
III. HEAVY TRUCK ENGINE

III.1 Heavy-Duty Truck Engine Program

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heavy-duty diesel engines and associated aftertreatment systems while maintaining a high level of fuel efficiency. This work will continue under new programs in pursuit of greater efficiency with further emissions benefits. Most notably:

- Continue the pursuit of combustion optimization towards efficient, low emission performance under the High Efficiency Clean Combustion Program.
- Pursue utilization of waste heat energy to benefit efficiency through the Exhaust Energy Recovery Program.

Objectives

- Program Phase I goal - demonstrate 45% brake thermal efficiency from a heavy-duty diesel engine capable of meeting 2002 U.S. Environmental Protection Agency (EPA) legislated emissions requirements.
- Program Phase IIA goal - demonstrate 45% brake thermal efficiency from a heavy-duty diesel engine capable of meeting 2007 U.S. EPA legislated emissions requirements.
- Program Phase IIB goal - demonstrate 50% brake thermal efficiency from a heavy-duty diesel engine capable of meeting 2010 U.S. EPA legislated emissions requirements.

Accomplishments

- Phase I goal successfully completed. Demonstrated 45% brake thermal efficiency from a heavy-duty diesel engine (Cummins' ISX) while meeting 2002 U.S. EPA legislated emissions requirements in Q2 of 2002.
- Phase IIA goal successfully completed. Demonstrated 45% brake thermal efficiency from a heavy-duty diesel engine (Cummins' ISX) while meeting 2007 U.S. EPA legislated emissions requirements in Q2 of 2004.
- Phase IIB goal successfully completed. Demonstrated 50% brake thermal efficiency from a heavy-duty diesel engine (Cummins' ISX) while meeting 2010 U.S. EPA legislated emissions requirements in Q2 of 2006.

Future Directions

The Heavy-Duty Truck Engine Program at Cummins Inc. concluded at the end of FY 2006. The program fostered significant technological development of

Introduction

The Heavy-Duty Truck Engine Program at Cummins Inc. was initiated in 2000. The Program's main goal was to drive heavy-duty diesel engine technology toward greater efficiency in the face of significant emissions reduction requirements. At the program's outset, emissions of nitrous oxides (NOx) were federally mandated to be no more than 6 gm per bhp-hr (brake specific NOx or BSNOx) and emission of dry particulate matter was limited to no more than 1 gm per bhp-hr (brake specific dry particulate matter or BSDPM). Typical engine efficiency at the program outset was approximately 44%. The Program's final demonstration goal set an emissions limit of 0.2 gm BSNOx and 0.1 gm BSDPM (2010 U.S. EPA legislated emissions) while achieving 50% efficiency from the engine system. This final program demonstration goal represented a 97% reduction in BSNOx emissions and a 90% reduction in BSDPM emissions while simultaneously demonstrating engine efficiency improvement by 14%.

During the program, the architecture of the Cummins ISX heavy-duty diesel engine was extensively revised. Most notably, high pressure, cooled exhaust gas recirculation (EGR) was introduced as a means to reduce BSNOx emissions. This technology was proven and successfully put into production where it has realized simultaneous benefits in efficiency and emission reduction. Particulate filtration aftertreatment technology was developed and is planned for production to meet 2007 emissions regulations. Fuel injection technology was advanced during the Program with high pressure, common rail fuel systems being successfully applied to achieve program demonstrations. Variable valvetrain (VVT) technology was examined for its benefits to efficient combustion and aftertreatment thermal management. Waste heat recovery methods

were explored and successfully applied to achieve the Program's high efficiency demonstration.

Approach

Cummins' approach to the Program objectives emphasized analysis-led-design in nearly all aspects of the research. An emphasis was placed on modeling and simulation results to lead the way into feasible solutions.

For the deliverable in each phase, a configuration matrix study was conducted to determine appropriate, feasible solutions. Engine system solutions included 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 was selected. A variety of laboratory tests were conducted to verify performance and to tune system functions. Model predictions were verified and models were refined as necessary. Often, different portions of systems were pre-tested independently to quantify their behavior so their data could be analyzed in a model-based simulation before combined test cell testing was conducted. Concurrent to laboratory testing and tuning, a vehicle system demonstration was planned and prepared for. Once satisfactory test cell system performance was verified, vehicle demonstrations were conducted.

