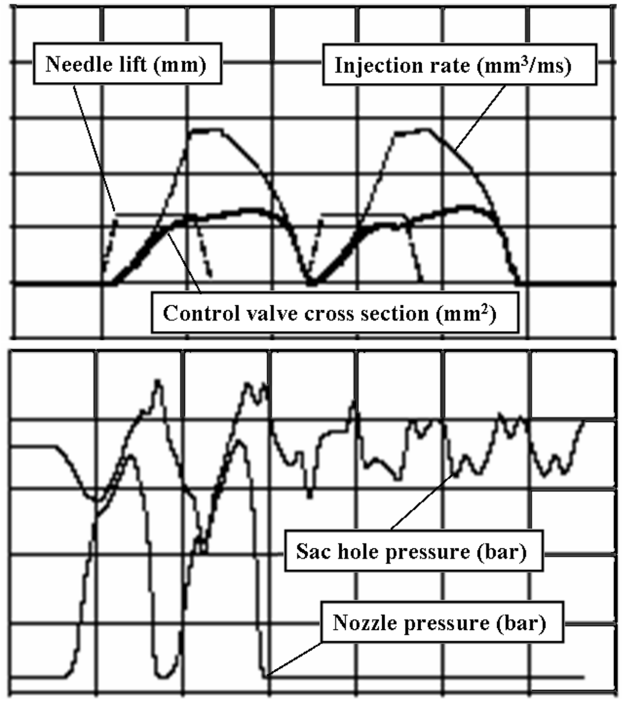

Figure 5. Needle and injection Behavior Using CRS Multiple Injections

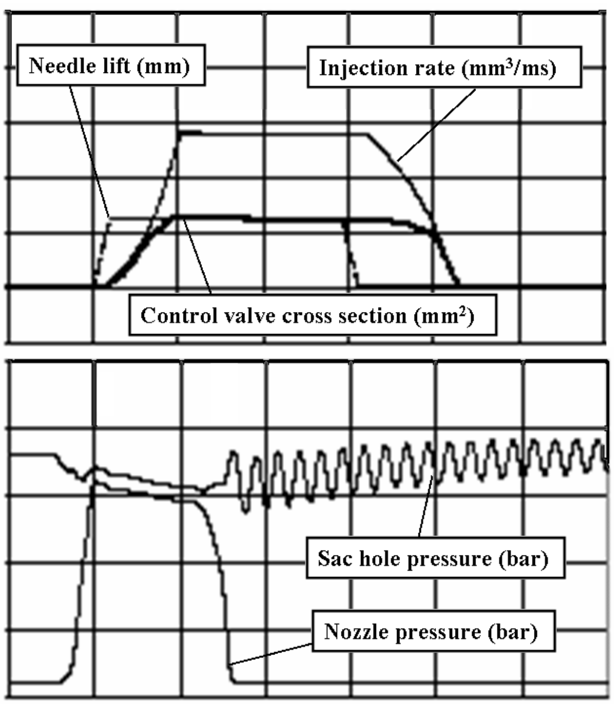

Figure 4. Needle and Injection Behavior Using MCRS Single Injection

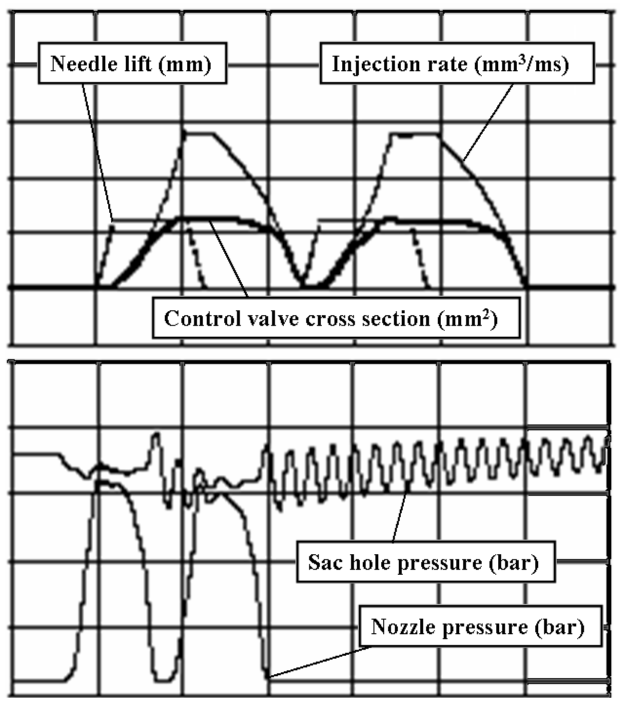

Figure 6. Needle and Injection Behavior Using MCRS Multiple Injections

engine. Figure 7 shows the top view of the engine with MCRS. For ease of operation and control, the high-pressure fuel pump was driven by an external electric motor. The injection profiles were selected

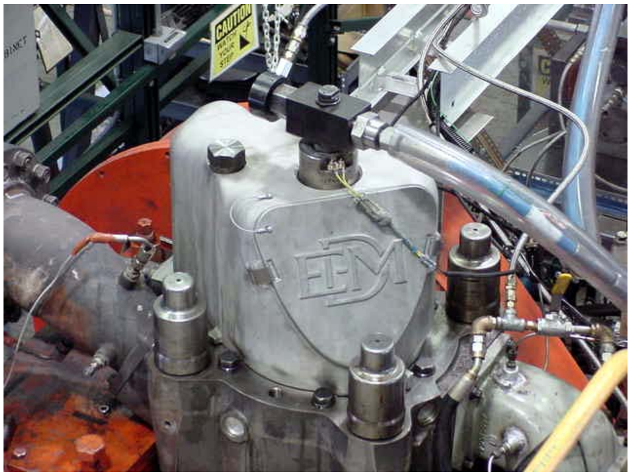

Figure 7. A Close-Up View of a Single-Cylinder Engine Integrated with MCRS Hardware

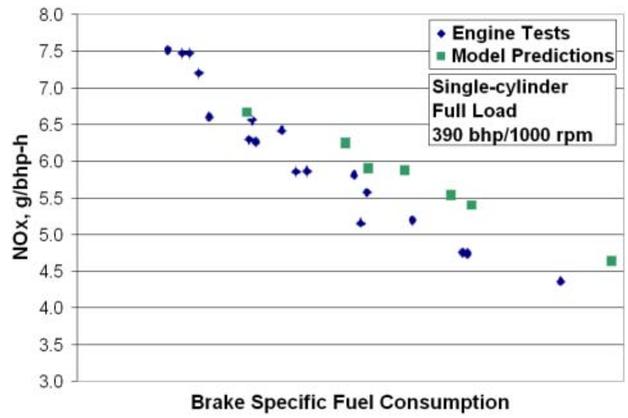

Figure 8. Performance and Emissions Tradeoff with MCRS (a comparison between experiments and CFD predictions)

from the CFD results for verification in the single-cylinder engine. Throughout our single-cylinder engine testing, inlet air density and exhaust backpressure were held constant. Figure 8 shows the key performance (BSFC) and target emissions (NO_x) tradeoff characteristics at full-load conditions using selected injection profiles. Each data point in this chart depicts a unique injection profile selected from a set of MCRS variables that include injection pressure, number of injections, injection timing of the first injection event, dwell time between the injection event(s), injection ramp-up rate, needle seat geometry, number of orifices, orifice aspect ratio, and spray included angle. The injection (duration) quantity was an output resulting from maintaining a constant engine full-load condition (constant engine output and engine speed.)

