# III Heavy Truck Engine

# III Heavy Track Engine

## III.1 Heavy Truck Engine Project

*Brett Barnhart (Principal Investigator), Chris Nelson (Primary Contact)*
*Cummins Inc.,*
*1900 McKinley Ave.*
*Columbus, IN 47201*

*DOE Technology Development Manager: Roland Gravel*

*NETL Project Manager: Carl Maronde*

### Objectives

- **Phase I** – Demonstration of 45% brake thermal efficiency (BTE) at cruise conditions while meeting 2002 Environmental Protection Agency (EPA) heavy-duty engine emissions regulations (completed).
- **Phase IIA** – Demonstration of 45% brake thermal efficiency at cruise conditions while meeting 2007 EPA heavy-duty engine emissions regulations (completed).
- **Phase IIB** – Demonstration of 50% brake thermal efficiency maximum while meeting 2010 EPA heavy-duty engine emissions regulations.

### Approach (Phase IIB)

- Engine Development
  - Identify combustion systems for best NOx/efficiency trade-off for 2010
  - Analyze data and develop sub-model
  - Develop controls architecture for advanced combustion systems
  - Develop air handling/exhaust gas recirculation (EGR) architecture
  - Conduct advanced single-cylinder engine testing of combustion systems
  - Define and demonstrate subsystem architecture for 2010
  - Analyze and design waste heat recovery techniques to support brake thermal efficiency targets
  - Design waste heat recovery system hardware for test cell demonstration
  - Design engine system controls to achieve optimal combined system efficiency
- Analysis/Development of NOx and Particulate Matter (PM) Aftertreatment Systems
  - Develop system architecture
  - Procure engine and test support
  - Develop and validate model
  - Integrate aftertreatment subsystem
  - Optimize aftertreatment subsystem
  - Demonstrate integrity of aftertreatment subsystem
- Exhaust Stream Conditioning for NOx Regeneration
  - Analyze and test in-cylinder exhaust conditioning
  - Evaluate fuel and air handling systems

  - Develop engine management strategy for NOx and diesel particulate filter (DPF) regeneration and exhaust stream conditioning
- Development and Integration of Control System
  - Develop controls architecture and model engine, aftertreatment, and heat recovery systems
  - Develop aftertreatment sensor
  - Define control architecture for 2010
  - Demonstrate control architecture for 2010
- Demonstrations
  - Demonstrate engine and aftertreatment system in a heavy truck
  - Demonstrate 50% BTE maximum @ 2010 emissions in test cell

## Accomplishments (FY 2005)

- Established base engine architecture for 2010 emissions
- Demonstrated 2010 emissions performance from base engine architecture assuming NOx reduction aftertreatment system
- Explored extremely high fuel injection pressures as a means of reducing NOx and PM while improving fuel efficiency
- Incorporated variable valvetrain system components into experimental engine systems
- Established performance potential of organic Rankine cycle (ORC) waste heat recovery (WHR) system; designed demonstration hardware and initiated fabrication
- Analytically determined ORC system configuration for WHR to achieve 50% BTE project goal

## Future Directions

- Demonstrate the ability to meet 2010 EPA emissions regulations in a heavy-duty diesel engine
- Demonstrate 50% BTE while meeting 2010 EPA emissions regulations
- Integrate a base engine capable of meeting 2010 EPA emissions regulations into a vehicle

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## 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. Phase I: Cummins demonstrated in 2002 engine BTE equal to or greater than 45% while complying with emissions regulations of 2.5 g/bhp-hr NOx-HC and 0.10 g/bhp-hr PM, as stated in the EPA/Department of Justice Consent Decree with the diesel engine manufacturers. Phase IIA: In 2004, Cummins demonstrated BTE of 45% in a multi-cylinder, heavy-duty, diesel engine while complying with 2007 EPA emissions regulations of 1.2 g/bhp NOx-HC and 0.01 g/bhp-hr PM. In Phase IIB, Cummins is working 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 NOx-HC and 0.01 g/bhp-hr PM.

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

## Approach

Cummins' approach to meeting 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 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, a vehicle system demonstration is planned and prepared for. 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 the final commercial products. Cummins intends to continue to hone its technical skill and ability through this research while providing satisfactory results for customers. Cummins continues to follow this cost-effective, analysis-led-design approach both in research agreements with the Department of Energy as well as in its commercial product development. Cummins feels this common approach to research effectively shares risks and results as well as resources.

## Results

During 2005, Cummins Inc. advanced toward the Phase IIB project goals with a focus on combustion development and waste energy recovery. 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 return from research effort, resulted in an excellent foundation from which to reach the final project goals.

### Major Accomplishments in 2005

***Established base engine architecture for 2010 emissions***

A conventional combustion strategy with cooled EGR was determined to be the best choice for 2010 emissions performance after extensive research was conducted into premixed charge compression ignition (PCCI) and homogeneous charge compression ignition (HCCI) combustion methods. Combustion noise (knock) and controllability in these more advanced combustion modes presented issues that required more extensive optimization than could be accommodated before 2010 emissions-capable architecture had to be established to support project goals. Efficiency and emissions performance were enhanced through the application of a more flexible, higher-pressure, common-rail fuel system that can accommodate variable injections of fuel during the combustion process.

Cummins continues to utilize the benefits of a high-pressure, cooled, recirculated exhaust gas strategy to mitigate NOx emissions. This architecture has been thoroughly production-proven to be effective, efficient and robust.