Data, experience, and information gained throughout the research exercise was applied wherever possible to commercial products. Cummins honed its technical skill and ability through this Program while providing satisfactory results for customers. Cummins continues to follow this cost-effective, analysis-led 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 2006, Cummins Inc. achieved the final Program goals (Phase IIB) by focusing on combustion development and waste energy recovery. Transient performance was demonstrated in compliance with 2010 emissions. The experimental Rankine cycle waste heat recovery system, designed and specified during 2005 was assembled and operated with the ISX engine to successfully demonstrate the 50% brake thermal efficiency goal.

Major Accomplishments in 2006

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

Cummins Inc. investigated a number of combustion/aftertreatment system combinations to meet the 2010 on-highway 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 program goals. Significant in-cylinder combustion optimization was conducted to minimize the need for aftertreatment cost and complexity. Cummins Inc. demonstrated the ability to reach the required program emissions levels under transient conditions across the engine operating map.

Demonstrated performance of an Organic Rankine Cycle (ORC) Waste Heat Recovery (WHR) system

ORC waste heat recovery system components were received during 2006 and assembled with an ISX engine capable of meeting 2010 emissions performance. The laboratory system for maximizing engine system brake thermal efficiency extracted heat energy from the engine's jacket water, compressed fresh air stream, main exhaust gas stream and EGR. The working fluid in the system was heated to boiling and superheated in this process. The temperature of the working fluid was approximately 460°F as it was passed into an expansion turbine/generator that converted the fluid's thermal energy and momentum into electricity. Generated electric power was measured in addition to the engine's brake power. Engine BSNOx emissions were assumed reduced through the application of urea-based SCR operating at 85% effectiveness. Engine BSDPM emissions were assumed reduced through the application of particulate filtration operating at 90% effectiveness.

The assembled system was designed to achieve peak operating efficiency at a torque peak operating condition for the base engine. This operating point afforded the Rankine cycle with the highest temperature waste heat available. At this condition the following operation was recorded:

Engine Load	378 hp
Engine Speed	1200 rpm
Engine Fuel Consumption	121 lbm/hr
Rankine Cycle Recovered Power	42.5 kWe (57 hp)
Combined Cycle Power	435 hp
Combined Cycle Brake Thermal Efficiency	50%

Conclusions

During FY 2006, Cummins successfully demonstrated systems against the Phase IIB goal. This was the last phase of the Program. We may conclude from this final program demonstration that:

- Compliance to 2010 U.S. EPA legislated emissions under transient cycle operation is feasible with the ISX engine using advanced combustion techniques
- A high level of base engine efficiency is possible and may be driven even higher through the application of a Rankine cycle WHR system

The Heavy-Duty Truck Engine Program at Cummins Inc. fostered the successful development of significantly advanced technology for heavy-duty diesel engines.

A high level of fuel efficiency has been maintained while achieving dramatic reductions in engine emissions. These results will in many cases be carried forward to benefit the end-user and the environment. The work was the result of a great many talented individuals who were supported through the program by the Cooperative Agreement. Cummins Inc. looks forward to a continued successful relationship with the Department of Energy in new, efficiency-focused development programs.

FY 2006 Publications/Presentations

1. 'Achieving High Efficiency at 2010 Emissions' – 2006 Diesel Engine Emissions Reduction (DEER) Conference, Christopher R. Nelson.

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

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- A demonstration engine capable of reaching high efficiency while meeting the 2010 on-highway truck emission regulations was built and tested. To date, the engine has been built with all the high efficiency components listed above except for the reduced heat rejection components and without one of the three high efficiency air system components. The test results for the engine showed the engine reached a peak efficiency of 47.5%. At the 2010 emissions levels, the efficiency achieved was 47%. This represents an improvement of 10-12% over the baseline engine.