The salient results from engine testing with MCRS show a conventional NO_x and BSFC tradeoff. Despite wide differences in injection profiles that were generated using MCRS, the tradeoff trend was qualitatively similar to that of UPS when injection timing was altered. The test data show that the Tier 2 NO_x emission target of about 5 grams per bhp-hr can be met using MCRS with an optimized injection profile. For comparison purposes, CFD results were superimposed on the chart. Although our CFD model was not tuned for MCRS prior to the engine tests, the model predictions tracked quite well with engine test results, which shows the usefulness of the CFD model as a tool to (1) predict engine performance and emissions, (2) screen injection profiles, and (3) guide the future experiments. Using the single-cylinder engine test data, we plan to further improve our CFD model and its predictive capabilities, which can help to guide our future engine experiments.

To illustrate the potential of MCRS with respect to UPS, the engine performance and emissions data at engine full-load condition were compared and are shown in Figure 9. Unlike the case of MCRS, injection timing is the only variable when using UPS. The NO_x-BSFC data with UPS were obtained by simply changing the injection timing. This chart quantifies the differences between UPS and MCRS in terms of NO_x at a given BSFC and vice versa. First of all, a target NO_x of 5 grams was unattainable with UPS without relaxing limits on the exhaust gas temperature (~1200 deg F). Second, the BSFC was adversely affected by retarding the injection timing beyond 6 grams of NO_x. Without changing the cam profile and thus the injection profile, further optimization would be very difficult with the UPS. On the other hand, exhaust gas temperatures were well within the maximum limits when MCRS was used. The flexibility in altering the injection profile through control software allowed us to mitigate the peak cylinder pressure and exhaust gas temperature limits. Test results further demonstrate the superior NO_x-BSFC tradeoff characteristics with MCRS when compared to UPS. For example, at a constant BSFC, NO_x was reduced by about 15 to 20 percent. In addition to the reduction in NO_x emissions, engine

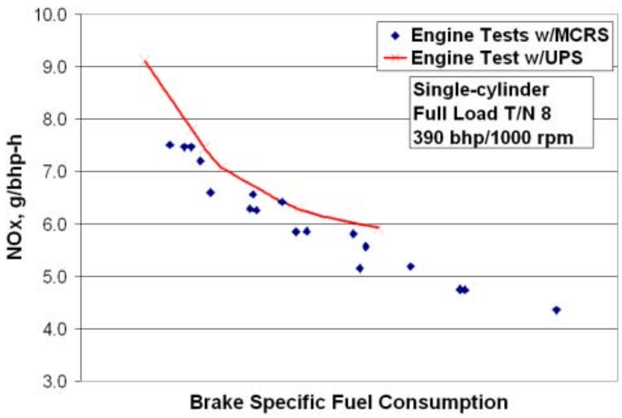

Figure 9. A NO_x-BSFC Comparison between UPS and MCRS at Full-Load Conditions

noise, and particulates, hydrocarbons and carbon monoxide emissions were also lower with MCRS (not shown). From the literature, it is obvious that the potential benefits of CRS can be fully captured when piston bowl shape is optimized with the fuel spray. Following trends in light-duty and heavy-duty diesel engines using advanced fuel-injection systems, the effects of piston bowl shape on emissions and performance are being studied along with various MCRS injection profiles; the ongoing engine tests are aimed to optimize the spray-bowl interactions.

Conclusions

- On the basis of single-cylinder engine tests, we demonstrated our Tier 2 internal NO_x goal of 5.0 grams per bhp-hr at engine full load with MCRS. Further, MCRS has better NO_x-BSFC tradeoff behavior when compared to UPS. Engine noise, visible smoke, and particulates were also lower with MCRS.
- To fully capture the potential of MCRS, spray-bowl optimization studies are being carried out using single-cylinder test engine facility. Studies aimed toward understanding the fuel spray behavior (using imaging techniques with high-pressure cold chamber) and cavitation behavior (using CFD tools) are ongoing in collaboration with our research partners.

Publications

1. "Comparing Cavitation in Diesel Injectors Based on Different Modeling Approaches," 2004, SAE Paper 2004-01-0027.

V.4 21st Century Locomotive Technology: Advanced Fuel Injection and Turbomachinery

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Objectives

1. Develop and demonstrate an advanced fuel injection system to minimize fuel consumption while meeting Tier 2 emissions levels.

