Off-Highway Heavy Vehicle Diesel Efficiency Improvement and Emissions Reduction – Final Report
DoE Program: DE-FC26-02AL67973

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Objectives:

- Design combustion systems that meet Tier 3 emission requirements with comparable fuel economy to Tier 2 engines.
- Verify the emission and fuel economy targets of the Tier 3 engines through single and multi-cylinder testing.
- Improve combustion system design tools to enable optimization of the combustion process for both emissions and fuel economy.
- Improve calibration development tools.
- Evaluate technology options for meeting the Tier 4 Interim emissions requirements.
- Identify technical solutions best able to meet customer and Tier 4 emissions requirements while maintaining or improving system fuel economy.

Approach

- Develop analytical modeling capability to facilitate the design and optimization of in-cylinder combustion recipes to meet the Tier 3 emissions levels while maintaining fuel economy.
- Utilize modeling tools to design combustion recipes on multiple engine platforms that meet the Tier 3 emissions targets while minimizing the impact on fuel consumption.
- Demonstrate the combustion recipes on single or multi-cylinder engine tests and optimize the emissions and performance of the engines.
- Develop and incorporate a global model for calibration development
- Define the technical and performance requirements of the Tier 4 engine systems
- Assess current and future technologies capable of meeting the Tier 4 requirements.

- Use analysis tools including combustion CFD and cycle simulation to evaluate the performance of emissions technologies proposed to meet Tier 4.

Accomplishments

- Improved and validated combustion CFD submodels have been developed.
- Calibration improvement model developed for steady-state and transient calibrations
- Combustion system design for Tier 3 completed on six engine platforms which resulted in an in-cylinder solution that optimizes fuel economy while minimizing the impact on the customers' application and cost.
- Experimental engine validation and optimization completed for Tier 3 combustion system design.
- Customer requirements understood and translated to critical technical requirements for Cummins' Tier 4 engine systems
- Identification of a number of emissions architectures for meeting the Tier 4 Interim emissions requirements
- Potential Tier 4 architectures have been evaluated against the critical technical requirements
- Combustion CFD and cycle simulation analysis to recommend combustion and air handling hardware for experimental validation.

Introduction

Cummins Inc. is a world leader in the development and production of diesel engines for on-highway vehicles, off-highway industrial machines, and power generation units. Cummins Inc. diesel products cover a 50- 3000 HP range. The power range for this project includes 174-750 HP to achieve EPA's Tier 3 emission levels of 4.0 NOx+NMHC gm/kW-hr and 0.2 PM gm/kW-hr and Tier 4 Interim emission levels of 2.0 gm/kW-hr NOx and 0.02 gm/kW-hr PM. Cummins' anticipated product offerings for Tier 4 in this range include the following: QSB6.7, QSC8.3, QSL9, QSM11, QSX15, QSK19. (For reference, numerical values indicate engine displacement in liters, the letter designations indicate the product model). A summary of the EPA's mobile off-highway emissions requirements is given in Figure 1.