Objectives

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

Accomplishments

- A diesel engine system capable of 50% thermal efficiency while meeting 2010 on-highway truck emissions levels was identified using simulation. The simulation work was conducted using Caterpillar's in-house cycle simulation code. The resulting system includes the following high efficiency components that are currently being developed under the HTCD project:
 - High efficiency aftertreatment
 - Reduced friction piston rings
 - Reduced flow restrictions
 - Reduced heat rejection components
 - High efficiency air systems
 - Turbo-compound system
 - Compact high efficiency cooling system
 - Optimized combustion system
 - A high pressure injection system
 - Variable intake valve actuation
 - Increased cylinder pressure limits
 - Increased compression ratio

Future Directions

This cooperative research project will conclude at the end of 2006. 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 FY 2006. The focus going forward will be on transfer of the technology developed in the project to production. Technology development continues in the following key areas:

- Caterpillar will continue to focus on developing supporting engine systems to facilitate full-load homogeneous charge compression ignition (HCCI) on a multiple-cylinder engines. Fuel efficiency, cost and manufacturability will also be areas of focus. As noted above, this work has been shifted to the high efficiency clean combustion (HECC) cooperative research project
- Caterpillar will continue to focus on efficient NO_x aftertreatment. The team will also focus on fuel efficiency, packaging and cost. Additional DOE funding would be valuable in developing highly efficient aftertreatment which allows the engine to be optimally calibrated.
- Caterpillar will continue to focus on the waste heat recovery. This work will continue on the EWHR (exhaust waste heat recovery) cooperative research project. The focus will continue to be on improving the thermal efficiency by 10% through improved waste heat recovery.
- Caterpillar will continue to focus on thermal efficiency improvements. This work will be shifted to the HECC cooperative research project. The focus will be on identification of a path to reach 55% overall thermal efficiency.

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 fuel used and the associated foreign oil dependency, reduce owning and operating costs, and still allow compliance with the more stringent emissions regulation. 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 improving 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. The unique team with over 70 years of experience delivering successful compression ignition engine technology to the marketplace is utilizing best in class design practices, advanced combustion, aftertreatment and engine system modeling techniques, rapid control strategy development tools, single-cylinder engine testing, and multi-cylinder engine testing. 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 projects.

This project focuses on developing multiple paths for meeting 2007 and 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 system for future production engines.

- Multiple emissions paths are being considered for meeting the 2010 emission requirements. HCCI systems and NOx aftertreatment systems are being explored to accomplish the 2010 emission requirements. The HCCI portion of this project

is under continued development in the HECC cooperative research agreement.

- Aftertreatment is being developed and evaluated to meet 2010 emission requirements. Technology areas that are being explored are aftertreatment system modeling, PM aftertreatment, and NOx Aftertreatment. Membrane technology was evaluated earlier in this project.
- Thermal efficiency improvements are being developed including novel approaches in the areas of reduced engine friction, improving airflow through the engine, improving brake specific fuel consumption/emissions trade-offs through developing advanced fuel systems and combustion system optimization.

Results

As stated above, Caterpillar has made significant progress in developing fuel-efficient solutions that will support the emissions standards. Figure 1 shows a schematic for the 50% overall thermal efficiency system capable of 2010 on-highway emissions levels. The system incorporates high efficiency aftertreatment to allow optimal calibration of the engine. The system also includes reduced friction from the pistons, rings, and liners. The system also reduces pumping losses through the use of a better breathing head and improved manifolds. The system also includes air system improvements to the series turbochargers and a turbocompound unit. There is an intercooler added between the compression stages. Finally, an optimization of the combustion system was performed including compression ratio, peak cylinder pressure, and valve timings. Figure 2 shows the contributions of the building blocks to reach 50% overall thermal efficiency.

The system was built and tested in 2006. The system was designed to be packaged in a Class 8 truck as seen in Figure 3. The results to date show the ability to

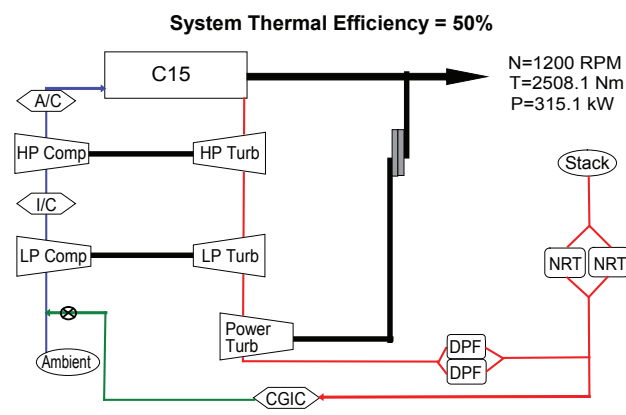


FIGURE 1. Schematic of 50% Thermal Efficiency Engine System

achieve a peak efficiency of 47.5%. The system achieved 47% overall thermal efficiency at 2010 on-highway emissions levels.

