III Advanced Engine Designs for Improved Efficiency

III.A Heavy-Duty

III.A.1 Heavy Truck Engine Program

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Objectives

- **Phase I** – Demonstration of 45% brake thermal efficiency (BTE) at cruise conditions while meeting 2002 Environmental Protection Agency (EPA) emissions regulations. Demonstration made in January of 2002.
- **Phase IIA** – Demonstration of 45% BTE at cruise conditions while meeting 2007 emissions regulations. Demonstration made in Q1 of 2004.
- **Phase IIB** – Demonstration of 50% BTE maximum while meeting 2010 emissions regulations. Demonstration due in 2006.

Approach

Phase I tasks are complete. Phase IIA tasks are complete. Phase IIB tasks are as follows:

- Engine Development
  - Advanced combustion systems for best NO_x/fuel economy trade-off for 2010
  - Analysis of data and sub-model development
  - Optimal combustion system design options
  - Controls architecture for an advanced combustion system
  - Air handling/exhaust gas recirculation (EGR) architecture
  - Advanced combustion single-cylinder testing
  - Definition and demonstration of subsystem architecture for 2010
  - Analysis and design of waste heat recovery techniques to support brake thermal efficiency targets
  - Design of waste heat recovery system hardware for test cell demonstration
  - Design of engine system controls to achieve optimal engine system efficiency
- Analysis/Development of NO_x & Particulate Matter (PM) Aftertreatment Systems
  - System architecture development
  - Engine procurement and test support
  - Model development and validation
  - Adsorber subsystem development
  - Soot filter subsystem development
  - Aftertreatment subsystem integration
  - Aftertreatment subsystem optimization
  - Aftertreatment subsystem integrity demonstration
- Exhaust Conditioning for NO_x and SO_x Regeneration
  - In-cylinder exhaust conditioning analysis and test

  - Evaluation of fuel and air handling systems
  - Development of engine management strategy for NO_x, SO_x, and diesel particulate filter (DPF) regeneration and exhaust stream conditioning
- Development and Integration of Control System
  - Controls architecture and modeling of engine, aftertreatment, and heat recovery systems
  - Aftertreatment sensor development
  - Control architecture definition for 2010
  - Control architecture demonstration for 2010
- Vehicle Demonstration
  - Engine and aftertreatment system demonstration in a heavy truck
  - Demonstration of 50% BTE maximum @ 2010 emissions in test cell
- Reporting
  - Implementation plan
  - Quarterly reports
  - Annual review & reports

Accomplishments

- Achieved and demonstrated 45% BTE while meeting 2007 emissions goals in test cell and in vehicle in support of Phase IIA deliverables.
- Demonstrated advanced recirculated exhaust gas cooling in support of Phase IIA efficiency goal.
- Developed a System Integration and Configuration Matrix to define potential engine architectures to support Phase IIB project goals.
- Developed a Pugh Matrix to define and identify optimal heat recovery techniques to achieve Phase IIB efficiency goals.
- Specified and procured a variable valve actuation (VVA) research tool to support advanced combustion research.
- Evaluated different forms of homogeneous charge compression ignition (HCCI) combustion and performed failure mode and effects analysis (FMEA) on each to identify and prioritize challenges.
- Developed engine-system models for HCCI and diffusion burn combustion techniques to help evaluate engine architectures and support system design.

Future Directions

- Evaluate different combustion types and refine hardware to achieve project deliverables. Follow analysis-led-design methods to maximize the return from research hardware expenses.
- Perform engine system modeling to predict engine, aftertreatment, and heat recovery system performance.
- Perform test cell testing to verify models and system performance.
- Define and acquire engine system components to support project goals.
- Develop model-based controls to support system performance.
- Perform bench-top component testing and system test cell testing.
- Define and acquire critical system components to verify model results and identify performance limits.
- Integrate the base engine into a heavy-duty vehicle for demonstration.
- Set up engine and heat recovery system demonstrations.

Introduction

Cummins Inc. is working to develop and demonstrate advanced diesel engine technologies to improve diesel engine thermal efficiency while meeting future emissions requirements. The effort meets the objectives outlined by the Department of Energy, which include two major phases. In Phase I (completed), Cummins worked to demonstrate by January, 2002, engine efficiency equal to or greater than 45% while complying with emissions regulations of 2.5 g/bhp-hr NO_x-hydrocarbon (HC) and 0.10 g/bhp-hr particulate matter, as defined in the EPA/Department of Justice Consent Decree with the diesel engine manufacturers. In Phase IIA, Cummins worked to demonstrate in early 2004, BTE of 45% in a multi-cylinder, heavy-duty diesel engine while complying with 2007 EPA emissions regulations of 1.2 g/bhp NO_x-HC and 0.01 g/bhp-hr particulate matter. In Phase IIB, Cummins shall work to demonstrate in 2006, BTE of 50% in a multi-cylinder, heavy-duty diesel engine while complying with the 2010 EPA emissions regulations of 0.2 g/bhp NO_x-HC and 0.01 g/bhp-hr particulate matter.

These project goals are challenging and require intensive research and development. Emissions reduction by traditional means will have a negative impact on BTE. The engine and emissions performance technologies advanced in this project will accelerate the development of high-efficiency, low-emission diesel engines.

Approach

Cummins' approach to these project objectives continues to emphasize analysis-led-design in nearly all aspects of the research. An emphasis is placed on modeling and simulation results to lead the way into feasible solutions.

For the deliverable in each phase, a configuration matrix study is planned to determine appropriate, feasible solutions. Engine system solutions include various air handling schemes, control system approaches, and aftertreatment system combinations. Based on extensive model/simulation data, previous testing experience, or verifiable supplier's information, a best-choice solution set of system components is selected. A variety of laboratory tests are conducted to verify performance and to tune system functions. Model predictions are verified, and models are refined as necessary. Often, different portions of the system are pre-tested independently to quantify their behavior, and their data is analyzed in a model-based simulation before combined test cell testing is conducted. Concurrent to laboratory testing and tuning are planning and preparation for a vehicle system demonstration. Once satisfactory test cell system performance is verified, the vehicle demonstration is conducted.

Data, experience, and information gained throughout the research exercise will be applied wherever possible to our final commercial products. Cummins continues to follow this cost-effective, analysis-led approach both in research agreements with agencies like the Department of Energy as well as in its commercial product development. Cummins feels this common approach to research effectively shares results as well as resources.

Results

During 2004, Cummins Inc. reached the Phase IIA project goals and moved on toward the Phase IIB portion of the project. A great deal of time was spent in modeling and analysis in preparation for the Phase IIB demonstration. Cummins' analysis-led-design methodology, which seeks to maximize the return from research expenses, resulted in an excellent foundation from which to reach the final project goals.

Achieved and demonstrated 45% BTE while meeting 2007 emissions goals (Phase IIA).

A Cummins ISX engine equipped with a high-capacity EGR system and prototype fuel system was operated in a test cell and was shown to be emissions compliant to 2007 emissions standards. This emissions-compliant engine also demonstrated achievement of a maximum BTE of 44% at a cruise condition when operated with a practical engine cooling system which included the heat rejection of recirculated and cooled exhaust gas.

An optimized cooled EGR method was developed which allowed further improvement in BTE to reach the project goal of 45%. This

System Selection Process (Pugh Matrix)

CRITERIA \ CONCEPT	RANKINE CYCLE WITH REGENERATION	RANKINE CYCLE (REHEAT)	THERMO ELECTRIC SYSTEMS	ELECTRIC TURBO COMPOUND SYSTEMS	RANKINE CYCLE +THERMO ELECTRIC SYSTEM
	1	2	3	4	5
1. Power Generated	S	S	-	-	+
2. System Complexity.	S	-	+	-	-
3. Resistance to temperature.	S	S	-	S	S
4. Fuel economy increase obtained.	S	-	-	-	+
5. Compatibility with actual engines.	S	S	S	S	S
6. Number of components.	S	S	+	S	-
7. Effect over the emissions.	S	S	S	S	S
8. Weight of the system	S	S	+	+	-
9. Size of the system.	S	S	+	+	-
10. Durability of the system	S	S	S	S	S
11. Price	S	+	-	-	-
12. Ease of maintenance.	S	S	+	+	S
13. Ease of installation.	S	S	+	+	-
14. Power consumption	S	S	+	+	S
TOTAL +	0	1	7	5	2
TOTAL -	0	2	4	4	6
TOTAL S	14	11	3	5	6
Best possible choice…	14	10	6	6	2

*No direct effect over emissions. Decrease emissions due to fuel economy increase.

Figure 1. Pugh Matrix - Comparison of Selected Waste Heat Recovery Systems

optimized cooling method was test-cell operated only. Vehicle integration of this optimized technique would have imposed significant delay in the effort toward the Phase IIB goal.

Developed a System Integration and Configuration Matrix to define potential engine architectures to support Phase IIB project goals.

Architectural concepts consisting of engine and aftertreatment hardware were generated to deliver the Phase IIB performance targets. System-level technical requirement documents were also generated. Failure mode and effects analyses (FMEAs) were performed on several of the most promising architectures identified to achieve 2010 emissions requirements.

NO_x and PM aftertreatment system architecture for the Phase IIB deliverable began during the first quarter of 2004 in coordination with the overall System Integration Configuration Matrix (SICM).

The overall concept matrix was narrowed by assessing architectures against predicted performance measures (such as rated power levels and emissions compliance) and predicted costs (such as installed cost, development expenses and capital expenses). Promising architectures have been identified and are now being investigated by the engine and aftertreatment component teams to refine architectural definitions and improve performance expectations.

Developed a Pugh Matrix to identify optimal heat recovery techniques to achieve program efficiency goals.

Work performed at the University of Illinois in Urbana-Champaign produced the Pugh Matrix of energy recovery methods shown in Figure 1.

As shown, the method of Rankine Cycle with regeneration proved to be the most promising method as compared with the others listed. This evaluation is heavily based on previous research performed and documented in Society of Automotive Engineers (SAE) Papers 760343, 780686, 790646, and 830122.

Thermal electric systems which seek to use semi-conductors to generate electricity from a differential in temperature were considered for this project. However, they were not weighted favorably in the analysis as their level of development (high Figure of Merit semi-conductor materials) is not considered great enough yet for feasible application. These systems may eventually be incorporated if significant progress is made in the durability and manufacturability of newer, higher-performance materials.

The Organic Rankine Cycle (ORC) method was modeled to determine optimal performance and establish component specifications. Figure 2 shows the basic thermodynamic loops for this energy cycle.

Figure 3 presents a schematic diagram of this recovery technique as it could possibly be incorporated into an engine system.

A neural-network control system approach is being pursued for the waste heat recovery system. Critical adjustable parameters (CAPs) and critical functional responses (CFRs) were identified over the last quarter and are being used as the basis for control system development. The CAPs include engine speed, fueling, coolant temperature, air massflow, EGR massflow or charge mass percent, etc. CFRs include heat transfer to the turbine generator, ORC condenser cooling requirement, etc. These control system parameters will continue to be investigated and refined in the fourth quarter.