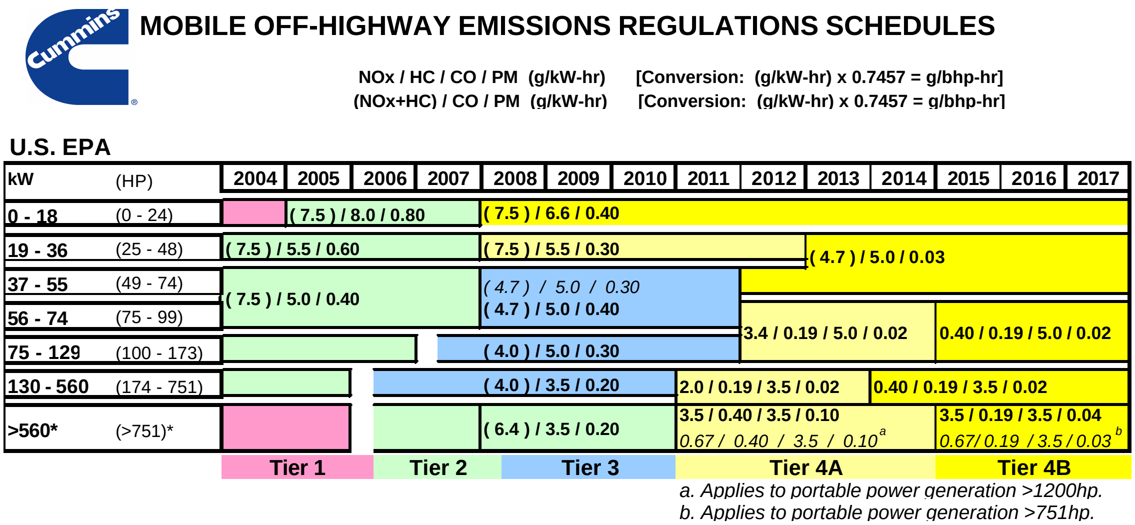

Figure 1- U.S. EPA Mobile Off-highway Emissions Regulations

Work started in fiscal year 2003 focused on the Tier 3 emissions requirements and began to shift to Tier 4 emissions requirements late in fiscal year 2004. The project focused on technology development to meet these increasing more stringent emissions requirements while optimizing the engine fuel economy and minimizing the impact on the application and the customer.

Approach

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

Cummins has developed a combustion computational fluid dynamics (CFD) capability based on the KIVA tool. This code has been improved by incorporating several new submodels as part of this project. The code has also been integrated with cycle simulation, fuel system simulation, and optimization routines to create a design tool as shown in Fig. 2. A rigorous design and validation process was followed using the diagram shown in Fig. 3.