2a. Validate prototype electrically assisted turbocharger to full speed and power. Develop conceptual design for multi-cylinder engine.

2b. Demonstrate turbocharger efficiency improvement using abradable seals on the compressor and turbine housings.

Approach

<u>Objective 1</u>

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

<u>Objective 2a</u>

- Install electrically assisted turbocharger and test over operating range in motoring and generator modes.
- Measure performance and dynamic stability characteristics.
- Identify key areas of improvement.
- Develop conceptual design for multi-cylinder engine.

<u>Objective 2b</u>

- Perform clearance tests to determine efficiency improvement attributable to abradable seals.
- Specify and develop abradable seal material candidates.
- Perform rub tests to identify best choice(s).
- Implement abradable seals on full-scale turbocharger and characterize performance.

Accomplishments

<u>Objective 1</u>

- Calibrated and commissioned the computational fluid dynamics (CFD) combustion model at the University of Wisconsin-Madison to predict the performance of the locomotive engine.

- Developed CFD mesh to maximize usefulness for a given computation time and improved snapper routine.
- Exercised a genetic algorithm optimization process to identify the optimum high-pressure common rail (HPCR) design variables for N8. Design variables included fuel pressure, injection schedule, and fuel spray cone angle.
- Evaluated the HPCR hardware on a stand-alone functionality bench.
- Validated the CFD combustion model for the single-cylinder engine (SCE) with HPCR experimental data.
- Collected baseline engine performance data with the production unit pump system (UPS).
- Established a method to compare the brake performance of the single-cylinder engine operating with the UPS versus the HPCR.
- Installed the HPCR on the SCE and launched optimization study.

<u>Objective 2a</u>

- Obtained data on turbocharger system performance in generator and motoring modes from idle to maximum altitude speed.
- Successfully demonstrated high turbocharger acceleration rates under motor assist to N5 speed.
- Successfully demonstrated increasing levels of power recovery in generator mode from N6 to N8 maximum altitude speeds.
- Demonstrated stable rotor performance over full operating range.
- Identified key areas for improvement in scaling to current turbocharger platform.

<u>Objective 2b</u>

- Obtained cold and hot running clearance measurements on two turbocharger models (HDL, V12) to baseline clearance reduction potential.
- Developed spray parameters and prepared test specimens of candidate polymeric coatings for the turbocharger compressor application.
- Evaluated candidate samples in the GE Global Research Center (GRC) rub test facility for abradability and potential blade wear.
- Obtained air inlet and coated with candidate polymer for early evaluation in the electrically assisted turbocharger.
- Developed methodology to alloy the base polymer with metallic elements to improve durability while retaining compatibility with the aluminum compressor wheel.
- Performed hardness, bond strength and erosion tests on selected candidate coatings.
- Established coating thickness requirements as a function of compressor shroud line location. Developed programs for the robotic spray equipment to allow thermal spray coating of air inlets on both HDL and V12 turbochargers.
- Tested three polymeric-based coatings in the full-scale V12 turbocharger in the GRC turbocharger development test cell. Collected compressor performance data at multiple speed lines to assess efficiency gains at reduced clearance. Measured rotor dynamic response during coating rub.

Future Directions

<u>Objective 1</u>

- Continue optimization studies at N8.
- Expand testing and modeling at lower notches.
- Further optimize by changing fuel injection hardware.

Objective 2a

- Perform conceptual design, including packaging, for the larger Tier II turbocharger in preparation for multi-cylinder engine testing, pending resumption of funding.

Objective 2b

- Assess morphology of the as-sprayed coatings tested to date.
- Develop spray parameters and composition for improved polymeric coatings. Prepare rub test samples.
- Evaluate the coatings in the GRC rub rig. Downselect candidates for evaluation in the full-scale turbocharger.
- Coat and evaluate full-scale air inlet housing.
- Coat and test a metallic abradable on the turbine shroud.