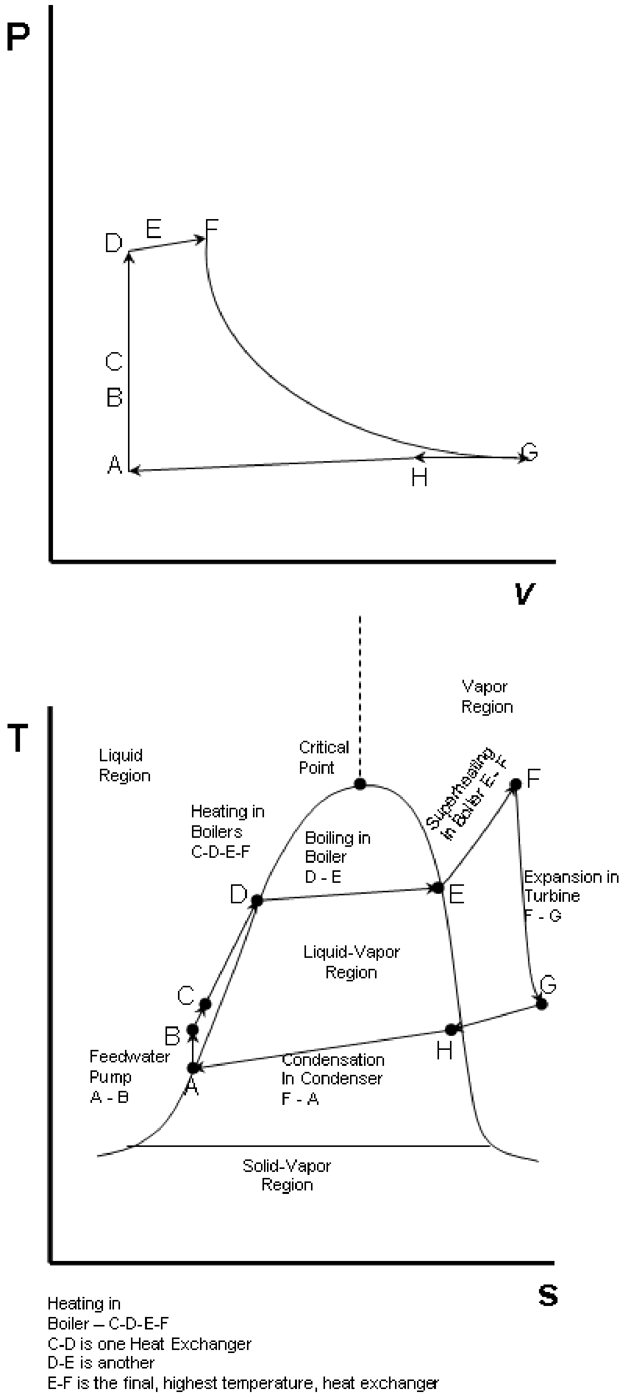

Figure 2. Rankine Cycle Pressure (P)-Specific Volume (*v*) and Temperature (T)- Entropy (s) Diagrams

Specified and procured a variable valve actuation research tool to support advanced combustion research.

Arrangements to purchase a variable valve actuation research tool were developed during the fourth quarter of 2003 and first quarter 2004. The acquisition lead-time for the tool was approximately 9 months. Delivery is expected to occur in mid-November, 2004.

The system will provide full-authority intake and exhaust valve motion control on a single-cylinder engine. This tool will support our research to identify the degree (if any) of valve control necessary to support combustion techniques capable of achieving emissions and thermal efficiency targets. This tool also offers us the ability to quickly test valve cam profiles without having to acquire hardware. This full-authority, electro-hydraulic valve actuation system is being acquired as a research tool only and is not expected to be considered as the Phase IIB demonstration engine system valve train design.

In relation to the acquisition of this variable valve actuation research tool, a single-cylinder ISX engine has been built. A test cell capable of handling the necessary controls, airflow, lubrication, and cooling requirements of a single-cylinder engine with a variety of combustion architecture possibilities has also been prepared.

The single-cylinder engine and variable valve train research tools are an investment in the future at Cummins. They are sure to be productive assets on this project and in future projects.

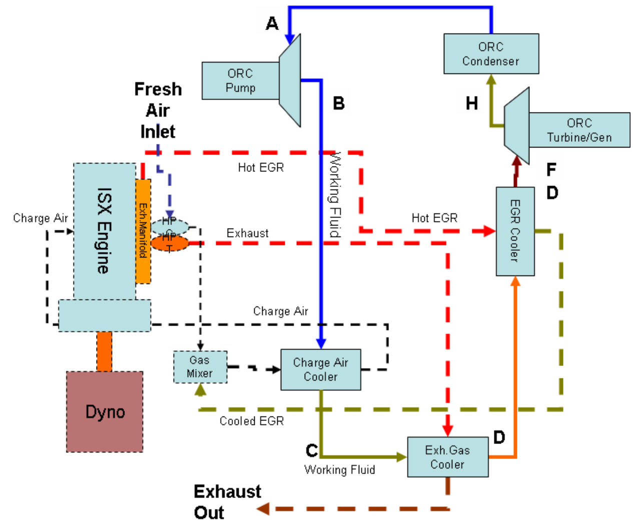

Figure 3. Organic Rankine Cycle Waste Heat Recovery Loop

Evaluated different forms of HCCI combustion and performed an FMEA on each to identify and prioritize challenges.

Combustion modeling was focused on how to best implement pre-mixed charge compression ignition (PCCI)/lean quasi-homogeneous charge compression ignition (LQHCCI) combustion modes into a 6-cylinder engine. Ultra-low emissions have been demonstrated on a single-cylinder engine with fixed-time valve actuation. It is much more difficult to implement this combustion technique on a multi-cylinder engine. The FMEA identified several important items that require work or will continue to require work.

A code developed at Cummins for general fitting and optimization has now been integrated into the cycle simulation workflow. With this tool, cycle simulation results can be fitted with a surface and then used for any general optimization. This gives the ability to optimize with a minimum number of simulation runs.

Developed engine-system models for HCCI combustion and traditional diffusion burn combustion techniques to help evaluate engine architectures and support system design.

Detailed work has been ongoing to match our cycle simulation model to the most appropriate low-NO_x engine data. In this work, temperatures, pressures and flows throughout the system are matched to measured quantities. The details of the sub-models are tuned to achieve this. Very good agreement was achieved at several operating modes with a single-cylinder engine model. No “tweaking” of the model is required in order to match data at several different operating conditions. As has been typical for our engine cycle simulation, experimentally derived heat release is fed into the current model. This model has been used to select EGR and air handling equipment for engine testing. As a next step in the model development, work is currently ongoing to generate combustion models that will predict heat release as a function of crank angle from injection information. This will represent a significant improvement in our modeling capability. In addition to not requiring test data, the model will now include the impact that in-cylinder parameters have on the time history of in-cylinder heat release.

Conclusions

During the 2004 fiscal year, Cummins successfully completed the requirements of Phase IIA and made significant progress toward the Phase IIB project goals. In this effort we:

- Demonstrated 45% BTE in a 15L, heavy-duty diesel engine while achieving 2007 emissions compliance with an advanced engine cooling technique.
- Developed and refined a Systems Integration and Configuration Matrix to evaluate all possible engine system architectures for Phase IIB project goals.
- Performed advanced combustion modeling of ultra-low NO_x solutions including HCCI types of combustion.
- Performed refinement of diffusion burn combustion to achieve further reductions in NO_x production.
- Refined our control system development techniques with the incorporation of model-based controls.
- Defined, evaluated, and chose a waste heat recovery technique to use in the pursuit of the Phase IIB 50% BTE goal. Performed system analysis to initiate prototype procurement.

III.A.2 Heavy Truck Engine Project (Heavy Truck Clean Diesel, HTCD)

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Objectives

- Demonstrate the technologies required to improve fuel efficiency and comply with the 2007–2010 on-highway emission standards (0.2 g/bhp-hr NO_x, 0.01 g/bhp-hr PM) for heavy-duty trucks.
- Thermal efficiency improvement from a baseline of 43% to 50% is targeted.

Approach

- This project focuses on developing multiple paths for meeting 2007–2010 emissions while striving for 50% thermal efficiency. The procedure used is to conduct research on multiple paths and to develop multiple fuel economy building blocks to enable a down-select to the most promising path and building blocks for future production engines.
- Multiple emissions paths are being considered for meeting the 2010 emission requirements. Homogeneous charge compression ignition (HCCI) systems & NO_x aftertreatment systems are being explored to accomplish the 2010 emission requirements.
- HCCI development can be broken down into injector development, single-cylinder development, and multi-cylinder engine development. Injectors are being evaluated by using a variety of laser diagnostic techniques. A single-cylinder test engine (SCTE) is being used to evaluate different HCCI technologies. Engine simulation, combustion modeling, and optical studies are supporting the development of the SCTE. A multi-cylinder engine is also being used to evaluate different HCCI technologies and full engine system issues.
- Aftertreatment is being developed and evaluated to meet 2010 emission requirements. Technology areas that are being explored related to aftertreatment are aftertreatment system modeling, particulate matter (PM) aftertreatment, membrane technology, and NO_x aftertreatment.
- Thermal efficiency improvements are pursued using higher-risk, novel approaches in the areas of reduced engine friction, improved airflow through the engine and improved brake-specific fuel consumption (BSFC)/emissions trade-offs through developing advanced fuel systems.

Accomplishments

- Demonstrator truck with 2007 emissions technology developed and showcased at the 2003 Diesel Engine Emissions Reduction (DEER) conference and the 2004 SAE Government/Industry conference. This truck has provided key insight into system integration challenges and real driving cycle performance and is a key part of the development project.
- Demonstrated full-load and full-power HCCI operation on a single-cylinder test engine while achieving 2010 emissions levels. These are world record levels for operation of an engine in HCCI mode.

- Demonstrated the potential of NO_x aftertreatment to achieve 2010 emissions levels on a multiple-cylinder engine.

Future Directions

The Caterpillar team will utilize best-in-class design practices, advanced modeling techniques, single-cylinder engine testing and multi-cylinder engine testing to advance the technology to build on the major advances made in 2004. Technology development continues in the following key areas:

- Caterpillar will continue to focus on developing supporting engine systems to facilitate full-load HCCI on a multiple-cylinder engine. Fuel efficiency, cost and manufacturability will also be areas of focus.
- Caterpillar will continue to focus on developing methods and techniques to overcome NO_x aftertreatment durability challenges. The team will also focus on fuel efficiency, packaging and cost.
- Focus will continue on development of fuel economy building blocks.
- Focus will also continue on the development of transient simulation capabilities for enhancing the prediction of systems performance in "real-world" settings.

Introduction

Increasingly stringent air quality standards have driven the need for cleaner internal combustion engines. Many emissions reduction technologies adversely affect fuel consumption (and subsequently U.S. dependence on foreign oil). This project seeks to find technology paths and fuel economy building blocks which allow a more favorable trade-off between fuel economy and emissions. This favorable trade-off will reduce fuel used and its associated foreign dependency, lower owning and operating costs, and still allow compliance with the tighter emissions regulations. This heavy truck engine cooperative research agreement provides the framework to research, develop and demonstrate methods to provide better fuel economy.