***Demonstrated 2010 emissions performance from base engine architecture assuming NOx reduction aftertreatment system***

Cummins Inc. investigated a great number of combustion/aftertreatment system combinations to meet the 2010 heavy-duty engine emissions standards. Urea-based selective catalytic reduction (SCR) and NOx adsorber technology were considered in combination with many different base engine architectures to reach the project goals. Cummins Inc. demonstrated the ability to reach the required project emissions levels at steady-state conditions across the engine operating map assuming efficient NOx aftertreatment reduction ability. Cummins continues to pursue enhanced combustion processes that minimize or eliminate the need for NOx reduction.

*Explored extremely high fuel injection pressures as a means of reducing NOx and PM while improving fuel efficiency*

During 2005 Cummins investigated the limits of fuel injection pressure and its influence on NOx and PM emissions. A significant benefit to efficiency with simultaneous NOx and PM reduction was considered theoretically possible, and test results verified the model predictions (see Figure 1). It is theorized that with high-velocity fuel jets (from high-pressure injection), fuel parcel equivalence ratios are reduced substantially prior to the start of fast combustion reactions. This combustion method yields a partial PCCI-type burn but also increases turbulence for post fast-burn cleanup of soot particles (standard diffusion burn process).

Consistent control of fuel injection when operating at high injection pressures proved a major technical challenge, but effective solutions were developed to address the issues encountered. Tougher and stronger injector and fuel system materials were chosen, and more robust component designs were developed. Parasitic draw on the engine was minimized and overall efficiency benefits were realized.

***Incorporated variable valvetrain system components into experimental engine systems***

A full-authority variable valvetrain system for a heavy-duty single-cylinder research engine was procured. This system is capable of complete control of individual intake and exhaust valve position at any step in the combustion cycle. The opportunity to manipulate valvetrain actuation will significantly shorten the development time necessary to identify and tune a combustion recipe. The demonstration of steady-state emissions performance was achieved through direct application of single-cylinder combustion tuning to a multi-cylinder engine.

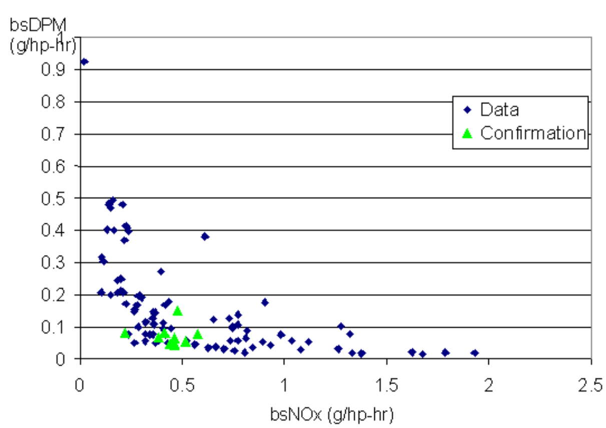


**Figure 1.** Brake-specific NOx – brake-specific DPM Tradeoff Data

***Established performance potential of an ORC WHR system; designed demonstration hardware and initiated fabrication***

ORC waste heat recovery technologies identified during 2004 were analyzed throughout FY 2005 to predict the performance potential of this technique in the effort toward the project's maximum BTE goal.

A combined cycle engine system (base engine plus ORC energy recovery system) was modeled to show a theoretically possible increase of BTE that will meet or exceed the project target. Concept designs were approved to fabricate hardware for the project's BTE demonstration. ORC hardware fabrication was initiated during Q2 of FY 2005 and continued through the end of the year. The turbine-generator, which will convert thermal energy from the ORC system working fluid to electrical power, was designed and machined (Figure 2) and assembled (Figure 3) in preparation for the system demonstration.

**Figure 2.** ORC Turbine, Generator, and Feedwater Pump Shaft Assembly

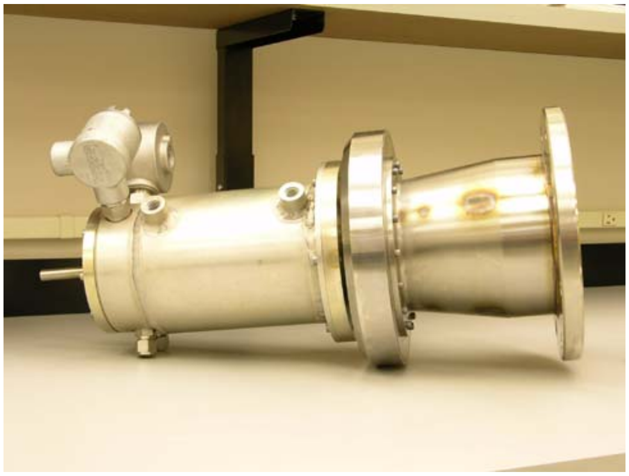

**Figure 3.** Assembled ORC System Turbine-Generator

The lab-based demonstration turbine-generator is approximately 24 inches long and 10 inches in diameter at its widest point. Fabrication of the assembly, including the turbine-generator, heat exchangers, and control hardware, was underway at the end of the fiscal year to deliver the laboratory-based system to Cummins before the end of 2005.

***Determined ORC system configuration for WHR to achieve 50% BTE project goal***

The laboratory system for maximizing engine system BTE will extract heat energy from the engine's jacket water, compressed fresh air stream, main exhaust gas stream and recirculated exhaust gas stream. A working fluid will be heated to boiling and superheated in this process. The temperature of the working fluid will rise to approximately 500°F as it is passed into an expansion turbine/generator that will convert the fluid's thermal energy and momentum into electricity. Electric power will be measured and dissipated as heat to cooling water in this experiment. Future project plans include providing this electrical energy to vehicle and driveline systems. Utilization of heavy hybrid electric vehicle driveline technology is anticipated in these future projects.