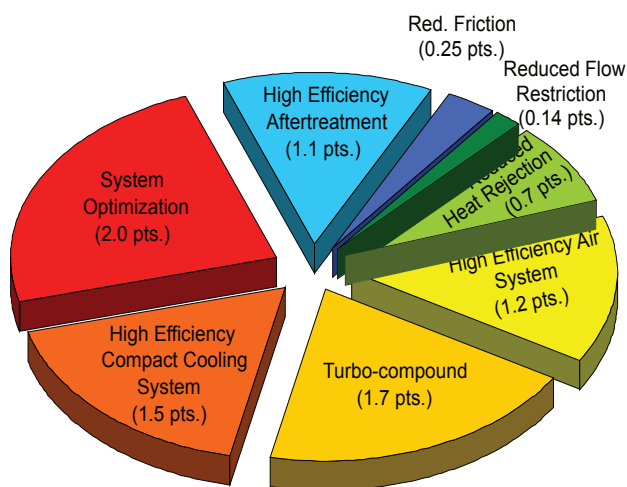


FIGURE 2. Contribution of 50% Thermal Efficiency Building Blocks

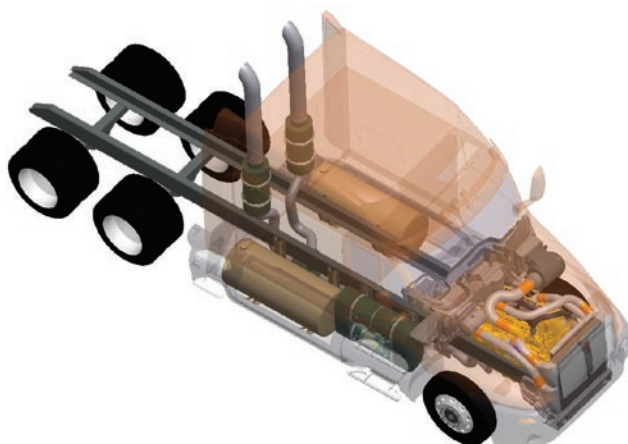


FIGURE 3. Design for 50% Engine Within Existing Class 8 Chassis

Conclusions

Through this project, 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 on-highway engine emission levels. The HCCI development reported in previous annual reports 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 meeting the future regulatory and commercial requirements of the marketplace. The development on NO_x aftertreatment concepts has shown the potential of this technology to help meet the 2010 challenges. The fuel economy building blocks demonstrated as part of this project have resulted in world class efficiency levels at the 2010 on-highway emissions levels. 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.

FY 2006 Presentations

1. Milam, D., Donaldson, G., Easley, W., Bond, M., Roozenboom S., Brucker, J., Hittle, C., and Coon, N., "Demonstration of a 50% Thermal Efficient Diesel Engine - Including HTCD Program Overview," DOE DEER Conference, Detroit, MI, Aug. 2006.

III.3 Heavy-Duty Engine Technology for High Thermal Efficiency at EPA 2010 Emissions Regulations