Approach

The development team is utilizing a multi-discipline approach to address these complex technical challenges. The development team has a unique mix of technical experts from the fields of controls, combustion fundamentals, aftertreatment, engine design, engine development, and manufacturing. The team is concurrently developing the analytical tools to model and better understand the fundamentals of combustion and aftertreatment while delivering novel hardware to the test stand to validate models, improve our understanding, and advance the technology. This unique team is utilizing best-in-class design practices; advanced combustion, aftertreatment and engine system modeling techniques; rapid control strategy development tools; single-cylinder engine testing; multi-cylinder engine testing; and over 70 years of experience delivering successful compression ignition engine technology to the marketplace. In the initial stages of the project, the approach is to focus on many higher-risk technology developments. As additional information and knowledge is gained on the technologies, work then shifts to final development of chosen concepts and then, finally, to technology demonstrations. These new technologies will then be incorporated into Caterpillar's New Product Introduction programs.

Results

As stated above, Caterpillar has made significant progress in developing fuel-efficient solutions that are compliant with the emissions standards. Figure 1 shows technical data for the 2007 emissions technology demonstrator truck. This vehicle was put together to investigate and understand first-hand the challenges of integrating fuel-efficient technology that meets the 2007 emissions standards. The truck builds on ACERT® technology and brings together additional combustion systems, aftertreatment systems, air systems, and controls technology to meet 2007 emissions in a fuel-efficient manner. Figure 2 shows how the truck is also providing data for model validation. The validated models are then used in developing robust 2010 technology paths.

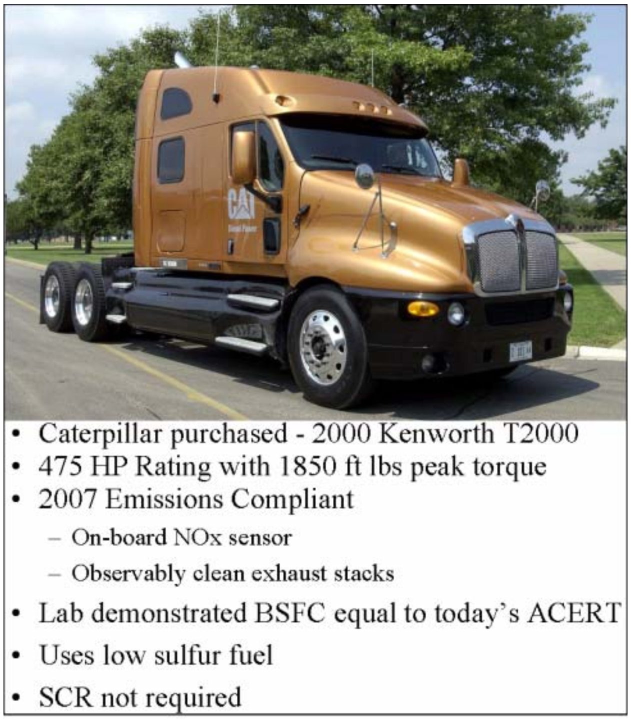

Figure 1. 2007 Emissions Demonstration Truck

In order to meet 2010 emissions in a fuel-efficient manner, HCCI is a key area of investigation within the HTCD program. Table 1 shows the multiple approaches that are used to develop HCCI under this project at Caterpillar Inc. The results showing the world-leading progress on HCCI are contained in the Diesel HCCI Development section submitted separately.

Another method or component to meet 2010 emissions is the use of NO_x aftertreatment. Figure 3 shows the elements of our NO_x aftertreatment system development at Caterpillar Inc. The figure shows that multiple aspects must be properly integrated to provide fuel-efficient operation of NO_x aftertreatment.

Conclusions

Through this Heavy Truck Engine Project cooperative research agreement, Caterpillar has developed and delivered a 2007 emissions technology demonstrator truck with fuel economy essentially equivalent to 2004 engines with ACERT technology. Caterpillar has aggressively developed multiple technology paths for efficiently meeting the challenges of 2010 emissions standards. HCCI development has resulted in world-class-leading power levels and significant technical progress against each of the key technical challenges. The progress has clearly positioned this advanced combustion technology as a potentially viable

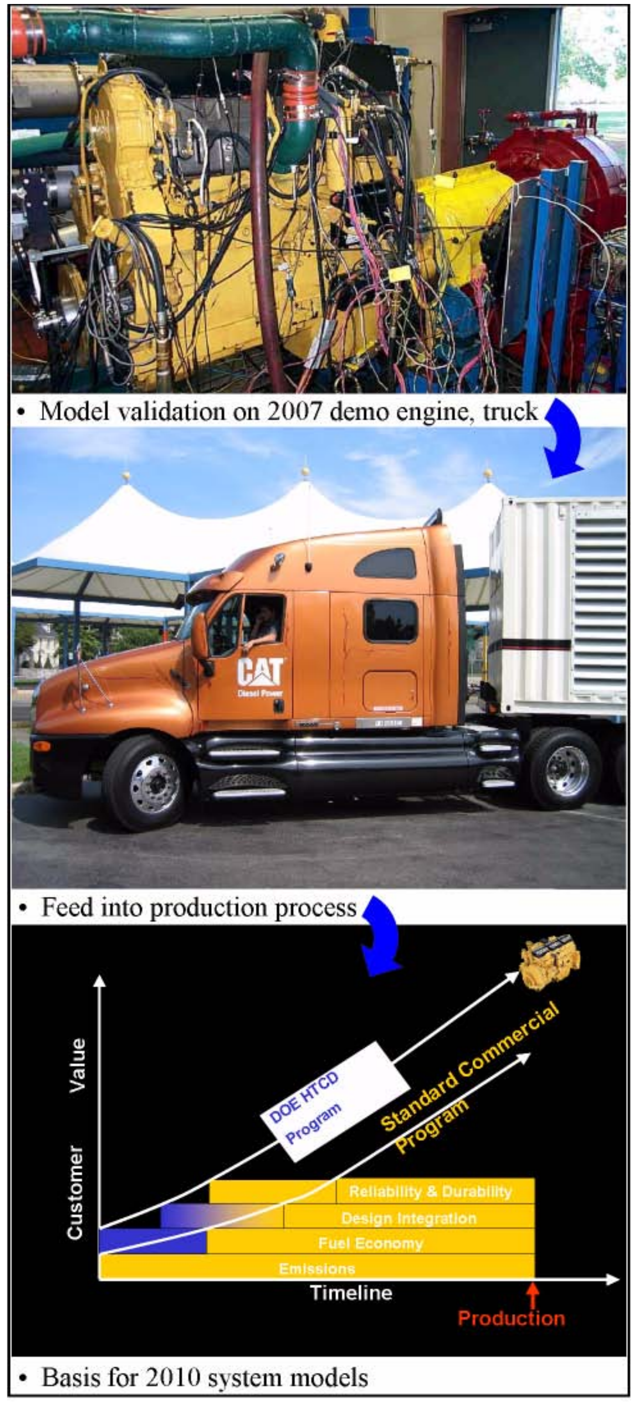

Figure 2. Simulation Process

Table 1. HCCI Development at Caterpillar

HCCI Fuels
Aftertreatment
Simulation
FEA
Single & Multi Cylinder Testing
Combustion Development
In-cylinder Diagnostics
Controls
Fuel Systems
Air Systems

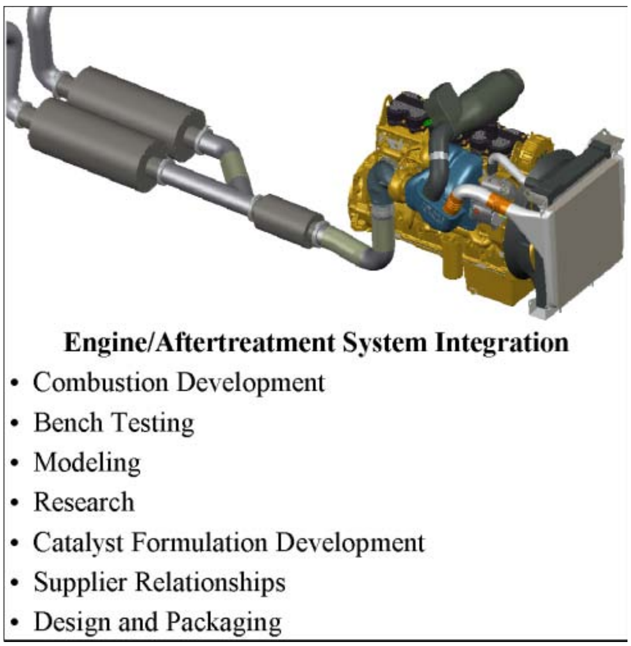

Figure 3. Diesel Aftertreatment System Development Process

approach to meeting the future regulatory and commercial requirements of the marketplace. The development on NO_x aftertreatment paths has shown the potential of this technology to help meet the 2010 emissions regulations. The system-level integration on which Caterpillar has focused is critical in developing this as a viable path. In summary, the technologies developed in this DOE/Caterpillar partnership have the potential to significantly reduce the nation's dependence on foreign oil and improve the trade balance.

FY 2004 Presentations

1. Duffy, K. "HCCI for Heavy Duty Engines," SAE Powertrain & Fluids Meeting, Pittsburgh, PA, October 2003.
2. Duffy, K. "HCCI for Heavy Duty Diesel Engines," SAE Government-Industry Meeting, Washington, DC, May 2004.
3. Duffy, K. "High Load Diesel HCCI Research," SAE Homogeneous Charge Compression Ignition Symposium, Berkeley, CA, August 2004.
4. Duffy, K., Fluga, E., Kieser, A. "Heavy Duty HCCI Development Activities," DOE DEER Conference, Coronado, CA, August 2004.
5. Verkiel, M., Driscoll, J. "Diesel Aftertreatment System Development," DOE DEER Conference, Coronado, CA, August 2004.
6. Rutan, K., Driscoll, J., Verkiel, M. "Transient Simulation of a 2007 Prototype Heavy Duty Diesel Engine," DOE DEER Conference, Coronado, CA, August 2004.
7. Duffy, K., Fluga, E., Faulkner, S., Heaton, D., Schleyer, C., and Sobotowski. "Latest Development in Heavy Duty Diesel HCCI," IFP International Conference on Which Fuels for Low CO_2?, Paris, France, September 2004.

FY 2004 Publications

1. Duffy, K., Fluga, E., Faulkner, S., Heaton, D., Schleyer, C., and Sobotowski. "Latest Development in Heavy Duty Diesel HCCI," IFP International Conference on Which Fuels for Low CO_2?, Paris, France, September 2004.

III.A.3 Improvement in Heavy-Duty Engine Thermal Efficiency While Meeting Mandated 2007 Exhaust Gas Emission Standards

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Objectives

- Quantify thermal efficiency degradation associated with reduction of engine-out NO_x emissions to the 2007 regulated level of ~1.1 g/hp-hr, starting from the Phase 1 project results achieved in calendar year 2002.
- Develop production-feasible technical solutions to achieve brake thermal efficiency of 45% while meeting 2007 regulated emissions.
- Develop roadmap of aftertreatment system requirements and related engine system technologies that can be effectively integrated while ultimately achieving 50% brake thermal efficiency and 2010 regulated emissions.

Approach

- Determine technical requirements for fuel injection, exhaust gas recirculation (EGR), and air mass systems.
- Utilize efficient combination of analytical and experimental tools to screen candidate engine subsystems and components.
- Determine precise and unique applications of multiple fuel injection events, advanced sensor or actuator hardware, and charge air/EGR management systems.
- Tune the integrated engine system for static and dynamic operation, using unique model-based controls approaches.
- Calibrate the integrated engine system across the engine speed-load range so that the engine can seamlessly navigate between local operating optimums.
- Strategize operation of the integrated engine system for best fuel economy while achieving low emissions and other engine system attributes such as driveability.