## Conclusions

During FY 2005, Cummins developed systems for a successful Phase IIB demonstration in 2006. This effort resulted in the following accomplishments:

- Established base engine architecture for 2010 emissions
- Demonstrated 2010 emissions performance from base engine architecture assuming NOx reduction aftertreatment system
- Explored high fuel injection pressures as a means of reducing NOx and PM while improving fuel efficiency
- Incorporated variable valvetrain system components into experimental engine systems
- Established performance potential of an ORC WHR system; designed demonstration hardware and initiated fabrication
- Determined ORC system configuration for WHR to achieve the 50% BTE project goal

Our analysis-led-design commitment has consistently achieved program deliverables. Cummins is confident that the final project goals will be met in 2006.

## FY 2005 Publications/Presentations

1. '2010 Emissions with Excellent Fuel Economy' – 2005 Diesel Engine Emissions Reduction (DEER) Conference, Christopher R. Nelson

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1. Cummins Inc. Quarterly Reports as submitted to the Department of Energy.

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

*David Milam*
*Caterpillar Inc.*
*Technical Center–F*
*Engine Research*
*PO 1875*
*Mossville, IL 61552-1875*

*DOE Technology Development Manager: Roland Gravel*

*NETL Project Manager: Carl Maronde*

## Objectives

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

## Approach

- This project focuses on developing multiple paths for meeting 2007 and 2010 emissions standards 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 emissions requirements. Homogeneous charge compression ignition (HCCI) systems and NOx aftertreatment systems are being explored to accomplish the 2010 emissions 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 on 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 emissions requirements. Aftertreatment technology areas being explored are system modeling, PM aftertreatment, membrane technology, and NOx aftertreatment.
- Thermal efficiency improvements are being developed, including novel approaches in the areas of reducing engine friction, improving airflow through the engine, and improving brake-specific fuel consumption (BSFC)/emissions trade-offs through development of advanced fuel systems and combustion system optimization.

## Accomplishments

- A diesel engine system capable of 45% thermal efficiency while meeting 2007 on-highway heavy-duty engine emissions and a diesel engine system capable of 50% thermal efficiency while meeting 2010 on-highway heavy-duty engine emissions levels were validated using simulation. The simulation work was conducted using Caterpillar's in-house cycle simulation code. The model was validated using results of various component tests before conducting this system simulation. The resulting system includes the following high-efficiency components that are currently being developed under the HTCD project:

- Reduced friction piston rings
- High-efficiency series turbochargers
- Ultimate flow cylinder head with improved port flow and increased peak cylinder pressure capability
- Compact high-efficiency cooling system
- A high-pressure injection system
- Variable intake valve actuation

- Optimization of the system gives an overall thermal efficiency just over 50%.
- Completed initial evaluation of advanced engine system concept to enable full-load and full-power HCCI operation on a multi-cylinder test 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 2005. 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 multi-cylinder engine. Fuel efficiency, cost and manufacturability will also be areas of focus. This work will be shifted to the HECC (high-efficiency clean combustion) project.
- Caterpillar will continue to focus on efficient NOx aftertreatment. The team will also focus on fuel efficiency, packaging and cost.
- The primary focus for the final year of the HTCD project will be on development of fuel economy building blocks to enable a demonstration of a 50% overall thermally efficient engine capable of meeting 2010 emissions standards.

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## 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 decrease the amount of fuel used, reduce 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 the 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. This will lead in turn to Caterpillar's New Product Introduction programs.

## Results

As stated above, Caterpillar has made significant progress in developing fuel-efficient solutions that will support the emissions standards. Figure 1 shows the building blocks for a 45% overall thermal efficiency 2007 emissions compliant system. The system incorporates reduced friction from the pistons, rings, and liners (PRL). The system also includes air system improvements, a better breathing head, and combustion optimization. Figure 2 shows the building blocks for a 50% overall thermal efficiency 2010 emissions compliant system. The system includes NOx aftertreatment, a further improved air system, reduced heat rejection components, a turbo-compound system and components capable of higher cylinder pressure.

In order to meet 2010 emissions in a fuel-efficient manner, HCCI is a key area of investigation within the HTCD project. Figure 3 shows the multiple approaches that are used to develop HCCI under this project at Caterpillar Inc. Figure 4 demonstrates how HCCI challenges are being overcome in the HTCD program. Figure 4 shows tremendous progress in using variable valve timing and advanced engine control systems to balance individual engine cylinders' auto-ignition start of combustion. As stated above, the HCCI and associated systems for full-range operation will be further developed under the newly awarded HECC project.

## Conclusions

Through the Heavy Truck Engine cooperative research agreement, Caterpillar has developed technology building blocks and integrated them into a system that will improve fuel economy from baseline production engines while meeting more stringent emissions regulations. Caterpillar has aggressively developed multiple technology paths for efficiently meeting the challenges of 2010 emissions. HCCI development has resulted in world-class power density and significant technical progress against each of the key technical challenges. The progress has clearly positioned this advanced combustion technology as a potentially viable approach to