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Objectives

- Develop, implement and validate an integrated experimental and analytical roadmap in support of the Phase 2B thermal efficiency and emissions goals of the collaborative Department of Energy (DOE)-Detroit Diesel NZ-50 (Near-Zero Emissions at 50% Thermal Efficiency) heavy-truck project.
- Demonstrate advanced engine component, sub-system and system technologies, feasible for subsequent product development and eventual commercialization, which are capable of achieving a brake thermal efficiency of 50% at Environmental Protection Agency (EPA) 2010 emissions regulations.
- Demonstrate the effectiveness of NZ-50 technologies to meet the stretch project goal of 7%-10% over-the-road fuel economy improvement, over and above the already aggressive project objective of 50% thermal efficiency at a single operating condition.
- Demonstrate the effectiveness of NZ-50 technologies to meet the stretch project goal of EPA 2010 emissions over transients (e.g. the Federal Test Procedure cycle, FTP), over and above the project objective of EPA 2010 emissions at a single operating condition.
- Experimentally demonstrated a brake thermal efficiency of 48.4% at EPA 2010 emissions regulations level at a single operating condition in a multi-cylinder engine test-bed environment. An additional 1.8%-point thermal efficiency improvement was demonstrated via analytical evaluation of potential engine system enhancements including reduced pumping losses, adaptive breathing cycles and reduced parasitic losses.
- Experimentally demonstrated greater than 45% thermal efficiency at several over-the-road representative operating conditions, thus demonstrating the potential to achieve 8.2% improvement in over-the-road vehicle fuel economy for a Class 8 heavy-duty tractor equipped with NZ-50 Phase 2B engine technologies (stretch project goal).
- Developed and experimentally demonstrated a multiple-mode, low emissions combustion concept to reduce engine-out emissions below EPA 2007 regulated levels over both steady-state and transient operation, while substantially mitigating the deterioration in brake fuel consumption typically associated with such advanced combustion processes.
- Experimentally demonstrated EPA 2010 emissions over steady-state and transient operation (FTP and over-the-road), enabled by the multiple-mode, low emissions combustion concept (stretch project goal).
- Developed and enhanced forward engineering methodologies for engine system technology development, enabled by advanced analytical tools. Utilized this technology development approach to develop and validate the NZ-50 technical roadmap.
- Developed model-based control algorithms for advanced combustion and integrated engine-aftertreatment system control to enable optimal 2010 and post-2010 system performance over transient over-the-road operation.
- Identified and partially mitigated the challenges and risk factors associated with application and viability of some of the NZ-50 sub-system enhancements and advanced technologies necessary to realize the emissions and thermal efficiency gains.

Accomplishments

- Demonstrated integrated experimental and analytical technologies capable of achieving 50.2% thermal efficiency at EPA 2010 emissions regulation at a single operating condition in a multi-cylinder engine configuration, thus meeting a key FY 2006 and overall NZ-50 project objective.

Future Directions

- Successfully wrap up the remaining technical activities of the current budget period, including the consolidation and refinement of the demonstrated

thermal efficiency milestone and the development of the integrated controls system. A technical report to document the salient aspects of the project through Phase 2B is also being prepared.

- Identify elements of a conceptual roadmap to achieve further improvement in thermal efficiency, with emphasis on over-the-road fuel economy.
- Utilizing the results of this system-based NZ-50 project, identify the foundation for the next generation of sub-system technology concepts (e.g. combustion and exhaust energy recovery) for further improvement in thermal efficiency.

Introduction

During the second half of last century, the brake thermal efficiency of heavy-duty diesel engines increased substantially, enabled by improvements in sub-system technologies and the introduction of electronic controls. Since the beginning of this decade, the regulations that mandate allowable nitric oxides and particulate matter emissions from diesel engines have also become increasingly stringent. Without external influences, such as collaborative government-industry programs, the increasingly stringent emissions regulations would have resulted in significant deterioration in thermal efficiency (Figure 1). This can be attributed to the increase in complexity of diesel engine and aftertreatment technology and yet extremely short technology introduction lifecycles of about three years. Collaborative government and industry programs have played a significant role in mitigating this anticipated thermal efficiency deterioration and are having a net favorable impact on commercial technology by allowing the development of higher risk but potentially higher reward technologies. Such programs are conducted at an advanced engineering level and substantial

time and effort is still required through subsequent, industry-led product development cycles for eventual commercialization. Nevertheless, these programs lay a strong technical foundation for such a product development phase to be undertaken.

An example of such a collaborative effort is the DOE-Detroit Diesel NZ-50 project, a multi-year effort initiated in CY 2000 with a key objective of demonstrating 50% thermal efficiency at EPA 2010 emissions regulations at a single operation condition. This primary objective was successfully met during FY 2006. In addition, the thermal efficiency benefit obtained at a single operating condition was extended to several representative over-the-road operating conditions thus demonstrating over 8% increase in fuel economy with NZ-50 technologies. Also, tailpipe-out emissions compliant with EPA 2010 regulations have been demonstrated over steady-state and transient operation (FTP and over-the-road), enabled by a multiple-mode, low emissions combustion concept developed as part of the NZ-50 project.