Accomplishments

- Achieved 43% brake thermal efficiency in a multi-cylinder engine configuration while demonstrating engine-out NO_x and particulate matter (PM) emissions of 1.1 g/hp-hr and 0.1 g/hp-hr, respectively, over the Environmental Protection Agency (EPA) hot cycle Federal Test Procedure (FTP).
- Produced subsequent tailpipe-out NO_x and PM emissions of ~1.0 g/hp-hr and <0.01 g/hp-hr, respectively, with integration of a diesel particulate filter (DPF).
- Completed 1st-order refinement of engine subsystems. By applying well-controlled multiple fuel injection events, the initial brake thermal efficiency penalty of ~3% relative to the production 2004 engine was eliminated. Subsequently, additional brake specific fuel consumption (BSFC) improvement potential was identified.

- Established a 1st-order technology roadmap to achieve the DOE thermal efficiency goal of 45% at 2007 regulated emissions level. These technologies are now being successively incorporated into a production-feasible engine testbed system and evaluated for their potential contribution.
- Developed model-based algorithms for future system controls, establishing a technology development platform and process for realizing advanced combustion characteristics that promise to reduce future emissions variability and provide opportunities for further fuel consumption reduction.

Future Directions

- Continue to incorporate promising technologies regarding high efficiency into pre-prototype engine testbeds while rationalizing production viability, driveability, reliability, and other desired attributes of the total engine system.
- Evaluate advanced fuel injection equipment, including hybrid systems, for the potential to enable combustion characteristics that will lead to over 45% thermal efficiency while meeting 2010 regulated emissions.
- Accelerate technology development regarding sensors and control algorithms required for a fully integrated multi-cylinder engine testbed.
- Solidify technology roadmap, demonstrating viability of key elements, while achieving 2010 emission levels with 50% brake thermal efficiency.

Introduction

This project (named Near Zero Emissions & 50% Thermal Efficiency, or NZ50) helps define conceptual engine configurations and advanced component technologies that can contribute to meeting DOE's thermal efficiency goals within stipulated future emission standards. Without ignoring 'real-world' considerations for commercialization, cost, and durability requirements, the technology concepts are pre-screened analytically. Each of the more promising approaches and subsystems influential to energy consumption, including those associated with fuel, charge air, EGR, combustion, sensing, and cooling, are then developed to a pre-prototype state so that tangible thermal efficiency potential can be quantified. Critical to this assessment, the concepts must be integrated, at least in a thermodynamic context, and then evaluated on a testbed representing prototype, multi-cylinder, future heavy truck engines. This technology evaluation process ensures that system solutions arising from the project that simultaneously exhibit potential for adequate emission control and fuel economy potential can be realistically earmarked for translation into future product development plans.

Approach

Major FY 2004 activities targeted the integration of engine subsystem technology in a pre-prototype configuration to achieve 2007 regulated emission standards while improving brake thermal efficiency. Analytical and experimental tools were used to tune advanced EGR cooler design, air/EGR delivery, and fuel injection control technologies. Unique multiple-input, multiple-output control techniques enabled more precise fuel, air, and EGR flow under diverse engine operating regimes. With 2007 regulated emission standards successfully demonstrated, the fuel and air/EGR management systems were rigorously exercised to forge thermal efficiency techniques that did not compromise emission reduction achievements. A major element of this activity involves novel application of multiple injection events with pre-prototype fuel injection systems.

Results

The basic test platforms used to march toward NZ50 goals include derivatives of 2004 production Series 60 engines, which were modified with advanced technology hardware and software. The

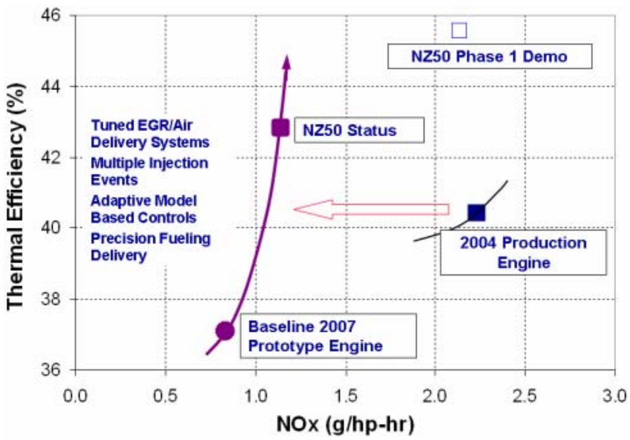

Figure 1. Thermal Efficiency vs. NO_x Emission Achievements

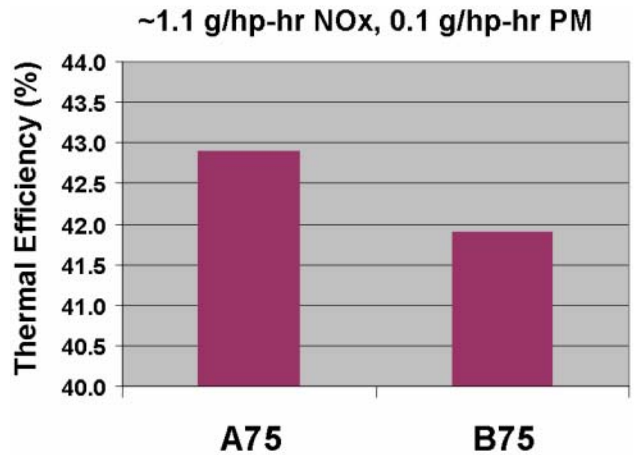

Figure 2. Thermal Efficiency Achievements at 2007 Emissions Levels

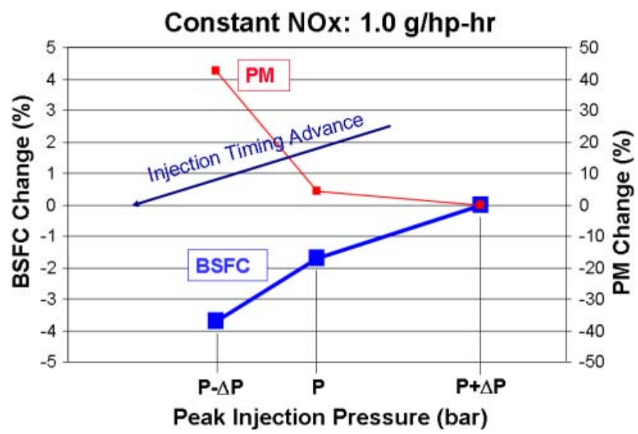

Figure 3. BSFC and PM Emissions Sensitivity to Injection Pressure

fuel injection and EGR subsystems were upgraded to provide prototype performance. Model-based controls within rapid prototyping software systems were integrated as the primary controller of the engine system. Supplementary electronic control units and actuators were used to drive the fuel injection system and other active subsystem hardware. Detroit Diesel Corporation's (DDC's) CLEAN Combustion© was applied to a limited degree under idle and low cycle power conditions. Preliminary calibration of the engine system produced engine-out emissions that are compatible with 2007 targets (NO_x = 1.0 g/hp-hr, PM emissions = 0.12 g/hp-hr) on both a steady-state (ESC) and transient (FTP) basis. Integration of the engine system with state-of-the-art DPF technology yielded demonstrated compliance with 2007 tailpipe-out emissions.

However, achievement of 2007 regulated emissions levels on the baseline 2007 prototype engine led to thermal efficiency degradation from the 2004 production baseline of ~40% to a level of ~37% (Figure 1). From this point, NZ50 project introduction of 2007 and later candidate technologies enabled recapture of lost efficiency. The application of advanced air/EGR delivery systems, multiple fuel injection strategies, more precise fueling delivery, and adaptive model-based control schemes improved thermal efficiency substantially. As illustrated in Figure 1, the current NZ50 status for demonstrated brake thermal efficiency is ~43%. Figure 2 expands the view of these experimental results at two key engine operating points, namely A75 (near peak torque speed and 75% engine load point of the ESC Test Procedure) and B75 (mid-speed and 75% engine load point of the ESC Test Procedure). Thus, the NZ50 achievements to date represent a 50% NO_x emissions reduction accompanied by nearly 6% improvement in absolute brake thermal efficiency relative to the prototype 2007 engine. It should be noted that the reference point for quoting thermal efficiency milestones corresponds to engine operation that is representative of over-the-road operation of a heavy-duty truck.

Application of multiple fuel injection event strategies to improve thermal efficiency is a critical technology being developed vigorously in the NZ50 project. For reference, as illustrated in Figure 3, with single fuel injection events, an injection pressure

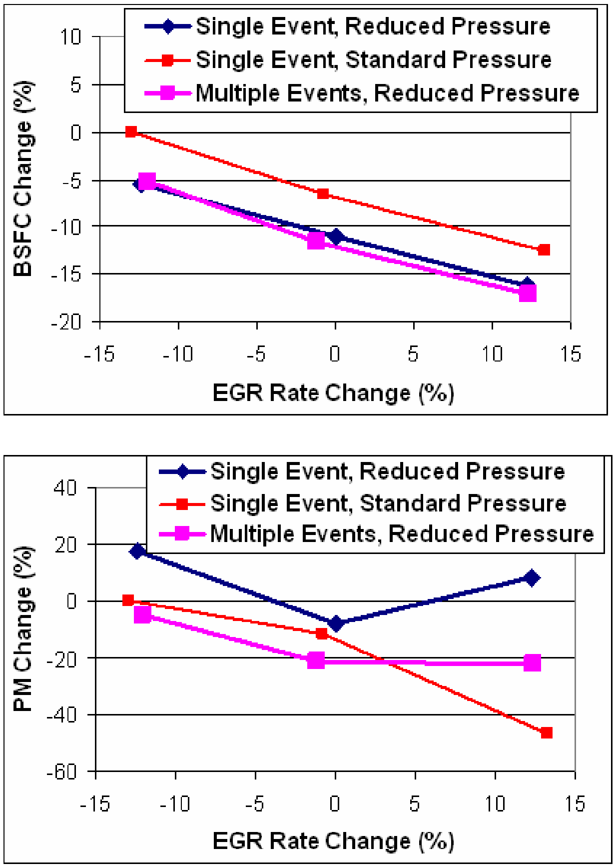

Figure 4. BSFC and PM Benefits from Multiple Injection Events at B100 (mid-speed and 100% engine load point of the ESC Test Procedure)

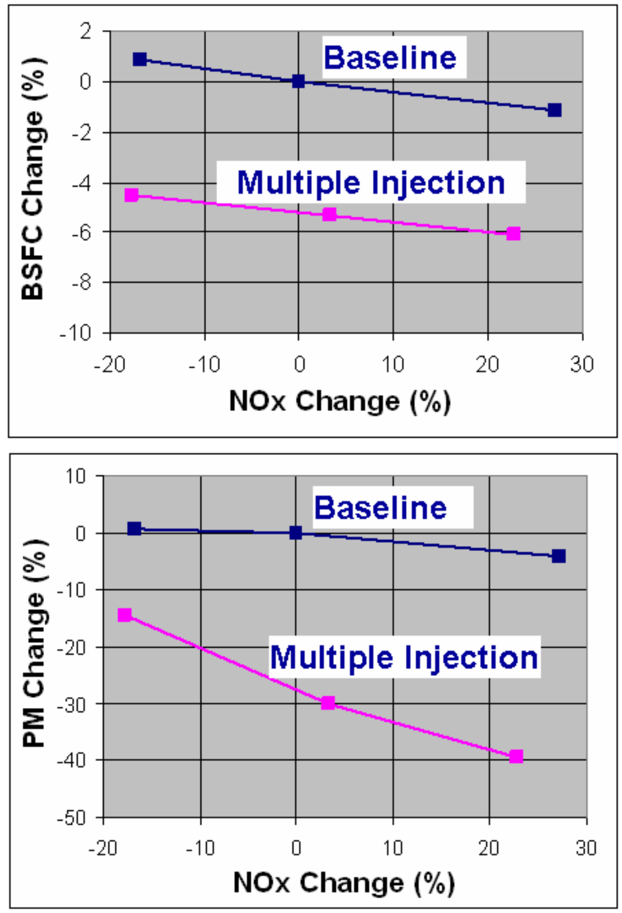

Figure 5. BSFC and Emissions Benefits from Multiple Injection Events at B25 (mid-speed and 25% engine load point of the ESC Test Procedure)

reduction may yield BSFC opportunities, but PM emissions will usually increase. This characteristic response is evidenced in Figure 3, whereby a 4% BSFC improvement is accompanied by 40% PM increase. Similarly, although not illustrated here, low NO_x emissions are achievable with high rates of EGR, but the resultant BSFC and PM and smoke emissions penalties can be prohibitively high.