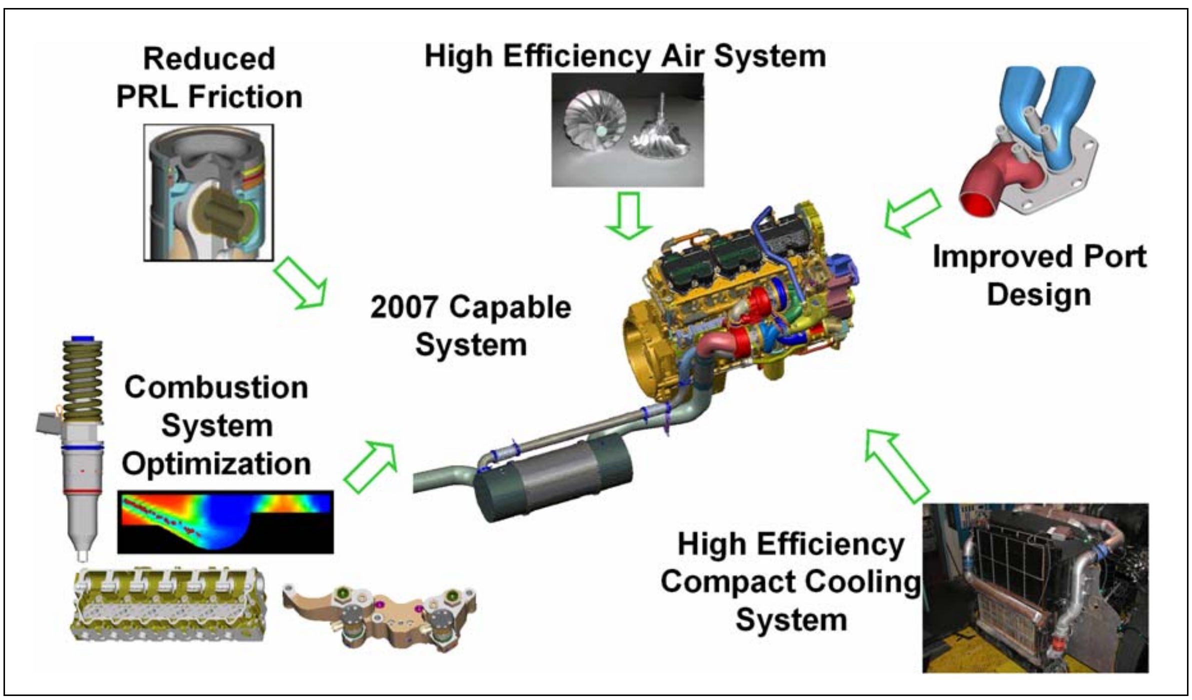


**Figure 1.** 2007 45% Thermal Efficiency

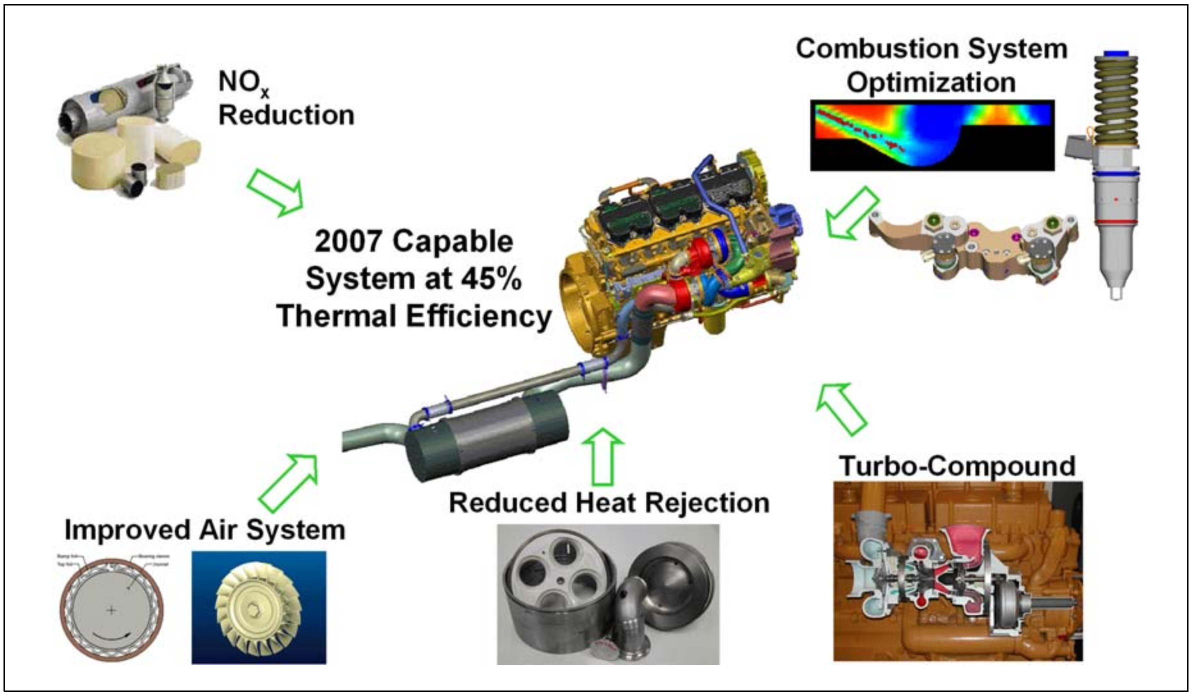


**Figure 2.** 2010 50% Thermal Efficiency

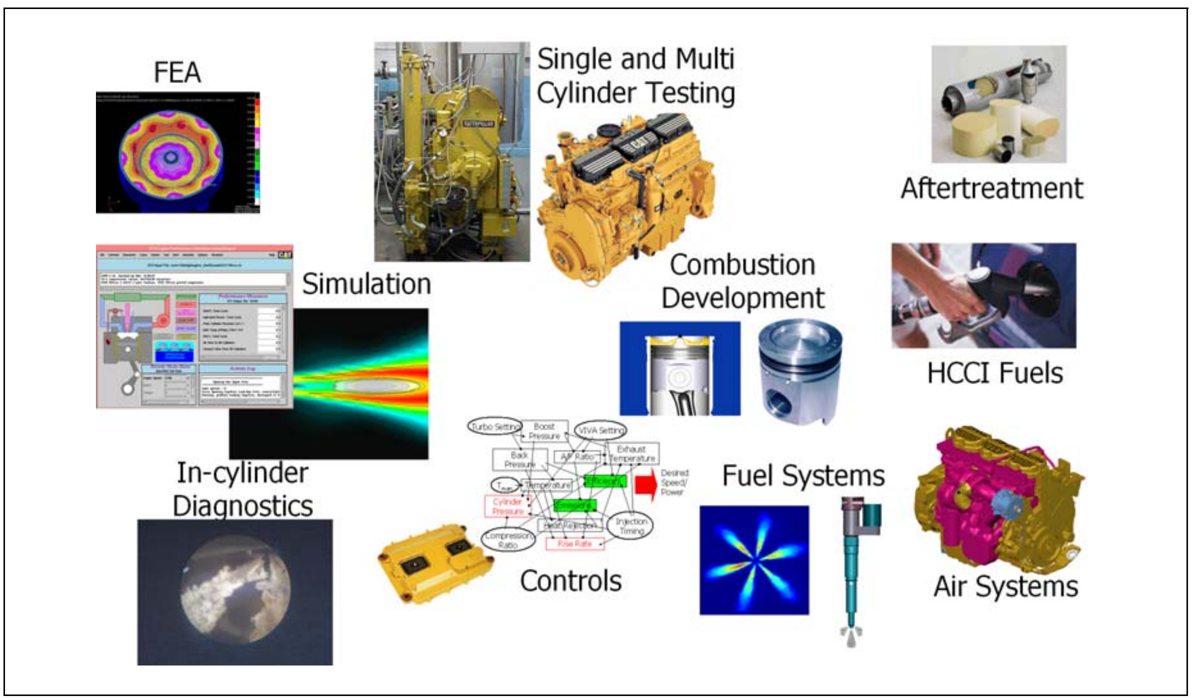


**Figure 3.** HCCI Development at Caterpillar

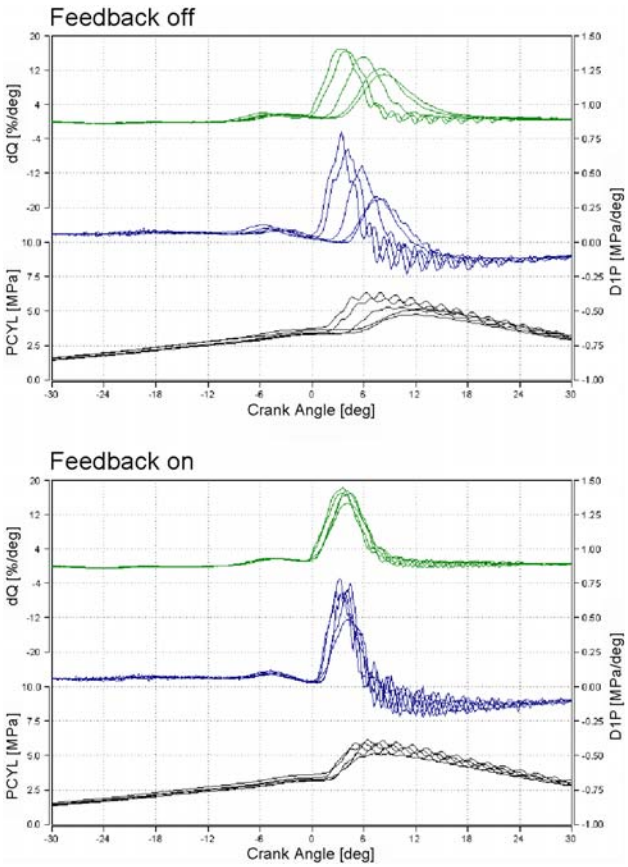


**Figure 4.** Variable Valve Actuation for Cylinder Balancing

meeting the future regulatory and commercial requirements of the marketplace. The development of NOx aftertreatment concepts has shown the potential of this technology to help meet the 2010 challenges. In summary, the technologies developed in this DOE/Caterpillar cooperative research agreement have the potential to significantly reduce the nation's dependence on foreign oil and improve the trade balance while also reducing emissions.

## FY 2005 Presentations

1. Duffy, K., Kieser, A., Liechty, M., Rodman, T., Hardy, B., Hergart, C., Schleyer, C., and Sobotowski, R. "Heavy-Duty HCCI Development," SAE Homogeneous Charge Compression Ignition Symposium, Lund, Sweden, September 2005.