Approach

The technological complexity of today's state-of-the-art and the future diesel powertrain requires a system-based development approach. This system-based development approach inherently requires an integrated experimental and analytical technology development methodology. During the last few years, Detroit Diesel has developed and validated such an integrated technology development methodology. Analytical tools, ranging from 0-D for controls development, 1-D for system optimization and 3-D for detailed component development, are an integral part of this approach. Such tools are typically utilized to develop and evaluate technical concepts, while deriving their boundary conditions from "real-world" vehicle and system operating conditions thus increasing the possible opportunities for eventual commercial viability. The analytical results are complemented by sub-component and component testing in a bench and/or fixture test-bed environment. Promising concepts are down-selected and then integrated in steady-state test-beds that validate the results of the analysis and "simulate" operation of a transient test-bed. In turn, transient test-beds are utilized to validate the findings of steady-state testing and to simulate vehicle operation, thereby completing one development cycle and laying the foundation for subsequent development iterations.

Detroit Diesel's integrated experimental and analytical system-based development approach was utilized to optimize the combustion processes to meet the project objectives of thermal efficiency and emissions. A multiple-mode, low emissions combustion concept was developed and validated over steady-state and transient conditions. Enabling specifications

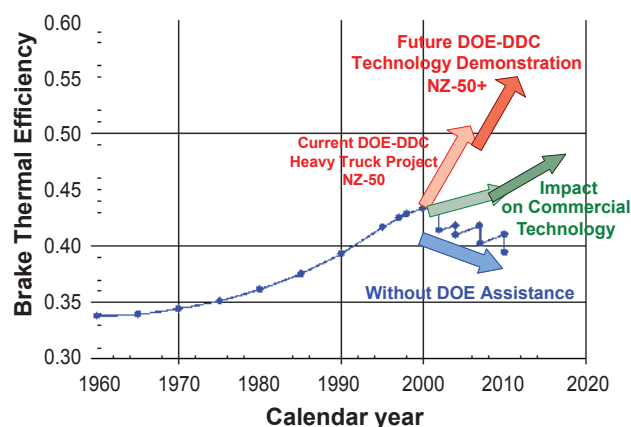


FIGURE 1. Heavy-Duty Thermal Efficiency Trend

of the other engine sub-systems such as the fuel injection sub-system and the air/EGR sub-system were identified via analysis and pre-prototype testing of combustion concepts. Analysis was also utilized to develop and optimize the enabling sub-systems and to define the design of prototype hardware. In some cases, pre-prototype test cell hardware was combined with in-house rapid prototyping controls strategies to provide the desired flexibility in fuel injection system characteristics. The core engine system was integrated with basic NO_x and particulate matter (PM) aftertreatment to enable meeting the EPA 2010 emissions regulations and to achieve the project thermal efficiency objectives. The entire system was then integrated within an overall model-based controls environment that works with multiple input and multiple output signals, while cooperatively managing the often conflicting requirements of individual sub-system via hierarchical functions.

Results

The most significant accomplishment during FY 2006 was the demonstration of technologies to achieve greater than 50% thermal efficiency at a single operating condition. A brake thermal efficiency of 48.4% was demonstrated through aggressive experimental tests and a brake thermal efficiency of 50.2% was achieved by combining hardware experiments with advanced analytical simulations. The integrated experimental and analytical approach incorporates promising pre-developed technologies that could be expected to ultimately mature into production-viable solutions, with the appropriate time and resources allocated to them. Figure 2 shows the technical roadmap of the progress in thermal efficiency and emissions during the various phases of the program.

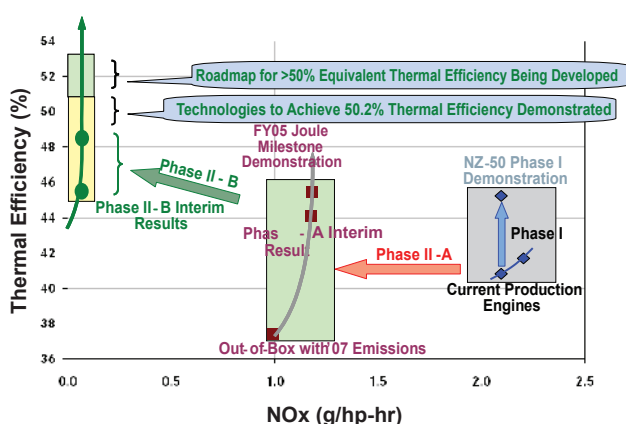


FIGURE 2. NZ-50 Thermal Efficiency Status – Integrated Experimental and Analytical Results