Introduction

The goals and objectives of the Department of Energy and GE's 21st Century Locomotive Program are to develop freight locomotives that are 25% more efficient by 2010, while meeting Tier 2 emissions standards. Traditional methods to reduce fuel consumption typically come with a penalty of NO_x and PM emissions. 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 levels. This document describes the technology at the diesel engine level, which involves improving the brake specific fuel consumption by development of advanced fuel injection and turbocharger systems.

Approach

The approach of the engine-related technology project varies by task. The methods by which GE will reach targets in the areas of advanced fuel injection, electrically assisted turbomachinery, and the turbocharger abradable seals are discussed below.

Advanced Fuel Injection

A Bosch high-pressure common rail (HPCR) system was implemented on a locomotive single-cylinder research engine. The system is capable of up to four injection events per cycle and produces injection pressures above 1800 bar. Parameters that must be optimized for best performance include rail pressure, injection schedule, and nozzle configuration. To better understand the combustion phenomena, CFD (KIVA) analysis was performed in collaboration with the University of Wisconsin – Madison. The KIVA modeling work provides input and guidance for the experimental study on the single-cylinder engine.

Electric Turbocharger

An electrically assisted turbocharger has been designed, built and evaluated. The advanced turbomachinery was tested at full scale in the GE GRC turbomachinery laboratory to identify performance potential. The opportunity to transfer energy between the electrical system and the flow stream provides an added degree of freedom for efficiency optimization. Modeling studies were used to predict performance gains given optimum airflow and pressure at the various locomotive notch settings (engine speed-torque combinations) of interest. Significantly improved transient engine response is expected in motoring mode at low notches, and up to 150 kW additional power recovery in generating mode at higher turbocharger speeds is expected.

Abradable Seals for Turbocharger

The application of abradable seals to the aluminum compressor wheel will be investigated in the literature. Materials that show potential for the temperature, speed, and blade material of the compressor will be selected and tested in a dedicated rub test facility. High-temperature metallic abradable seals will be selected for test on the turbine end of the turbocharger. Promising candidate materials will be downselected for test in a full-scale locomotive turbocharger. The turbocharger tests will be performed in the turbomachinery laboratory at GE GRC.

Results

Advanced Fuel Injection

The major accomplishments pertaining to the advanced fuel injection are the CFD model validation and the engine performance results with the HPCR. The CFD combustion model, which has the capability of multiple injections, predicts engine combustion very well. Previous reports showed that the model is well-calibrated for the UPS combustion event. The heat release curves were shown to match well, implying that the model is calibrated correctly and can be used for optimization studies. Figure 1 shows the common rail fuel system installed on the SCE. Experimental trends with the HPCR agree with the KIVA-based predictions. This allows us to build confidence in modeling capability for use on locomotive-scale engines, providing a foundation for further analysis. Results from the N8 optimization study were used to guide the experimental roadmap. Model optimization at N4 and N1 is now in progress.

Figure 1. Common Rail Fuel System Components Installed on the Single-Cylinder Locomotive Engine at GE GRC

Electric Turbocharger

The electrically assisted turbocharger has been designed, constructed, and successfully operated over a full range of conditions in both motoring and generator modes. The system has been run from idle to full speed with no issues encountered regarding structural integrity or rotor dynamics of the combined turbocharger, drive shaft and motor/generator. The system has met the design rating of 150 kW in generator mode at maximum rated sea level turbocharger speed. Transient testing in motoring mode has indicated significant improvement in turbocharger load rate. Useful design data has been obtained regarding the vibration characteristics of the system, the efficiency of the compressor with and without the drive motor in place, and system surge limits. Optimization and characterization of the system control system were performed to maximize transient response of the turbocharger in motoring mode. Temporary damping was added to the inlet transition to correct a casing resonance in the middle of the speed range. An improved encoder was built and installed on the motor. Figure 2 shows the electrically assisted turbocharger installed on the test stand at GE GRC.

Additional modeling and simulations were performed to evaluate the potential improvement of the electrically assisted turbocharger on passenger locomotive station-to-station transit times under different scenarios of train size, turbocharger assist levels, engine idle rpm level, and station duty cycle.