2. Duffy, K., Kieser, A., Liechty, M., Rodman, T., Hardy, B., Hergart, C., Schleyer, C., and Sobotowski, R. "Heavy-Duty HCCI Development," SAE Heavy Duty Diesel Emissions Symposium, Goteberg, Sweden, September 2005.
3. Duffy, K., Kieser, A., Liechty, M., Rodman, T., Schleyer, C., and Sobotowski, R. "Heavy-Duty HCCI Development," 9th International Conference on Present and Future Engines for Automobiles, San Antonio, Texas, May 2005.
4. Duffy, K. "Government/Industry Partnering to Develop Advanced High Efficiency Low Emissions Combustion Solutions," SAE Government-Industry Meeting, Washington, DC, May 2005.
5. Duffy, K., Kieser, A., Liechty, M., Rodman, T., Hardy, B., Hergart, C., Schleyer, C., and Sobotowski, R. "Heavy-Duty HCCI Development Activities," DOE DEER Conference, Chicago, IL, August 2005.
6. Easley, W., Kapic, A., and Milam, D. "The Path to a 50% Thermal Efficient Engine," DOE DEER Conference, Chicago, IL, August 2005.
7. Kesse, M., Jayachandran, A., and Schuh, D. "2010 Emissions from an Electronics Perspective," DOE DEER Conference, Chicago, IL, August 2005.