To combat these characteristics, one angle of attack is the application of novel multiple injection strategies. Figures 4 and 5 show preliminary results for two distinctly different multiple injection strategies now being incubated in the NZ50 project. By careful development and strategic deployment of such strategies, improved thermal efficiency may be realized without detrimental impact on regulated emissions output.

Conclusions

Advanced development and integration of engine subsystems have led to the achievement of demonstrating 2007 EPA regulated emissions while improving thermal efficiency to 43%, representing a substantial improvement relative to the 2004 production engine baseline and to the baseline 2007 prototype engine. Model-based controls have been systematically proven as effective methodologies for exploiting benefits from the fueling, air, and EGR systems. The transition to more pervasive model-based controls with increased robustness and on-board optimizing functions is now underway. Active correction schemes are now being incorporated to widen the envelope within which low emissions and improved thermal efficiency can be attained.

III.B Light-Duty

III.B.1 Cummins/DOE Light Truck Clean Diesel Engine

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DOE Technology Development Manager: John Fairbanks

Objectives

To develop a diesel engine system for light trucks and sport utility vehicles with the following attributes:

- Improved fuel economy
  - 50% improvement over the gasoline powered vehicle it replaces
- Emissions
  - Tier 2, Bin 5 full useful life emissions of 0.07 g/mi NO_x and 0.01 g/mi particulate matter (PM)
- Positive gasoline engine attributes
  - Noise
  - Acceleration
  - Cold start and warm up
  - Serviceability
  - Weight

Approach

- Fully analyze the overall combustion and performance of new smaller diesel engines using practical tools, including computational fluid dynamics, combustion kinetics, stress and heat transfer finite element analyses, and overall transient performance simulation.
- Establish bench tests to confirm the above models.
- Optimize the complete system design using the above models.
- Build and test complete system prototypes.

Accomplishments

- Improved engine-out emissions by 25% through variable nozzle turbocharger application.
- Completed improved air handling algorithm development to control the variable nozzle turbocharger and to provide air handling compensation at altitude.
- Completed evaluation of engine cold start and stable idle at -30 Centigrade.
- Achieved active aftertreatment regeneration with closed-loop lambda controls.
- Demonstrated power density of 48 HP/liter on a 4.2 liter V6.
- Demonstrated Tier 2 Bin 5 emissions capability through emission testing at sea level and at altitude with 150,000 mile thermally aged catalyst.
- Achieved engine-out emissions (EOE) of less than 0.3 g/mi NO_x and 0.1 g/mi PM using a steady-state transient test cycle approximation, using currently available diesel fuel.

Future Directions

Research and engineering work at Cummins over the past several years has focused on developing low-emission solutions and demonstrating those solutions in vehicle chassis testing. The project has emphasized realistic and cost-conscious solutions involving original equipment manufacturers and production intent suppliers. The project has been successful in demonstrating that light-duty diesel vehicles certified to Tier 2 Bin 5 tailpipe emissions standards are technically viable. However, there are several areas that the project has not addressed that are very suitable for future work to further the development of "Advanced Combustion Engine Enabling Technology". These areas include the following:

- Low-temperature combustion (LTC) zone expansion
  - Develop exhaust gas recirculation (EGR) cooling temperature and pressure targets versus speed and load required to maintain LTC-type combustion.
  - Develop calibration that will operate in LTC over the entire certification cycle.
  - Develop rich operation up to 10 bar brake mean effective pressure (BMEP).
  - Target:
    - 0.1 g/mi EOE NO_x
    - 23 mpg at 6500 lb inertia test weight (ETW) (steady-state approximation)
- Closed loop controls development
  - Build rapid prototype control systems with feedback capability on air/fuel ratio (both rich and lean), fueling correction and start of combustion or ignition timing.
  - Run transient operation on closed loop system.
  - Target:
    - Transient operation at Tier 2 Bin 5 emissions calibration
- Aftertreatment system optimization
  - Demonstrate low-cost, highly effective PM filter.
  - Demonstrate low-cost, highly effective NO_x control.
  - Demonstrate low-cost, highly effective 4-way catalyst.
  - Target:
    - PM filter effectiveness at 90%
    - NO_x-adsorbing catalyst (NAC) effectiveness at 60%
    - 4-way catalyst demonstration at Tier 2 Bin 5 emissions calibration
- System integration
  - Integrate advanced vehicle, transmission, engine and aftertreatment systems.
  - Tune advanced vehicle, transmission, engine and aftertreatment systems.
  - Tune vehicle for drivability and emissions performance.
  - Target:
    - Tier 2 Bin 5 emissions compliant
    - 23 mpg combined city/highway fuel economy
    - Good transient response

Introduction

Beginning in the mid 1980's, the light truck and sport utility vehicle (SUV) market share has steadily increased from 30 percent of all new light vehicles sold in the U.S. to what is now over 50 percent of a 14 million vehicle per year market. As this market has shifted from cars to trucks, the U.S. fleetaveraged fuel economy has decreased. The increase in fuel consumption has driven the need to increase imported oil, affecting the overall trade balance and economy (and eventually, national security). This Department of Energy project is aimed at reducing America's dependence on foreign oil while not compromising America's choice of available vehicles.

Diesel engines have long been known for efficiency, reliability and durability. Unfortunately, due the nature of the physics involved, the emissions of oxides of nitrogen (NO_x) and particulates (PM) are significantly higher than legislated limits for light vehicles. America's limited knowledge of light vehicle diesels requires that a saleable product must not only meet the legislated parameters, but must exceed the positive attributes of gasoline-powered vehicles without exceeding the threshold market pricing. This Cummins project includes development of a diesel engine that will not require vehicle design changes or unrealistic fuel specifications, nor require the end user to modify driving or maintenance practices.

Approach

This diesel engine has been developed with a production design intent in mind since inception. This is evident in the use of high-volume, gasoline production accessories and components. Also notable in the design is the use of modern, design for manufacturing initiatives, such as integrated components and reduced bracketry.

The base architecture is designed specifically for light-duty use, as opposed to an adaptation of an industrial or medium-duty engine. This ensures the lightest design without compromise for varied applications. This also ensures the design can be optimized for the important customer attributes, including NVH (noise, vibration, and harshness), weight, and cost.

Development of this diesel engine has considered the use of the latest technology for emission controls. High-pressure, common rail diesel fuel injection systems used in high-volume European production engines are being utilized. Due to the U.S. emissions requirements, advanced aftertreatment devices are being used. Engine-out emissions (EOE) development continues to reduce the engine-out emission levels, thereby reducing the volume (displacement), total material needed and cost of the aftertreatment devices. Catalysts are typically loaded with expensive precious metals such as platinum, palladium and rhodium. The total cost for the aftertreatment system is targeted to be equivalent with that of an equal-emitting gasoline emission control system.

Results

The diesel engine developed by Cummins Inc. has demonstrated numerous objectives for this project (see Table 1). The basic design architecture of the engine lends itself to one overriding objective of a production intention program: low cost. The engine design utilizes integrated components that allow subassemblies to be assembled and tested prior to final engine assembly. These subassemblies, or modules, reduce final assembly times and material handling in a production environment.

Integration of the aftertreatment controls into the base engine and emission controls has been a major effort in this project. The NO_x aftertreatment device requires periodic conditions of fuel-rich exhaust stoichiometry in order to regenerate, or reduce, the stored emissions. This rich operation is not normal for diesel engines that typically only operate under lean conditions. Major emphasis was placed on being able to operate under rich conditions without adding additional hardware devices, such as an additional injector in the exhaust piping. Also, maintaining the original objectives set for this project, development had to focus on not inducing torque or noise fluctuations during these fuel-rich excursions. The successful integration of these controls, along with advanced catalysts, made possible achievement of Tier 2, Bin 5 emissions (see Figure 1).

Other significant accomplishments include the following:

Power Density

The Phase 2 V6 engine was targeted to have a peak power of 186 kW (250 bhp) at 4000 rpm. The best power achieved by July 2003 was 180 kW (241 bhp) @ 3600 rpm with a wastegated

Table 1. V Family Goals and Status

Description	Target		Actual (Status)	
	V6	V8	V6	V8
Emissions	EPA Tier 2 & CA LEV II		Tier 2 Bin 10 Interim Demonstrated, Tier 2 Bin 5 Final, Met in Vehicle	
Noise, dBa	69 Hood Open, Equal to Gas		72.7 db, Bare Engine in Test Cell	65.0 Interior, Cruise @ 65 mph, 1500 Pickup
Fuel Economy, MPG	50% Better than Gas		22.1 Combined, Durango (+60%)	21.7 Combined, BR1500 (+60%)
Quality/Reliability	Equal to Gas, <2 RPH First Year and <10 RPH Five Years		Focus in Phase 3	
Rated Speed	4000 rpm (5000 max.)		4000 rpm (5000 max.)	
Useful Life km(mi)	B10 > 325,000 (200,000)		Focus in Phase 3	
Performance	Gasoline-Like (9-10 sec 0-60 mph)		9.6 sec, 0-60 mph, 5940 lb PTW	8.8 sec, 0-60 mph, 6200 lb PTW
Displacement, Liter	4.2	5.6	4.2	5.6
Power, kW(hp) @ rpm	190 (250) @ 4000	260 (350) @ 4000	189 (254) @ 3600 WG 201 (270) @ 3800 VNT	224 (300) @ 4000 WG Interim Target Met
Torque Peak, Nm(ft-lb)	455(335), 569(420) max.	597(440), 760(560) max.	569 (420)	623 (460)
Warm Up	75 C(167 F) Coolant in 10 min. @ -30 C(-22 F)		49C in 10 min @ -30C	Focus in Phase 3
Serviceability	Equal to Gasoline		No Adjustments, Diesel Fuel Filter Added	
Cold Start	< 20 sec. @ -30 C (-22 F)		7.1 sec (1.2 sec Glow) @ -30C	Focus in Phase 3
Weight	295 (650)	340 (750)	301 (663)	357 (788)

turbocharger. The engine architecture has since been upgraded to include a variable geometry turbocharger, higher flow cylinder heads and new common rail fuel system equipment that allows for higher injection pressures. With the addition of this new hardware to the engine, the rated power moved from 180 kW (241 bhp) @ 3600 rpm to 205 kW (275 bhp) @ 3600 rpm, and 201 kW (270 bhp) @ 3800 rpm. Significant gains were also made to the torque curve below the torque peak. At 1600 rpm, torque output increased by 137 lb-ft (see Figure 2). The project goals were achieved while maintaining the mechanical limits of the engine.