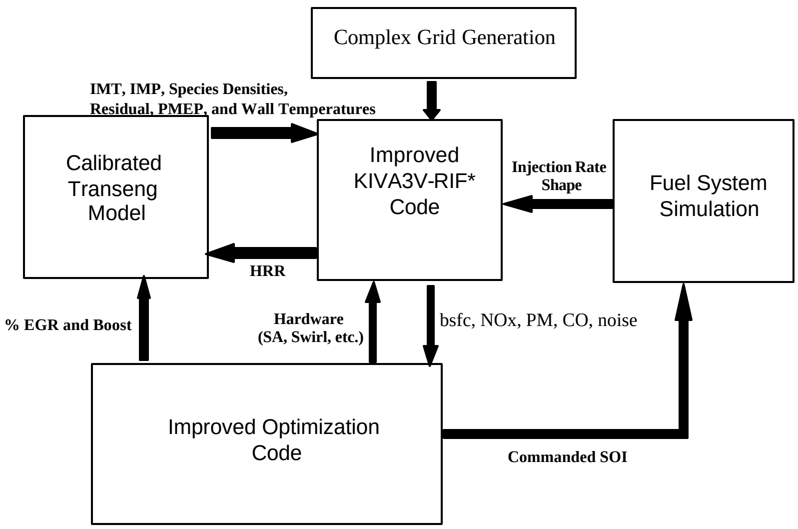

Figure 2 - Combustion CFD Design Tool

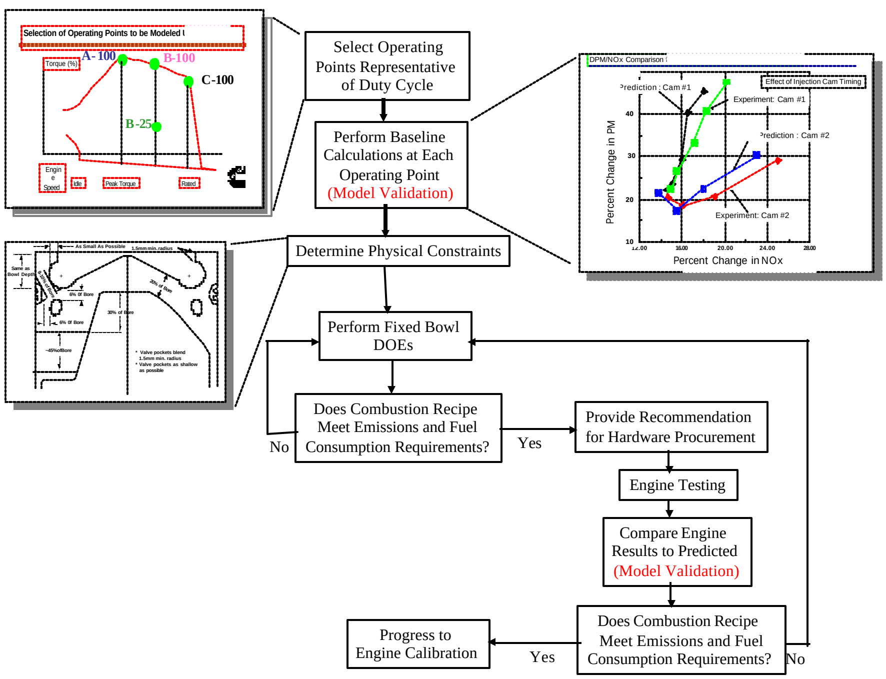

Figure 3 - Combustion Design Process

This analysis-led approach enabled a much larger design space to be covered within the mechanical and customer constraints for these engines as well as the project time and cost constraints. The resultant designs will provide more energy efficient engines than could have been developed using past experimental techniques.

Once the fundamental building block of the combustion design is defined, the flexibility of the electronic controls must be managed. To that end a new method of developing engine calibrations was initiated. This method moves away from traditional methods of optimizing engine parameters at a speed and load to a global approach that incorporates a space-filling design of experiments. This methodology is expected to reduce the time required to develop a calibration by over 50%.

Results

As a part of this project, a number of improvements to the KIVA code were incorporated and validated:

- NOx Transport Model
- Combustion Model
- Spray Model
- Combustion Noise
- Complex Grids

For Tier 3, the combustion design was completed and validated on each of the engine platforms in the 174 – 750 HP power category. A strategy was developed that allowed Cummins' engines to meet the Tier 3 emissions requirements with an in-cylinder solution that did not require cooled EGR or aftertreatment. Figure 4 contains a NOx-PM plot of one of the engine platforms. This plot shows the effect of swirl on engine performance for the combustion geometry chosen. It shows that proper selection of swirl was a key part of finding a combustion configuration that meets Tier 3 emissions while optimizing fuel economy.

Sample Engine Results

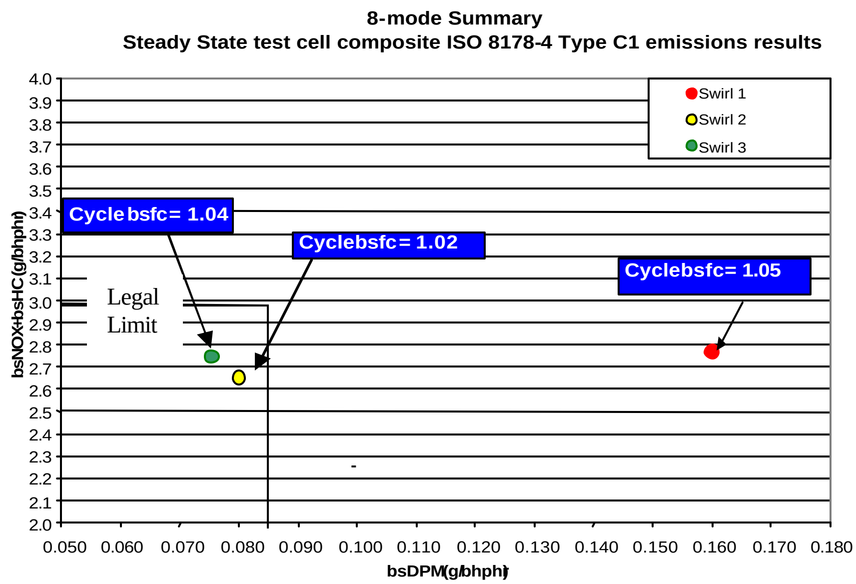

Figure 4 – Impact of Swirl on Tier 3 Engine Performance

A global optimization methodology for steady-state and transient calibration development was defined and several data sets were gathered for validation. MLR (Multivariate Local Regression) is a calibration technique that has been developed which allows the calibration of the engine to be completed with 2 to 3 less test cell development time than the conventional technique and results in a more optimized calibration. This technique improves the ability to prevent emissions overshoots and reduce fuel consumption during transient operation. Figure 5 shows a comparison of MLR's predicted NOx and particulate emissions and actual emissions recorded over a transient cycle. Opacity is shown as an experimental indicator of DPM.

Additional details on the Tier 3 project tasks and results can be found in Appendix A.