Figure 2. Electric Turbocharger Installed on a Test Stand at GRC

Abradable Seals for Turbocharger

Candidate abradable seal materials have been identified for the turbocharger compressor and turbine shrouds. Polymeric samples for the compressor were prepared and evaluated in a dedicated rub rig under varying conditions of temperature, speed, and incursion rate. Four candidates were selected for application to the turbocharger based on rub test performance, tensile strength and bond strength. Two of the materials were pure polyester blends of varying particle size from alternate vendors. The remaining two were alloyed blends of polymeric and metallic components designed to provide additional strength and hardness to the coatings while still maintaining compatibility with the aluminum compressor wheel. Desired coating thickness profiles were developed for the compressor shroud through a series of measurements taken at cold, static conditions, and at full operating speed. The coatings were designed to permit near line-on-line contact at low N8 turbo physical speed and to rub at wheel speeds above this. Suitable programs were developed for the robotic thermal spray equipment to allow coating full-scale inlet housings for both the HDL and V12 turbochargers at the required varying thickness profile from inducer to exducer. A photograph of a coated air inlet before testing is shown in Figure 3.

Figure 3. Turbocharger Air Inlet after Application of Polymeric Abradable Coating

Four coatings have been evaluated on the turbocharger test stand at conditions from idle to maximum rated speed. Results have varied depending on coating composition, with the pure polymeric blends exhibiting good abradability characteristics but somewhat low bond strength, and the alloyed blends exhibiting higher hardness but also some aggressiveness towards the aluminum compressor wheel. Performance gains measured at the tighter clearances are attractive. Real-time measurements of rotor shaft motion indicate no undesirable subsynchronous behavior during contact with the coating. Shaft motion and overall vibration remained within design limits. Contact with the coating is typically a one-time event at a given shaft speed. Once a rub has occurred at a given rpm, the wheel will run at or below that speed without continuing to contact the coating.

Two metallic-based coatings have been selected for application to the turbine shroud. The material is a NiCrFe-based alloy that is applied using the combustion spray process. Tests are planned to determine the hot running clearance between the turbine blades and stationary shroud for selection of initial coating thickness. A local vendor has been qualified under a separate program to spray the coating selected for initial trials.

Conclusions

- The genetic algorithm approach is an appropriate tool to optimize injection parameters.
- SCE experimental trends agree with the KIVA-based predictions.
- Potential engine performance improvements with HPCR were identified and demonstrated.
- Additional experiments and hardware refinements are required to determine the optimum HPCR strategy over the range of locomotive operation.
- The prototype electrically assisted turbocharger met performance goals of acceleration, power recovery and rotor stability.
- Polymeric zero-clearance abradable coatings provide improved compressor efficiency with no loss in surge margin.
- Additional optimization is required to develop a coating that provides the desirable abradability characteristics while retaining sufficient durability for long-term locomotive service.

V.5 Off-Highway Emission Control with High System Efficiency (CRADA with John Deere)

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DOE Technology Development Manager: John Fairbanks

Objectives

- Evaluate the potential of NO_x-reducing aftertreatment technologies to achieve interim Tier 4 NO_x emission levels for off-highway heavy-duty diesel engines. The initial focus is to utilize urea-based selective catalytic reduction (SCR) to achieve brake-specific NO_x levels of 2 g/kWh over the ISO 8178 Off-Highway test cycle.
- Optimize key injection parameters to achieve improvements in fuel efficiency while meeting the 2011 Tier 4 emission levels for NO_x. The initial target value for brake-specific fuel consumption (BSFC) is 195 g/kWh.

Approach

- Install and set up a urea-SCR system in the exhaust system of a heavy-duty off-highway engine. The system consists of an oxidation catalyst, Bosch urea injector and dosing unit, and a Johnson-Matthey urea-SCR catalyst.
- Evaluate the performance of the urea-SCR system to reduce NO_x emissions for six modes of the ISO 8178 Off-Highway test cycle. Examine the slip of ammonia from the SCR catalyst during urea injection.
- Analyze the performance of the urea-SCR system to identify areas of further improvement.