Emissions Durability

In order to further the product demonstration, an altitude assessment was completed. The main purpose of the evaluation was to conduct emissions testing at altitude to demonstrate compliance with the Tier 2 Bin 5 emissions standards (see Table 3). Auxiliary objectives included evaluating vehicle driveability, measuring fuel consumption on a standard route, documenting cold start capabilities and assessing the aftertreatment system performance. Emissions testing at high altitude demonstrated that the vehicle is capable of operation at Tier 2 Bin 5 emissions levels with a thermally aged catalyst at 150,000 miles. Testing and documentation was performed on vehicle driveability, cold start performance and aftertreatment performance.

Cold Start

An engine calibration was developed that met many of the engine starting deliverables. Table 2 summarizes the results of this development.

Table 2. Summary of Optimized Calibration Test Results

VOC: Engine Must Start Well Cold			
Time to 1st Engine Fire	6.5 +/- 4.4 seconds	Target: Minimize	Development Target Achieved
Time to Engine Start:	7.1 +/- 4.8 seconds (0 sec glow plug preglow, newait start)	Target: 9 seconds	Development Target Achieved
VOC: Vehicle Must Warm Up Fast and Drive Well			
Coolant Tempera-ture @ 600 seconds	49.2 +/- 2.1 degC	Target: 75 degC	Development Result in Progress
Time to Exhaust Stack Temp > 275F	8.7 +/- 1.1 minutes	Target: Minimize	Development Target Achieved
1st Time UHC < 1000ppm	43 +/- 11.7 seconds	Target: Minimize	Development Target Achieved
1st Time UHC < 250ppm	75 +/- 32.4 seconds	Target: Minimize	Development Target Achieved
Idle RPM Std. Dev. < 30rpm	1.2 +/- 0.74 seconds	Target: Minimize	Development Target Achieved

Table 3. V6 Chassis Test Results

Test	CO [g/mi]	CO2 [g/mi]	NOx [g/mi]	NMHC [g/mi]	FE [mpg]	PM [g/mi]	
FTP-75 FUL limits	4.2	-	0.07	0.090	-	0.01	
FTP-75	0.399	480.27	0.033	0.089	21.12	0.006	•Start
FTP-75	0.367	491.67	0.038	0.056	20.32	-	•1600 mi
	0.241	519.18	0.074	0.043	19.16	-	•Aged & Alt.
bag 1	0.971	547.87	0.141	0.222	18.47	0.008	~150,000 mi
	1.051	583.44	0.181	0.269	17.08	-	5400 ft
	1.121	578.14	0.243	0.207	17.15	-	
bag 2	0.272	475.03	0.003	0.057	21.37	0.004	
	0.200	475.27	0.000	0.000	21.04	-	
	0.060	517.34	0.002	0.001	19.24	-	
bag 3	0.207	439.17	0.009	0.049	23.11	0.007	
	0.166	453.40	0.003	0.000	22.05	-	
	0.018	478.05	0.080	0.000	20.83	-	

V6 Bag Results @ 5000 lb. and 12.7 hp @50 mph

Reduced Engine-Out Emissions

Steady-state optimization work was performed which resulted in an early emissions demonstration of 0.64 g/mi NO_x and 0.11 g/mi PM over the FTP75 test cycle. This transient response and emissions testing indicated issues with the turbocharger vane position control method that was initially used on the engine. Boost pressure response was initially worse than that of the engine with a wastegated turbocharger. This work drove the need for improved algorithms in the engine control module (ECM) to control the turbocharger. During later development, a boost/fresh air flow control system demonstrated significantly better control. Transient emissions testing in-vehicle have also shown that the air handling system performs very well. Tailpipe emissions targets have been demonstrated at both sea level and altitude using this control system. Transient response data were repeated using the new air handling system with very good results. The steady-state boost stabilized much quicker and with less overshoot compared to the wastegated turbo. Further work needs to be done to optimize the transient response performance of the engine while balancing smoke emissions.

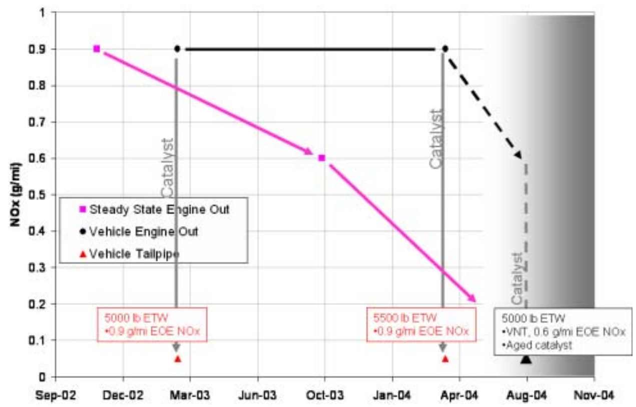

Figure 1. V6 Emissions Progression

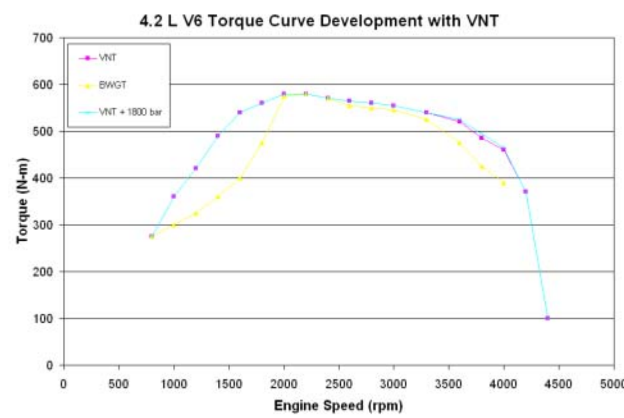

Figure 2. V6 Performance Results

The demonstrations for this project have been done using Phillips 66 “DECSE” (Diesel Emission Controls Sulfur Effects, another DOE project) fuel and relatively fresh “degreened”-only catalyst systems. The “DECSE” fuel has very low sulfur content in solution (<4 ppm). Sulfur has tendency to poison the NO_x-adsorbing catalyst, resulting in poor performance as the catalyst ages. Fuel specifications for future diesel fuels include a maximum sulfur content of 15 ppm. While the low sulfur content of future fuels should aid in reducing catalyst poisoning, catalysts will eventually fail due to build-up of sulfur. Future work will include desulphation development and related catalyst durability work.

Conclusions

- Increased power density can be demonstrated with advanced air handling and fuel system technologies while achieving targeted emissions levels.
- NO_x adsorbers have the potential to meet the emissions durability target of 150,000 miles.
- Cold start and stable idle performance similar to gasoline engines can be achieved with advanced glow plug systems and high-pressure fuel injection equipment.
- Reduced engine-out emission levels can be attained which will balance both fuel consumption and driveability needs while having the potential to reduce the cost of the aftertreatment system.
- The advanced diesel engine can provide a viable business case for light trucks and sport utility vehicles.

Special Recognitions & Awards/Patents Issued

1. Air/oil coalescer with improved centrifugally assisted drainage, Patent No. 6,640,792.
2. Valve train with a single camshaft, Patent No. 6,390,046.

FY 2004 Publications/Presentations

1. CARB Global Climate Change Workshop, March 2004.
2. SAE Government and Industry Conference with DOE 21st Century Truck Display, May 2004.
3. DOE Diesel Engine Emission Reduction Workshop, San Diego, CA, August 2004.

III.B.2 Light-Duty CIDI Engine Technology Development

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Detroit Diesel Corporation (DDC)
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Detroit, MI 48239-4001

DOE Technology Development Manager: John Fairbanks

Objectives

- Demonstrate production-viable diesel engine technologies, specifically intended for North America.
- Demonstrate Tier 2 emissions compliance with significant fuel economy advantages.

Approach

- Apply advanced engine technology development methodology to concurrently develop the engine, vehicle powertrain and aftertreatment systems, as well as to systematically integrate and optimize these systems.
- Develop and use emerging combustion technologies in synergy with advanced aftertreatment technologies to pursue integrated engine, aftertreatment and vehicle system technical targets.
- Minimize development cycle time by leveraging technical findings from other government-sponsored and internally-funded programs at DDC.

Accomplishments

- Demonstrated Tier 2 Bin 3 emissions over the FTP75 cycle for a light-duty truck (LDT) equipped with a Diesel Engine for Light Truck Application (DELTA) engine using a diesel particulate filter plus selective catalytic reduction (DPF + SCR) system, while synergizing efforts with another DOE-DDC project. This aggressive reduction in emissions was obtained without ammonia slip and with a 41% fuel economy improvement, compared to the equivalent gasoline engine equipped vehicle. Demonstrated Tier 2 emissions compliance over the US06 cycle.
- Demonstrated engine-out Tier 2 Bin 10 emissions compliance. Demonstrated Tier 2 near-Bin 9 emissions compliance without active NO_x aftertreatment devices.
- Developed a fuel burner for DPF regeneration. Identified technical issues for a commercially-viable fuel burner that can potentially be utilized on a 2007 light-duty vehicle.
- Systematically characterized air system management options, including air bypass, post injection, and their combination, as part of developing a comprehensive commercially viable DPF regeneration strategy.
- Completed over 1540 hours of durability testing. Over time, a slight fuel consumption improvement was observed. Also, piston mechanical issues were identified and are being resolved.
- Conducted ash-loading tests of sintered metal diesel particulate filters. The objective of this study is to understand the effect of aging on aftertreatment performance, which is a key driver for commercialization potential. Over 1000 hours in ash-loading testing have been accumulated, and it is planned to continue these tests up to 3000 hours.
- Characterized DPF performance using a reactor bench. A key objective of this study is to provide fundamental performance data that will be utilized to calibrate DDC's state-of-the-art aftertreatment models. This integrated analytical and experimental approach to develop aftertreatment technology will benefit efforts to reduce the cost and complexity of aftertreatment devices, which is another key driver for light-duty commercialization potential for 2007 and beyond.

Future Directions

- Continue ash-loading tests up to 3000 hours.
- Complete DPF performance characterization utilizing a reactor bench.

Introduction

Detroit Diesel Corporation (DDC) is developing engine and aftertreatment technologies in support of the Department of Energy-sponsored Light-Duty Truck Diesel Engine development project. The objective of this effort is to demonstrate production-viable diesel engine technologies which are specifically tailored for the North American light truck market. Light-duty truck diesel engines are intended for a variety of vehicle applications, which range from small and mid-size sport utility vehicles (SUVs) and passenger vans to full-size pick-ups, SUVs and vans.