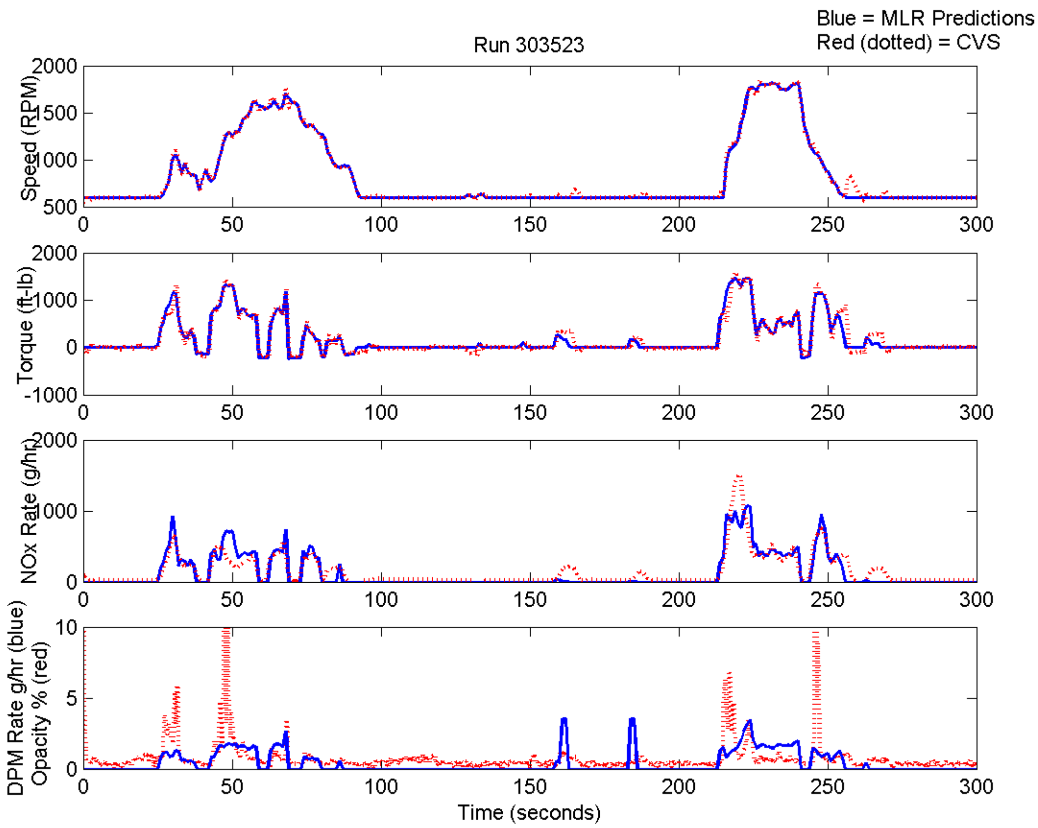

Figure 5 – MLR Predictions and Actual NOx and Particulate Emissions over a Transient Cycle

As the project moved into the Tier 4 technology development, it was critical to ensure that the customer requirements were clearly understood. The emissions reduction required to meet the Tier 4 interim and final emissions standards cannot be met with an in-cylinder solution alone. As a result the OEM and end customer impact and the integration of the Tier 4 engine systems will be critical. A number of customers were interviewed to better understand the technical requirements of our Tier 4 products. These included internal Cummins people, equipment manufacturers, and end users. Several Six Sigma tools were utilized to facilitate the process of conducting interviews and translating the input into meaningful technical requirements. This process is summarized in Figure 6. These technical requirements or critical parameters and target values for each are utilized to evaluate each of the potential emissions technology approaches.