# III.3 Thermal Efficiency Improvement While Meeting Emissions of 2007, 2010 and Beyond

*Craig Savonen (Primary Contact), Rakesh Aneja*
*Detroit Diesel Corporation*
*13400 Outer Drive, West*
*Detroit, MI 48239-4001*

*DOE Technology Development Manager: Roland Gravel*

*NETL Project Manager: Carl Maronde*

## Objectives

- Implement integrated analytical/experimental development plan for improving subsystem and component capabilities in support of emerging engine technologies for Phase 2 emissions and thermal efficiency goals of the project.
- Test prototype subsystem hardware featuring technology enhancements and demonstrate effective application on a multi-cylinder, production-feasible heavy-duty engine test-bed.
- Optimize subsystem components and engine controls (calibration) to demonstrate thermal efficiency that is in compliance with the DOE 2005 Joule milestone greater than 45% thermal efficiency at 2007 emissions levels.
- Develop technology roadmap for meeting emissions regulations of 2010 and beyond while mitigating the associated degradation in engine fuel consumption. Ultimately, develop technical prime-path for meeting the overall goal of the NZ-50 project, i.e., 50% thermal efficiency at 2010 regulated emissions.

## Approach

- Develop and test prototype engine subsystem hardware that can provide technical requirements for fuel injection, exhaust gas recirculation (EGR), and air mass as identified from integrated analytical/experimental conceptual studies.
- Down-select subsystem hardware and components with the most promising capabilities to meet the required needs for fuel delivery, air/EGR improvements and combustion process optimization.
- Optimize the integrated multi-cylinder engine system performance to meet the thermal efficiency goal while meeting 2007 emissions regulations.
- Develop concepts for application of advanced low-temperature combustion processes to achieve in-cylinder emission reduction beyond the 2007 EPA regulations and evaluate the potential of some of the concepts to achieve 2010 emissions levels using a multi-cylinder, steady-state engine test-bed.

## Accomplishments

- Achieved 45.4% brake thermal efficiency at 2007 emissions levels on a multi-cylinder engine configuration, thus meeting the 2005 DOE Joule milestone.
- Experimentally demonstrated brake thermal efficiency of 44% at 2007 emissions levels on the multi-cylinder engine test-bed. Also achieved additional 1.4%-point in thermal efficiency using analytical evaluation of potential engine system enhancements including reduced pumping loss, improved turbocharger efficiency, and integration of basic exhaust recovery. Aggregation of the experimental and analytical results produced the overall thermal efficiency achievement of 45.4%.

- Demonstrated near-45% thermal efficiency at relevant road-load engine operating points in addition to achieving a peak thermal efficiency of 45.4%. Consequently, there is a potential for over 10% improvement in over-the-road vehicle miles per gallon for a Class-8 heavy-duty truck powered with an engine equipped with the demonstrated technologies.
- Developed advanced combustion and engine subsystem roadmap to meet post-2007 EPA-stipulated emissions levels, including 2010 regulations and beyond. Also assembled and expanded the capability of advanced analytical tools to aid the development and screening of the advanced technologies.
- Identified the challenges and risk factors associated with application and viability of some of the subsystem enhancements and advanced technologies necessary to realize the emissions and thermal efficiency gains.
- Successfully demonstrated application of a multiple-mode combustion concept on a multi-cylinder engine test-bed, reducing emissions below 2007 levels while significantly mitigating the associated deterioration in brake fuel consumption.
- Commenced conceptual definition and development of a model-based controls algorithm for advanced combustion and integrated engine-aftertreatment system control in order to ensure optimal post-2007 total-system performance.

## Future Directions

- Continue to incorporate promising technologies with regard to high efficiency into pre-prototype engine test-beds while rationalizing production viability, driveability, reliability, and other desired attributes of the total engine system.
- Use analytical tools to develop strategies for mitigating subsystem challenges and risk factors such as those associated with un-conventional diesel combustion processes, including fuel-oil dilution; uncontrollable heat release phasing; stability of operation; and noise, vibration and harshness associated with unusual rates of pressure rise.
- Continue evaluation of the potential for advanced fuel injection equipment, including hybrid systems, to enable combustion characteristics that achieve improved thermal efficiency while meeting regulated emissions standards for 2010 and beyond.
- Accelerate technology development regarding sensors and control algorithms required for a fully integrated multi-cylinder engine test-bed.
- Solidify and systematically evaluate the advanced technology roadmap, demonstrating viability of key elements, while achieving post-2007 emissions levels with 50% brake thermal efficiency.

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## Introduction

The focus of the NZ-50 project includes the definition and verification of conceptual engine system technologies and component enhancements to meet DOE's thermal efficiency goals while complying with stipulated emissions standards for 2007, 2010 and beyond. Without ignoring 'real-world' considerations for commercialization, cost, and durability requirements, the various advanced technology concepts are screened using both analytical and bench-testing tools. Based on the results of the screening, the more promising technologies are further evaluated on a multi-cylinder engine test-bed to further define requirements and identify constraints to achieving desired in-cylinder combustion process characteristics, and consequently the emissions and thermal efficiency targets. A few of these evaluations are done using conceptual pre-prototype hardware, such as an advanced fuel injection system that substantially increases flexibility for injection rate shaping. With such an evaluation, the specific requirements for fuel injection, charge air and EGR delivery, combustion phasing and control, engine cooling and thermal management, and other relevant performance enablers are clearly defined and prototype components designed to achieve those requirements. In the entire process, significant attention is paid to potential over-the-road engine operating characteristics and likely boundary conditions. This way, efficient integration of the various concepts will ensure that engine system solutions that arise from the project exhibit the potential for adequate emissions control and fuel economy gains while ultimately being capable of realistic translation into future product development plans.