Approach

The DOE-DDC light-duty truck project has benefited substantially from DDC's integrated analytical and experimental approach to advanced engine technology development. This integrated development approach was utilized to concurrently develop the engine, vehicle powertrain and aftertreatment systems, as well as to systematically integrate and optimize these systems utilizing a robust control strategy. Figure 1 shows the key elements of this integrated approach. The focus of this project, however, is on the core engine system and those areas of the vehicle powertrain and aftertreatment systems that are closely coupled with core engine development. The project has also benefited from leveraging technical findings from other government-sponsored and internally-funded projects at DDC.

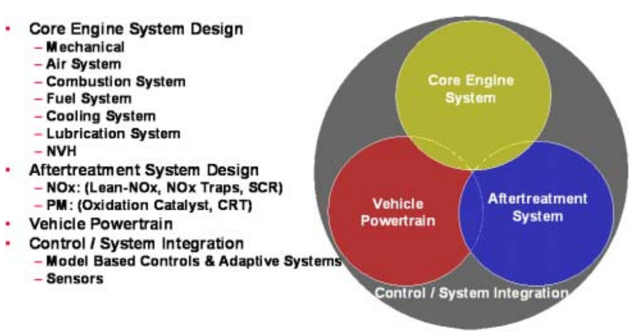

Figure 1. Integrated System Development Approach

Results

DDC successfully demonstrated Tier 2 Bin 3 emissions on a light passenger car platform as early as 2002 (Bolton, et al 2002[1]) as part of the DOE-DDC LEADER project. Building upon this technology demonstration and with increased emphasis on system integration, Tier 2 Bin 3 results were demonstrated on the light truck platform (Aneja, et al 2003[2]). Tier 2 compliance was also demonstrated over the US06 cycle on the light truck platform. In addition to the substantial emissions reduction, a 41% fuel economy improvement compared to the baseline gasoline engine equipped vehicle was obtained. Tier 2 Bin 10 emissions compliance was demonstrated without utilizing any aftertreatment, and Tier 2 near-Bin 9 emissions were demonstrated without the use of active NO_x aftertreatment. These accomplishments can be attributed to advanced combustion and aftertreatment technologies, synergistically integrated utilizing robust control strategies. Figures 2 and 3 present DDC's roadmap for LDT FTP75 emissions.

Having successfully demonstrated Tier 2 Bin 3 emissions compliance, the project's focus this year included increased emphasis on commercialization

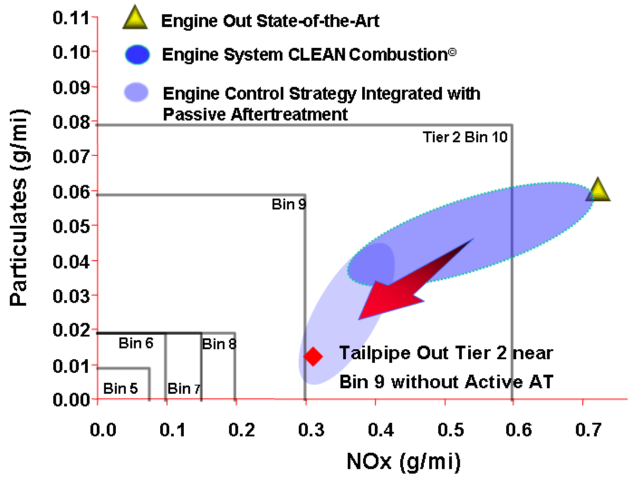

Figure 2. Passive Aftertreatment Emissions Reduction Roadmap; Light Truck Chassis Dynamometer Results

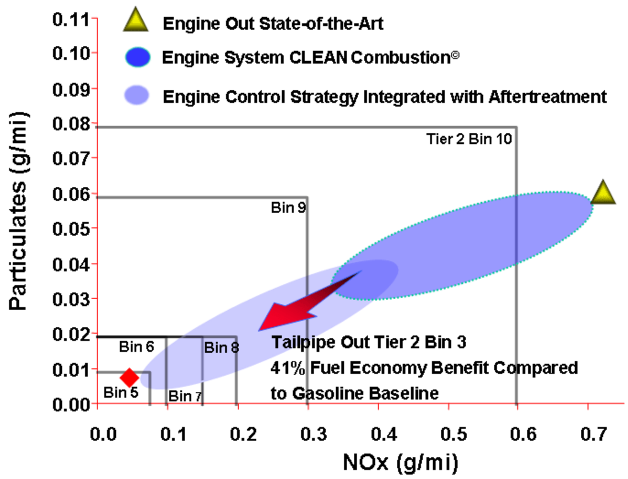

Figure 3. Tier 2 Bin 3 Emissions Roadmap; Light Truck Chassis Dynamometer Results

potential. Focus areas included durability testing, impact of aging of aftertreatment devices, development of a robust strategy for DPF regeneration, and reduced complexity and cost of aftertreatment devices.

A DELTA engine was installed in a durability test cell and has accumulated over 1540 hours of representative over-the-road durability testing. Component wear, fuel consumption and oil consumption were observed as a function of time. The fuel economy was observed to improve slightly over time, and the oil consumption was within acceptable limits, although slightly higher than GEN 0 version of the DELTA engine.

A fuel burner with emphasis on commercial viability was developed as part of a robust strategy for DPF regeneration. This fuel burner was demonstrated to ignite using exhaust gas without air assistance at a range of operating conditions. Figure 4 shows the temperatures at various spatial locations along the exhaust pipe during idle operation, which is a challenging operating condition with respect to exhaust temperature management. The fuel burner was ignited at 300 seconds in time as shown in Figure 4 and allowed the DPF inlet temperature to be raised from 100ºC to 650ºC.

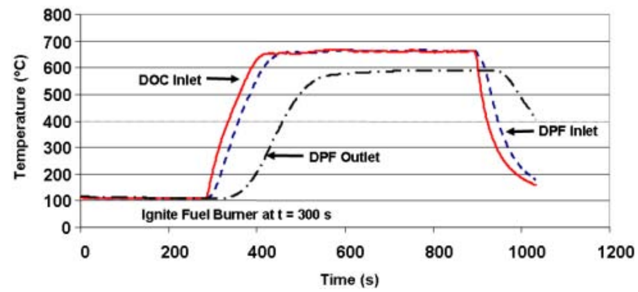

Figure 4. Exhaust System Temperatures at Idle; DPF Regeneration Utilizing Fuel Burner

Conclusions

Use of integrated combustion, aftertreatment and vehicle technologies allowed the DDC team to demonstrate state-of-the-art performance and emissions levels, meeting the project's emissions objectives. Specifically, Tier 2 Bin 3 emissions compliance was demonstrated along with a 41% fuel economy improvement over the gasoline engine baseline. Having successfully demonstrated Tier 2 Bin 3 emissions compliance, the project's focus this year included increased emphasis on commercialization potential. Focus areas included durability testing, impact of aging on aftertreatment device performance, development of a robust strategy for DPF regeneration, and reduced complexity and cost of aftertreatment devices.

FY 2004 Publications

1. Houshun Zhang, "Aftertreatment Modeling Status, Future Potential and Application Issues," 10th DEER Workshop, San Diego, August 29-September 3, 2004.

References

1. Brian Bolton, Nabil Hakim, and Houshun Zhang, "Demonstration of Integrated NO_x and PM Emissions for Advanced CIDI Engines," FY2002, Progress Reports for Combustion and Emission Control for Advanced CIDI Engines, U.S. Department of Energy, November, 2002.
2. Rakesh Aneja, Brian Bolton, Bukky Oladipo, Zornitza Pavlova-MacKinnon, and Amr Radwan, "Advanced Diesel Engine and Aftertreatment Technology Development for Tier 2 Emissions", 2003 Diesel Engine Emissions Reduction (DEER) Conference, August 24-28, 2003.

III.B.3 Variable Compression Ratio Engine

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DOE Technology Development Manager: Roland Gravel

Objective

- Design and build a variable compression ratio (VCR) variant of the DaimlerChrysler 4-cylinder common-rail, turbo-compression direct injection (CDI) engine.
- Incorporate second-generation VCR subsystems into the 4-cylinder VCR DaimlerChrysler CDI engine.
- Demonstrate ability to integrate VCR into high-volume production inline and "V" configuration engine blocks.
- Provide VCR hardware that supports control of CDI and spark ignition (SI) homogeneous charge compression ignition (HCCI) combustion.
- Evaluate part-load efficiency potential for advanced SI engines having VCR and Atkinson-cycle cam timing.

Approach

- Design/build of VCR CDI engine applying design optimization computer models and prior hardware build analysis and data.
- Computer-aided design (CAD) modeling of a 90° V-8 engine VCR crankshaft cradle to establish fit within production engine block.
- GT-Power computer modeling of SI engine using prior dynamometer test data to tune the computer model.

Accomplishments

- The Envera VCR mechanism was successfully packaged into an inline 4-cylinder CDI engine, demonstrating feasibility of manufacturing VCR variants of production engines.
- The ability to package the Envera VCR mechanism into a production 90-degree V-engine block was successfully demonstrated using CAD modeling. Near-identical compression ratio was maintained on both cylinder banks.
- Second-generation VCR components have been successfully designed and are currently being built, including a small profile crankshaft cradle, lubrication system, oil sealing system, actuator mechanism, and chain drive.
- The spark-ignition VCR combustion system was tuned using GT Power modeling. Projected brake specific fuel consumption at the light load condition of 2 bar bmep and 2000 rpm is 330 g/kWh. The part-load efficiency of the SI-VCR engine is projected to be higher than that of the DaimlerChrysler A170 common-rail turbo-CDI current production engine.
- A patent has been allowed for intake ports designed by Envera LLC. The ports have industry-leading performance.

Future Directions

- A VCR variant of the DaimlerChrysler 1.7L 4-cylinder common-rail turbo-diesel will be operational in Spring 2005. The engine will be used to investigate CDI emissions, fuel economy, and advanced combustion benefits that can be attained with VCR.
- Demonstrate through hardware testing and computer modeling the ability to attain 25 percent improvement in SI fuel economy with HCCI combustion using VCR and adjustable valve settings for controlled combustion from idle to high load levels.
- Demonstrate through hardware testing and computer modeling the ability to attain 30 percent improvement in fuel economy with VCR, supercharging, and engine down-sizing at significantly lower production cost than hybrid electric vehicle (HEV) technology (dollars per percent increase in fuel economy) while meeting federal and state emission standards.

Introduction

Multiple project tasks were undertaken in 2004, including design/build of a VCR variant of the DaimlerChrysler 1.7L common-rail turbo-diesel, VCR packaging studies for a V-8 engine, and SI combustion system tuning using computer modeling.

The 4-cylinder CDI engine includes several all-new VCR components, including a small profile crankshaft cradle, lubrication system, oil sealing system, actuator mechanism, and chain drive. The VCR mechanism is compact and is packaged inside a modified stock engine block. One bay of the crankshaft cradle is shown in Figure 1, and Table 1 shows selected data for the engine. The engine will be operational in spring 2005.

A CAD model of a VCR crankshaft cradle for a V-8 engine was built to demonstrate that VCR can be packaged into stock V engine blocks and that the difference in compression ratio from bank to bank is minimal. Minimizing difference in compression ratio from bank to bank is needed for attaining high efficiency.