Figure 3 illustrates the primary technical building blocks of the thermal efficiency demonstration effort, including advances in in-cylinder combustion, fuel injection system, exhaust recovery, air system and parasitic load reduction. For part of the technical demonstration effort, the peak cylinder pressure was driven to the vicinity of 250 bar by overstressing the current production engine core (block, head and bearing system) into an operating regime of major mechanical concern and very limited life expectation. Substantial advanced material and design technology insertion will be required to enable the application of the very aggressive demonstration settings in a reliable and cost-effective production setting.

One example of the technical building blocks that were evaluated during the course of the project is adaptive engine breathing technologies. A cycle simulation based analytical model was utilized to optimize intake and exhaust valve events to improve thermal efficiency by reducing pumping losses. Figure 4 shows the improvement in fuel economy over several engine operating conditions. The application of this adaptive breathing technology was also extended to assess its potential for thermal efficiency improvement and for thermal management of aftertreatment devices during transient operating conditions.

A multiple-mode, low emissions combustion concept was developed and successfully validated over several steady-state and transient conditions. Figure 5 shows the cumulative engine-out NO_x and PM emissions over the transient FTP cycle for the baseline combustion process representative of prototype EPA '07 combustion versus the low emissions combustion process. The low emissions combustion process demonstrates the potential to reduce NO_x by 20% without any PM trade-off. For this case, the fuel

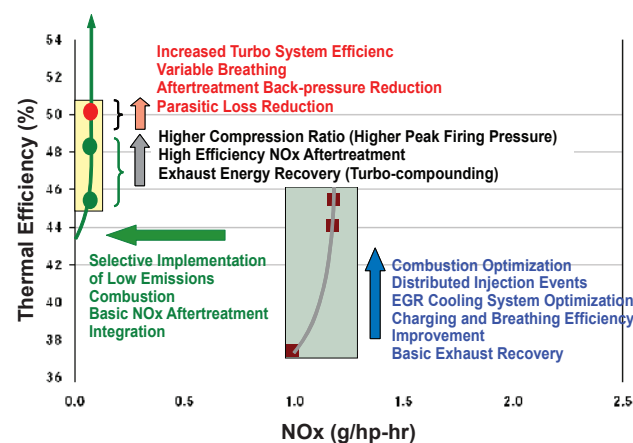


FIGURE 3. NZ-50 Thermal Efficiency Roadmap – Key Technical Building Blocks

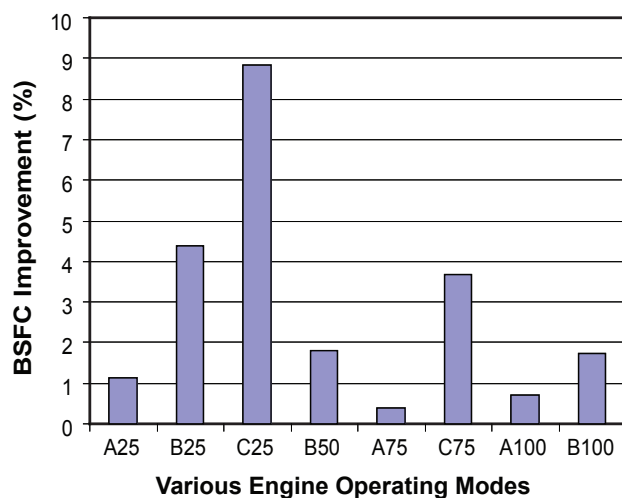


FIGURE 4. Potential of Adaptive Breathing Optimization for Thermal Efficiency Improvement