## Approach

The FY 2005 activities involved integration of advanced subsystem technologies and their validation on a multi-cylinder engine test-bed to realize 2007 regulated emissions while significantly improving brake thermal efficiency. Using analytical and experimental tools, subsystem components encompassing advanced fuel injection system, increased EGR cooling capacity and combustion process optimization are developed and tested. Model-based controls employing multiple input and multiple output techniques enable efficient integration of the various subsystems and ensure optimal performance of each system within the total engine package. Novel application of multiple injection strategies and improved EGR cooling efficiency serve as critical technologies that allow brake thermal efficiency to be significantly improved while meeting the 2007 emissions regulations. Following achievement of the Joule thermal efficiency milestone, selective application of single- and multiple-mode low-temperature combustion processes is used to push the boundary of in-cylinder emissions down to post-2007 EPA regulation levels in pursuit of 2010 emissions regulations and beyond. Optimization of the multiple-mode combustion process is used to improve tradeoff of NOx with specific fuel consumption so that the brake-specific fuel consumption (BSFC) degradation associated with the low emissions is significantly curtailed.

## Results

The NZ-50 engine test platform includes derivatives of the 2004 production Series 60 engines on which advanced subsystem components incorporating new technologies were implemented. The advanced subsystem hardware features

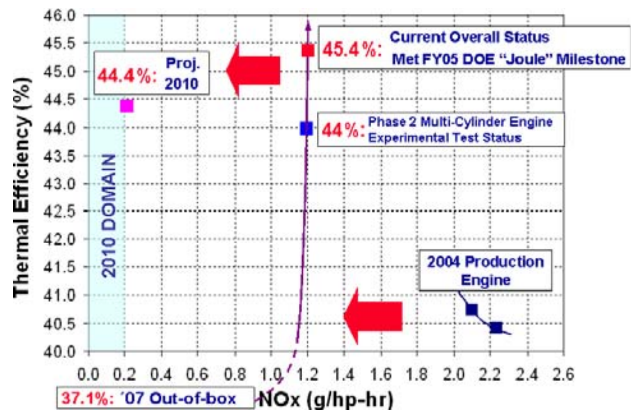


**Figure 1.** Brake Thermal Efficiency and NOx Emission Achievements

innovative concepts that provide fuel injection advancement, premium EGR cooling, improved air delivery system, and optimized advanced combustion processes. The integration of these elements produces an experimentally demonstrated thermal efficiency of 44% at 2007 regulated emissions levels (Figure 1). On top of the experimentally demonstrated results, analytical tools were used to screen and evaluate further subsystem technology improvement options prior to the cutting of refined prototype hardware. The results of these studies produced a further 1.4%-point increase in thermal efficiency due to reduced pumping loss, improved turbocharger efficiency, and integration of the basic exhaust recovery concept. Consequently, the overall achievement of the development effort over FY 2005 is a 45.4% brake thermal efficiency at 2007 regulated emissions, thus meeting the DOE's 2005 Joule milestone.

In developing the technologies for achieving Phase 2 goals of the NZ-50 project, significant attention is paid to the potential over-the-road engine operating characteristics and likely boundary conditions. While a peak thermal efficiency meeting the project goal will be an excellent achievement, more rewards will potentially result from the emerging engine technology if the gains can eventually be translated to future energy savings through realistic translation into future product development plans. Figure 2 shows the thermal efficiency results at today's typical over-the-road engine operating conditions. As can be seen from the figure, a near-45% thermal efficiency was