A finding of the V-8 design study is that the Envera VCR mechanism may facilitate use of aluminum engine blocks in diesel engines and provide weight reduction relative to cast iron block engines. The VCR crankshaft cradle is cast in ductile iron and provides significant bottom-end support.

Large gains in fuel economy can be attained by down-sizing in the V-engine market segment. For example, a 4.6-L V-8 engine could be replaced by a 50-percent smaller boosted 3.0-L V-6 engine to provide both efficiency and cost benefits.

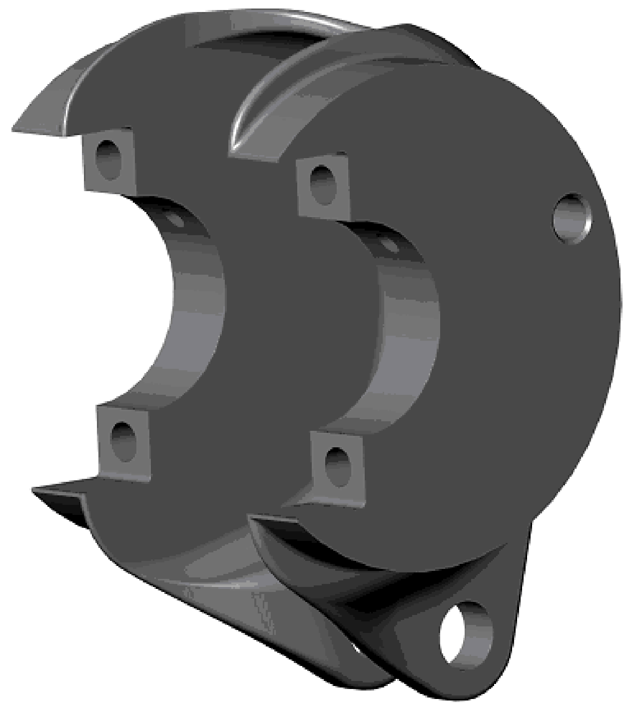

Figure 1. Single Bay of the Envera Crankshaft Cradle

In 2003, Envera LLC reported that indicated fuel efficiency values from dynamometer testing demonstrate potential for attaining a peak efficiency of over 38 percent using high-octane pump gasoline (93 octane) running at stoichiometric air/fuel ratio for effective reduction of emissions using proven 3-way catalytic converter technology.[1] In 2004, Envera used GT Power software to tune the engine for high efficiency at the part-load setting of 2 bar bmep and 2000 rpm. Brake specific fuel consumption was

Table 1. VCR 4-Cylinder Turbo-CDI Engine Specifications

Cylinders	4
Valves per cylinder	4
Valve actuation	DOHC
	Roller finger followers with hydraulic lash
Bore spacing	90 mm
Bore	80 mm
Stroke	84 mm
Bore/stroke ratio	0.95
Displacement	1.689 L
Compression ratio	18:1 maximum
	9:1 minimum
Fuel injection	Common-rail direct-injection
Cold-start	Glow plug
Boosting	Turbocharger

projected to be 330 g/kWh, and efficiency was projected to be 25.6% at the part-load condition. By comparison, the common-rail turbo-CDI currently sold in the DaimlerChrysler A170 has an efficiency of about 24% at 2 bar bmep and 2000 rpm.[2] This spark-ignited VCR engine is projected to be more efficient than the DaimlerChrysler CDI engine at part load. New camshafts have been made for dynamometer testing of the VCR engine to evaluate projected efficiency values.

Approach

The 4-cylinder VCR turbo-CDI engine is currently being designed and built. Design optimization computer models, prior analysis, and data are being used in the current project. The engine will be operational in spring 2005.

CAD modeling was used to evaluate packaging of the VCR crankshaft cradle in a 90° V-8 engine. The VCR crankshaft cradle fit within the production engine block, valuable for minimizing production cost and lead time.

GT-Power computer modeling was used to evaluate SI engine efficiency at part load.

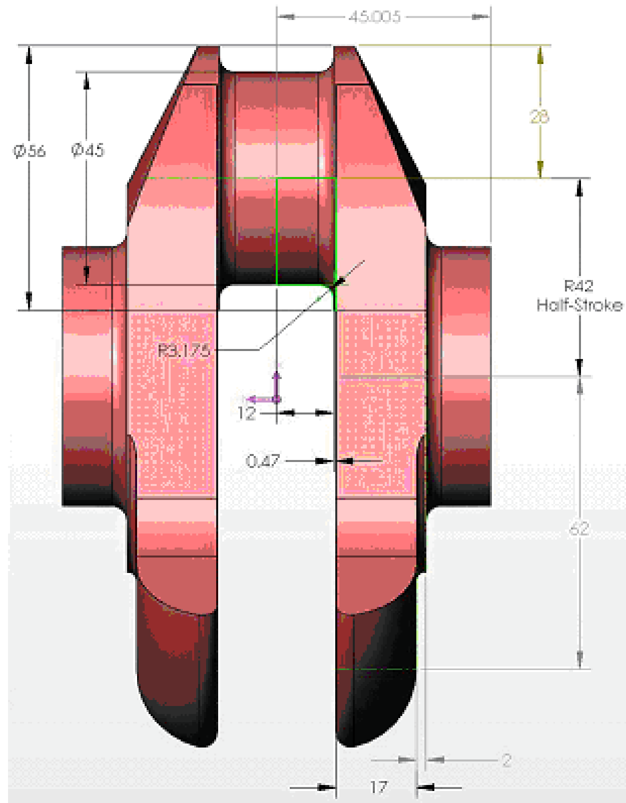

Figure 2. VCR crankshaft with rounded counterweight webs for tight packaging in the crankshaft cradle. The crankshaft has massive cheeks between the main journals and connecting rod journals to provide structure for highly boosted CDI operation.

Combustion burn rate values were assumed based on earlier dynamometer test data from the same engine.

Results

All-new VCR subsystems, including a small profile crankshaft cradle, lubrication system, oil sealing system, actuator mechanism, and chain drive, enhance commercial prospects of the Envera VCR mechanism.

To attain a small profile crankshaft cradle, crankshaft balance web size needed to be minimized. Figure 2 shows a portion of the VCR crankshaft which has rounded counterweight webs for tight packaging inside the crankshaft cradle. The crankshaft is internally balanced for each cylinder bay and features massive cheeks between main and rod journals to provide structure for highly boosted CDI operation.

Table 2. Efficiency Projections

General engine specifications SI-VCR 2-Cylinder	
Cylinders	2
Bore	81 mm
Stroke	90 mm
Displacement	928 cc
Bore off-set	15.5 mm
Valves per cylinder	4
Compression ratio	18:1 maximum
	8.5:1 minimum
Specific power output design limit	150 hp/L (139 hp)
Fuel	93 octane gasoline
Engine management	PFI Motec
Peak engine efficiency Results reported in 2003	
Engine Speed	2350 rpm
Fuel to air mixture ratio	Stoichiometric, lambda 1
Indicated mean effective pressure	10.7 bar
Projected friction mean effective pressure, fmep	1.10 bar
Brake mean effective pressure with assumed fmep	9.60 bar (imep - fmep)
Specific fuel consumption with assumed fmep	220.7 g/kWh (42.58 LHV)
Brake efficiency with assumed fmep	38.3%
Part-load engine efficiency 2004 Projection using GT Power computer modeling	
Engine speed	2000 rpm
Power at test condition	3.08 kW (4.13 hp)
Fuel to air mixture ratio	Stoichiometric, lambda 1
Fuel	93 octane gasoline
Indicated mean effective pressure	2.86 bar
Projected friction mean effective pressure, fmep	0.86 bar
Brake mean effective pressure with assumed fmep	2.0 bar (imep - fmep)
Specific fuel consumption with assumed fmep	330.0 g/kWh (42.58 LHV)
Brake efficiency with assumed fmep	25.6%

Table 3. SI-VCR and Turbo-CDI Efficiency Compared

Engine	SI-VCR	DaimlerChrysler A170 CDI[2]
Fuel	Gasoline	Diesel
Fuel System	PFI	Common-rail direct injection
Effiency Projections		
– 2 bar bmep 2000 rpm	25.6%	24.1% (interpolated)
– 3.09 kW (4.15 hp) at 2000 rpm	25.6%	16.7% (interpolated)
– Peak efficiency	38.3%	38.95%
Rated power with boosting	150 hp/L	56 hp/L (MY 2004)
Emission system	TWC	

The ability to fit the Envera VCR mechanism into modified production inline and V engine blocks was demonstrated. Compression ratio is almost identical on both sides of a 90° V engine, important for attaining high efficiency. CDI cast iron block engines may be lightened by using a ductile iron crankshaft cradle and an aluminum engine block.

Efficiency was projected for the gasoline-fueled Envera SI-VCR engine. At part-load of 2 bar bmep and 2000 rpm, brake specific fuel consumption of 330 g/kWh and brake thermal efficiency of 25.6 percent were predicted using GT Power software. The projected SI-VCR engine efficiency values are of particular interest because they are higher than the DaimlerChrysler A170 common-rail turbo-CDI efficiency values. Table 2 shows peak efficiency values reported by Envera in 2003 and new part-load efficiency projections from 2004. Table 3 provides a comparison of the SI-VCR engine efficiency and the DaimlerChrysler A170 CDI efficiency. The data indicates that the gasoline SI-VCR engine would return higher fuel economy than the diesel without the benefit of engine down-sizing. With down-sizing, the gasoline engine would provide better mileage than the diesel by a larger margin.

SI-VCR engines may have an advantage over smaller-displacement CDI engines (under roughly 200 horsepower). CDI engine efficiency improves with increase of engine displacement because turbocharger efficiency improves with increased airflow. Larger CDI engines have higher efficiency than the DaimlerChrysler A170.

CDI engine efficiency can also be improved with VCR. The baseline for comparison is a moving target, and VCR is anticipated to advance CDI efficiency as well.

Conclusions

A second-generation Envera VCR engine will be operational in spring 2005. The CDI engine includes all-new VCR subsystems that enhance commercial prospects for the technology.

Efficiency projections conducted in 2004 suggest that gasoline-fueled SI-VCR engines may provide better fuel economy (without benefit of down-sizing) than some diesels, such as the DaimlerChrysler A170 common-rail direct-injection turbo-diesel engine. If down-sizing is allowed, fuel economy can be increased by a larger margin. The efficiency of CDI engines is improving and may remain higher than that of gasoline engines. Nevertheless, SI-VCR engine technology developed with funding from DOE has been a success and could play a significant role in reducing growth of national petroleum consumption.

Significant national oil savings could initially be realized by down-sizing large V-engines with smaller boosted V-engines having VCR (both CDI and SI). Saab and others estimate that VCR and down-sizing can improve SI fuel economy by about 30%.[3] The efficiency of the VCR engines could be further improved by HCCI combustion as that technology matures. GM and others estimate that HCCI combustion offers the potential for improving gasoline fuel economy by about 25%.[4] The VCR technology can be integrated into production engines and has significantly lower cost than HEV technology.

Patents

1. A patent has been allowed on a high-performance intake port invented by Charles Mendler. The port exhibits industry-leading flow values, which increases engine torque and reduces boost pressure requirements for engine down-sizing. The port was developed with funding from the U.S. Department of Energy. The publication number and date have not yet been issued.

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