Accomplishments

- Installed the urea-SCR system, including the dosing unit and catalysts. This included the fabrication of wiring harnesses and switches, and the setup of the software interface and drivers to operate the dosing system.
- Urea-SCR has been demonstrated to reduce NO_x emissions to interim Tier 4 levels over the ISO-8178 Off-Highway test cycle. Conversion efficiencies over 90% were observed for modes 1, 2, 3, 5, and 6 at near-stoichiometric delivery rates. Low exhaust temperatures for modes 4 and 8 prevented the application of the SCR system for these set points.
- Achieved apparent improvement in BSFC.

Future Directions

- Install and evaluate advanced engine control software. Initial focus will be to determine the influence of injection parameters on energy efficiency.
- Explore the potential for other NO_x reduction strategies to meet final Tier 4 NO_x and PM emissions.
- Conduct further urea-SCR studies to optimize NO_x conversion with selected injection control strategies to lower BSFC.

Introduction

Tier 3 Federal standards for new off-highway diesel engines require that NO_x and PM levels be regulated to 4 g/kWh and 0.2 g/kWh, respectively, for engines between 130 and 560 kW. The phase-in period for Tier 3 compliance is set to begin in 2006 and to be completed by 2008. Urea-SCR has been shown to effectively reduce NO_x emissions for on-highway applications but needs to be thoroughly evaluated for off-highway engines since both engine design and operating conditions are different. The utilization of advanced injection systems and controls is to be evaluated for improvements in both PM emissions and BSFC. This project seeks to develop and evaluate emission control methodologies with the goal of identifying pathways to meet interim Tier 4 and retrofit solutions.

Approach

The principal activity for FY 2004 was the installation and performance evaluation of a urea-SCR system for reducing NO_x emissions from a heavy-duty off-highway diesel engine. Upon receipt of the SCR system components, the system was installed. This required significant effort to make the urea dosing system operational. The urea-SCR evaluation was performed over a period of several weeks, and at the end of this period, the catalysts were sent to the manufacturer for refurbishment. The test protocol followed the ISO 8178 C1 test cycle for off-highway engines. Data were collected for a range of urea delivery rates, up to and exceeding the stoichiometric value. The level of ammonia slip was measured using a photoacoustic spectrometer and analyzed for each operating mode. In addition, the NO_x reduction performance was evaluated with and without use of a diesel oxidation catalyst (DOC) to condition the NO to equilibrium levels of NO_2.

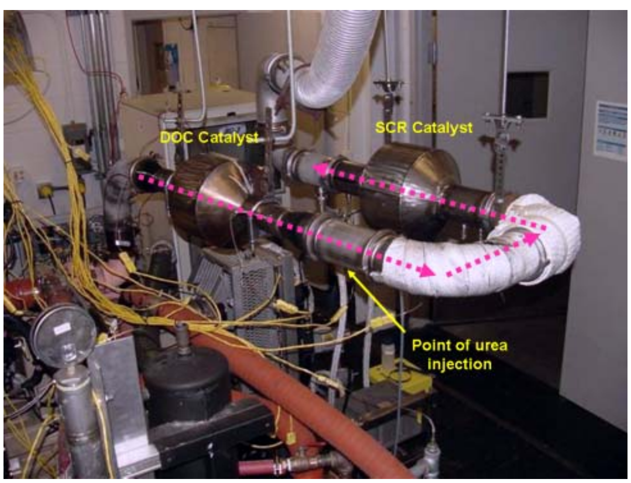

Figure 1. Urea-SCR System

A second activity for this FY was the installation of an advanced fuel injection system and evaluation of its effect on energy efficiency. The data was collected (for each mode) and compared to an earlier study using the original fuel injection system.