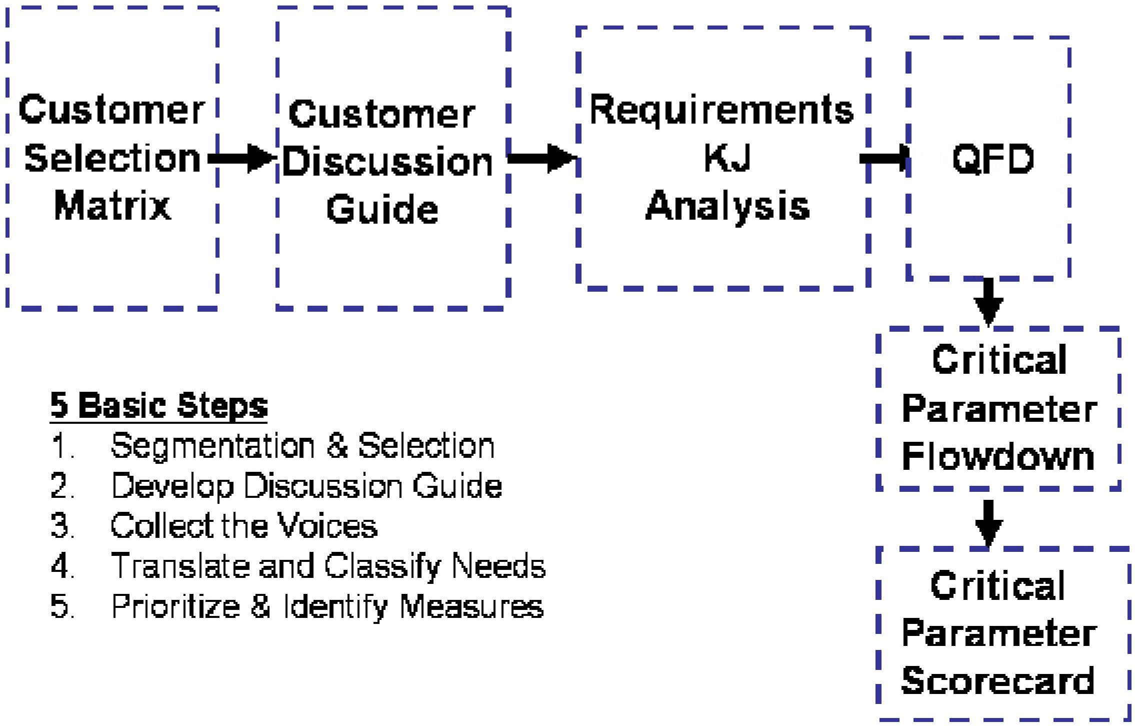

Figure 6 – The Process for gathering customer requirements and translating them to technical requirements

A number of technologies have been identified for meeting the Tier 4 Interim emissions requirements as a part of this project.

NOX Reduction

- Diffusion burn with cooled EGR
- Diffusion burn with oxygen membrane for charge nitrogen enrichment
- Combustion hardware optimization through piston, nozzle, and swirl modifications
- SCR – hydrocarbon or urea based
- NOx Adsorber
- Premixed combustion

Particulate Reduction

- Particulate filter
- Oxidation catalyst
- Partial filter

- Combustion hardware optimization through piston, nozzle, and swirl modifications
- Increased injection pressure
- Premixed combustion

An initial down selection of technologies was based on the ability of each to meet the Tier 4 Interim emissions requirements and the projected initial cost. More detailed analysis was completed on the remaining candidates. Combustion CFD analysis has been completed on the QSB similar to that which was completed as a part of the Tier 3 work to assess in-cylinder emissions capability and define the optimal combustion system for each emissions architecture. A sample result from this DOE for one emissions architecture is shown in Figure 7. Additional combustion recipe analysis and optimization for the remaining engine platforms will occur in the future outside the scope and funding of this project.