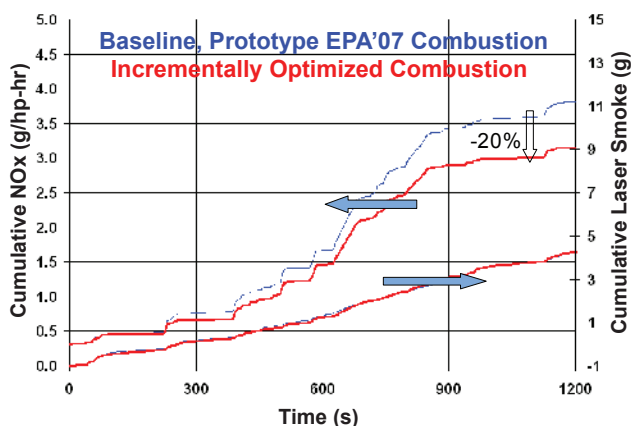


FIGURE 5. Selective Implementation of Low Emissions Combustion over Transient Hot FTP Cycle – Experimental Multi-cylinder Results

economy penalty that is typically associated with low emissions combustion processes was substantially mitigated. In another similar development effort, an advanced combustion process was developed to reduce the engine-out PM over a transient cycle by about 20% without increasing NOx.

These low emissions combustion concepts to incrementally reduce the engine-out NOx and PM emissions provided the foundation for the demonstration of EPA 2010 tailpipe-out emissions standards over the transient emissions cycle, thus fulfilling another stretch target of the project. Figure 6 shows the roadmap for the achievement of transient EPA 2010 tailpipe-out emissions through selective implementation of low emissions combustion to reduce engine-out NOx, integration of model-based controls and overall system optimization. Once again, model-based controls played

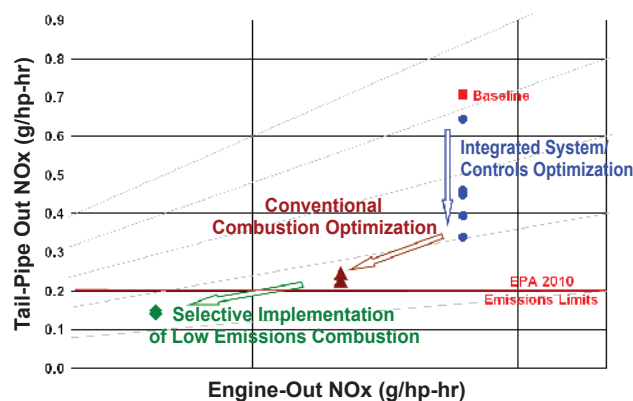


FIGURE 6. Transient Emissions Reduction Roadmap – Experimental Multi-cylinder Results

a critical role for effective integration and optimum performance of the advanced sub-systems. 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 ensuring optimum performance of the total engine and aftertreatment system.

Conclusions

- Demonstrated integrated experimental and analytical technologies capable of achieving 50.2% thermal efficiency at EPA 2010 emissions regulation at a single operating condition in a multi-cylinder engine configuration, thus meeting a key FY 2006 and overall NZ-50 project objective.
- Experimentally demonstrated a brake thermal efficiency of 48.4% at EPA 2010 emissions regulations level at a single operating condition in a multi-cylinder engine test-bed environment. An additional 1.8% thermal efficiency improvement was demonstrated via analytical evaluation of potential engine system enhancements including reduced pumping losses, adaptive breathing cycles and reduced parasitic losses.
- Experimentally demonstrated greater than 45% thermal efficiency at several over-the-road representative operating conditions, thus demonstrating the potential to achieve 8.2% improvement in over-the-road vehicle fuel economy for a Class 8 heavy-duty tractor equipped with NZ-50 Phase 2B engine technologies (stretch project goal).
- Developed and experimentally demonstrated a multiple-mode, low emissions combustion concept to reduce engine-out emissions below EPA 2007 regulated levels over both steady-state and transient operation, while substantially mitigating the

deterioration in brake fuel consumption typically associated with such advanced combustion processes.

- Experimentally demonstrated EPA 2010 emissions over steady-state and transient operation (FTP and over-the-road), enabled by the multiple-mode, low emissions combustion concept (stretch project goal).

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2. Craig Savonen, Guangsheng Zhu, Houshun Zhang, Sandeep Singh, Rakesh Aneja, "Heavy-Duty Engine Technology for High Thermal Efficiency at EPA 2010 Emissions Regulations", 12th Annual Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, MI (August 20–24, 2006).
3. Craig Savonen and Marc Allain, "Integration of Control System Components for Optimum Engine Response", 12th Annual Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, MI (August 20–24, 2006).