Results

A photograph showing the arrangement of the catalysts in the engine exhaust line is shown in Figure 1. Installation of the urea-SCR system was completed by February. During the urea-SCR evaluation, it was necessary to closely monitor the temperature profile of the exhaust, especially that of the SCR catalyst since performance is closely related to temperature. The temperature profile for each mode is shown in Figure 2. As shown in this figure, the catalyst temperatures for modes 4 and 8 were too low to enable urea injection and were thus not considered during the evaluation.

For each mode, the baseline NO_x emissions were monitored before application of the urea. When steady state was reached, the urea was applied at a low level (usually around 500 g/h) and the temperature and emissions were allowed to stabilize. The engine-out, DOC-out, and tailpipe emissions of NO_x, hydrocarbons (HC), CO, CO_2, and O_2 were recorded for each setting. The urea level was gradually increased at selected values up to and slightly exceeding the stoichiometric level of urea required for theoretically complete conversion of the NO_x. This was performed with and without a DOC

ISO 8178 Mode	Turbo outlet	DOC inlet	DOC outlet	SCR Cat inlet	SCR Cat outlet
1	430	376	380	364	362
2	355	349	352	337	335
3	317	309	312	298	297
4	203	200	198	191	191
5	473	450	467	415	397
6	422	405	417	382	370
7	349	338	340	319	312
8	99	90	94	81	75

Figure 2. Key Exhaust Temperatures for Each Mode (degrees Celsius)

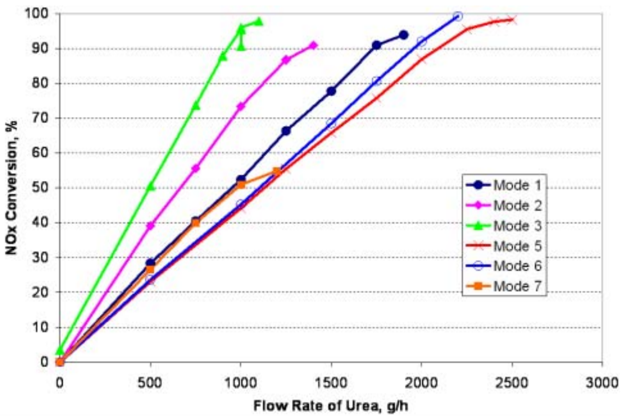

Figure 3. NO_x Reduction Performance of the Urea-SCR System for ISO 8178 Modes 1, 2, 3, 5, 6, and 7

placed in the exhaust upstream of the urea injector. In general, for modes 1, 2, 3, 5, and 6, the DOC improved the NO_x conversion significantly for urea delivery rates approaching the stroichiometric value, but it was less effective at improving the conversion during low applications of urea. The utilization of the DOC during mode 7, however, improved the NO_x conversion by 30% for all rates of urea injection. The NO_x conversion results (using the DOC) for each mode are shown in Figure 3. For modes 1, 2, 3, 5, and 6, the NO_x conversion increased to levels exceeding 90%. The urea delivery rate at which conversion passed 90% usually corresponded to the stoichiometric value. At urea levels at or exceeding stoichiometry, the conversion began to level and ammonia began to slip past the catalyst.

Unlike the other modes tested, the exhaust conditions during mode 7 did not allow for greater than 90% NO_x conversion. The highest value that could be attained was around 50%, which occurred significantly below the calculated stoichiometric value. As with the other modes, ammonia slip was observed for mode 7 once the rate of NO_x conversion with urea flow decreased. The total brake-specific NO_x level obtained using this system was determined to be around 1 g/kWh, which is well below the Tier 3 target level of 4 g/kWh and below the interim Tier 4 level of 2 g/kWh.

Conclusions

- Tier 3 NO_x emission levels were reached using a urea-SCR system. The addition of a DOC significantly improved the NO_x conversion efficiency of the system. However, the exhaust temperatures for modes 4 and 8 were too low to permit urea injection.
- The energy efficiency of the engine was improved through the application of an advanced fuel injection system. For all modes, except 4 and 8, the BSFC values were below the target level.