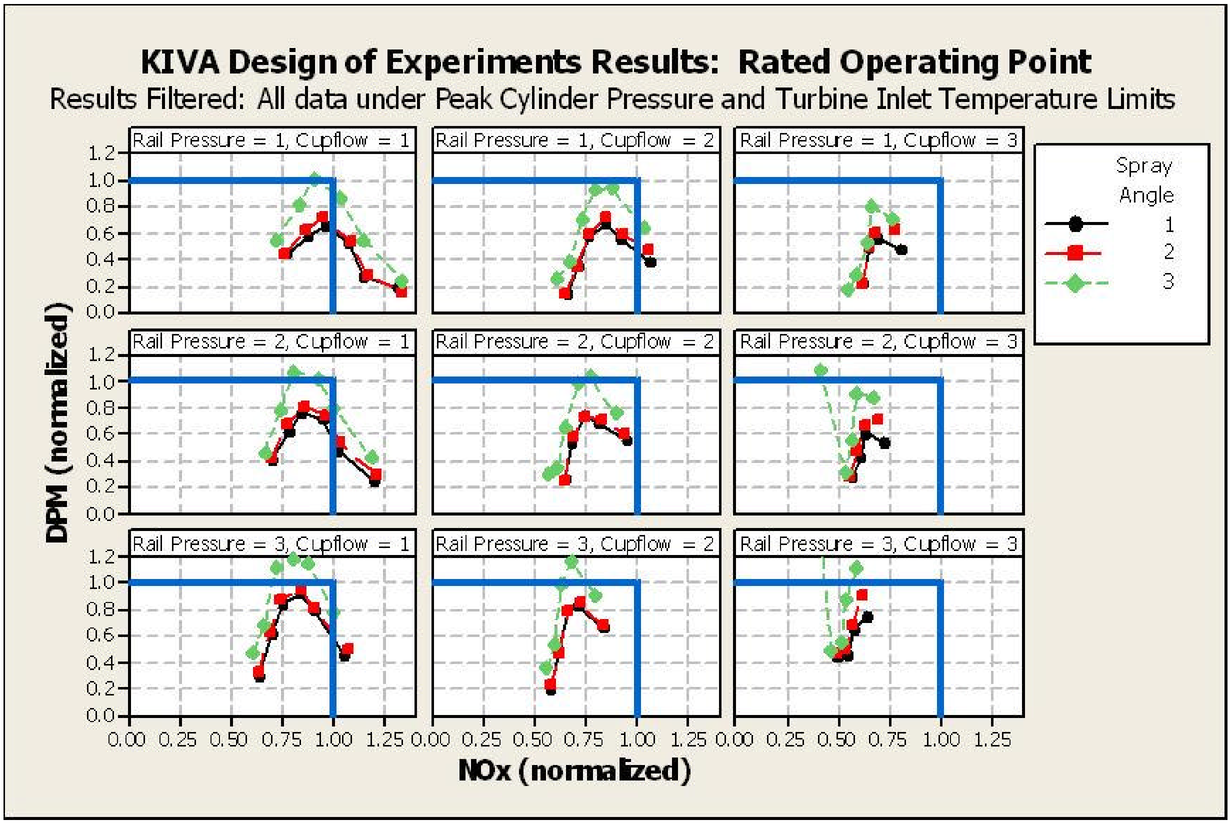

Figure 7 – Sample combustion CFD design of experiments results for Tier 4 emissions capability

In addition to the detailed combustion analysis, cycle simulation analysis was completed on both the QSB and QSX to assess the overall fuel economy, altitude capability, and other performance characteristics. Results indicate that several emissions architectures present the opportunity to maintain or improve fuel economy over Tier 3. Life-cycle cost modeling for several key industrial applications was completed to compare the impact of each of the emissions architectures on annual operating cost. All of this information will be utilized in selecting the best emissions technology for meeting the Tier 4 Interim emissions requirements.

Limited experimental validation of the combustion CFD and cycle simulation analysis has been completed as a part of this project. The remaining validation and optimization of the prime path emissions technology selected for Tier 4 Interim will occur beyond the scope and funding of this project.

Additional details on the Tier 4 project tasks and results can be found in Appendix B.

Conclusions

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

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

Publications/Presentations

Presentation at DOE to Kick Off Project-December 18, 2002
Q1 2003 Progress Report
Q2 2003 Progress Report
Q3 2003 Progress Report
Q4 2003 Progress Report
Q1 2004 Progress Report
Q2 2004 Progress Report
Q3 2004 Progress Report
Q4 2004 Progress Report
Q1 2005 Progress Report
May 2005 DOE Technical Update in Columbus, IN
Q2 2005 Progress Report
Q3 2005 Progress Report
2005 DEER Conference Poster Presentation

Special Recognition & Awards/Patents Issued

None

Acronyms

CFD - Computation Fluid Dynamics
EGR – Exhaust Gas Recirculation

KJ	- Initials of Jiro Kawakita, the Japanese anthropologist who invented the technique
MLR	- Multivariable Local Regression
NOx	- Oxides of Nitrogen
PM	- Particulate Matter
QFD	- Quality Functional Deployment – a tool to map customer requirements to technical requirements
QSB5.9	- Quantum System B Series 5.9Liter (Midrange Industrial Product)
QSC8.3/QSL9	- Quantum System C Series 8.3 Liter, Quantum System L Series 9 Liter
QSK19	- Quantum System K Series 19 Liter
QSX15	- Quantum System X Series 15 Liter
SCR	- Selective Catalytic Reduction