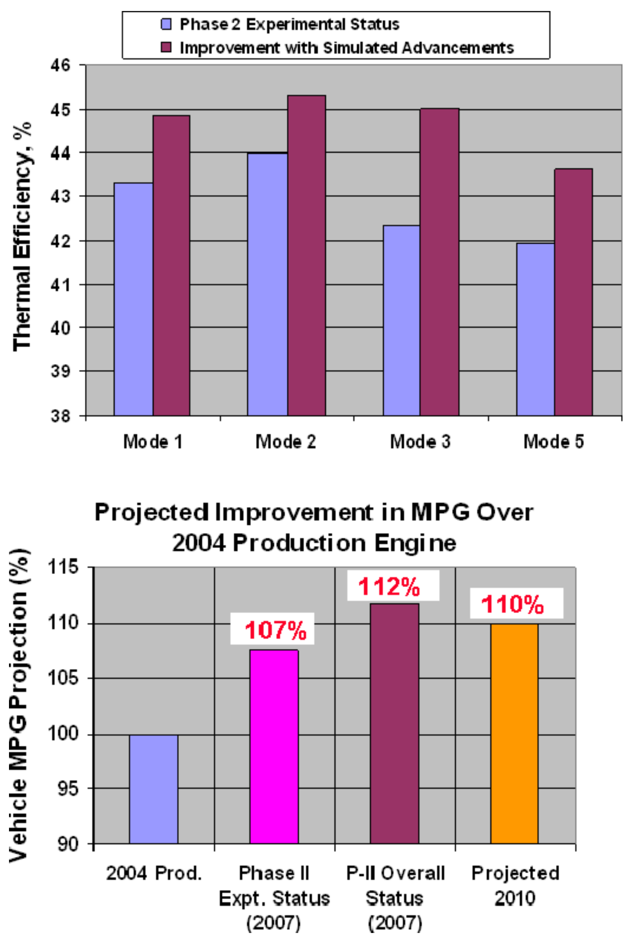


**Figure 2.** Thermal Efficiency Improvements at Typical Over-the-Road Operating Points

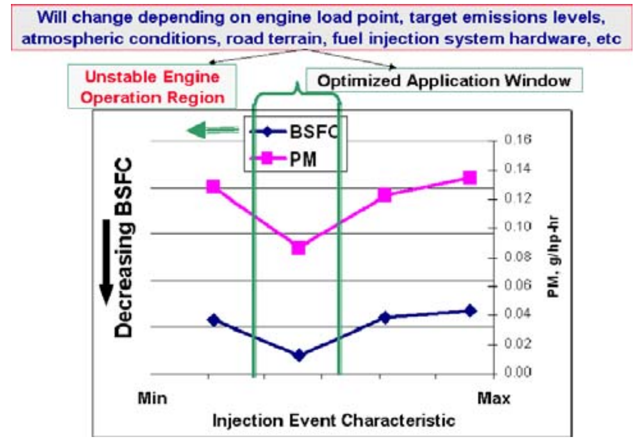


**Figure 3.** Challenges for Successful Application of Novel Multiple Injection Events

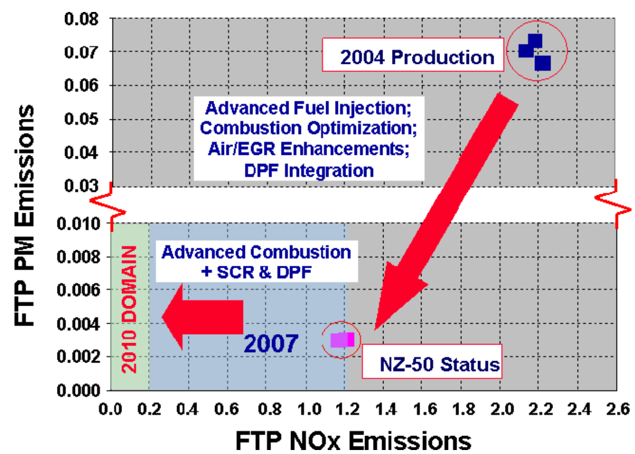


**Figure 4.** Development Path to Achieving Post-2007 EPA Emissions Regulations

demonstrated at each of the points, with the implication that there is a potential for over 10% improvement in vehicle mile per gallon with the emerging engine technologies.

Although novel application of multiple injection strategies leads to desired improvement in thermal efficiency without having a detrimental impact on NOx and PM emissions, there are hardware-related challenges and risks associated with such strategies. Such challenges include stability of the injection events over varying operating cycles, road terrain, atmospheric conditions and fuel injection system hardware. As indicated in Figure 3, the optimum window for application can be narrow and may easily shrink depending on specific hardware and application. A great deal of effort must be expended to identify and bracket such windows of opportunities so that the required subsystem capabilities can be effectively designed and prototyped.

Following the successful achievement of the 45%-plus thermal efficiency at 2007 emissions, the major part of the FY 2005 activities focused on the development towards emissions regulations of 2010 and beyond (Figure 4). Application of advanced combustion concepts including homogeneous charge compression ignition (HCCI) and other low-temperature concepts is used to reduce in-cylinder emissions beyond the 2007 EPA levels. Furthermore, combustion optimization employing multiple modes is used to improve NOx-BSFC tradeoff at low NOx such that degradation of BSFC

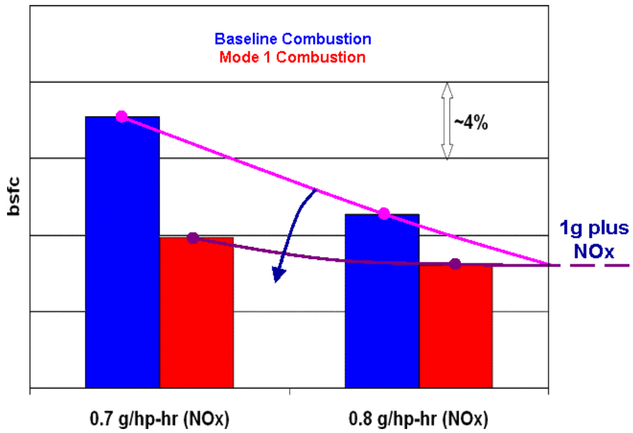


**Figure 5.** Improving Thermal Efficiency at 2010 Emissions and Beyond

associated with low NOx levels is significantly reduced. Figure 5 shows the achievement in this effort where an advanced combustion process allows significant reduction in BSFC penalty at low NOx emissions.

## Conclusions

Advanced development and integration of engine subsystems have led to the achievement of 45.4% brake thermal efficiency while meeting the 2007 EPA regulated emissions. It has also been shown that near-45% thermal efficiency can be achieved at relevant over-the-road engine operating conditions, suggesting a potential improvement of greater than 10% in vehicle miles per gallon for a Class-8 truck powered with a heavy-duty engine effectively employing the emerging technologies. Advanced combustion processes, including application of multiple modes of combustion, have shown promise for reducing in-cylinder emissions beyond the 2007 EPA regulations and also for mitigating the customary deterioration in engine BSFC. For effective integration and optimum performance of the advanced subsystem components, model-based controls have been systematically proven as an effective tool. Emerging concepts of more pervasive model-based controls with increasing robustness and on-board optimizing functions are expected to enhance seamless transition between operating modes as well as ensure optimum performance of the total (engine plus aftertreatment) system.

## FY 2005 Publication/Presentation

1. Aneja, R., Oladipo, B., Savonen, C., and Zhu, G., "Thermal Efficiency Improvement While Meeting Emissions of 2007, 2010 and Beyond," 11th Annual Diesel Emission Reduction (DEER) Conference, Chicago, IL (August 21-25, 2005).