# Final Report

**December 13, 2010**

**Prepared for:**

**U. S. Department of Energy**

**Submitted by:**

**Cummins, Inc.**
**Columbus, IN**

# *High Efficiency, Clean Combustion*

## DoE Program: DE-FC26-05NT42418

## Program Duration: October 2005 to March 2010

**Prepared by:**

**Donald W. Stanton, Ph.D.**
**Principal Investigator**

# Executive Summary

The Cummins High Efficiency, Clean Combustion (HECC) program was completed in March 2010. All program objectives were met, and the engine efficiency targets were exceeded. The commercial viability of the technology was established. Highlights of the accomplishments are summarized:

## Heavy Duty – 15L ISX Engine

- Can meet the 10% fuel efficiency improvement target using no NOx aftertreatment while compliant with the US EPA 2010 emissions for Class 8 commercial vehicles.
- Achieved greater than 15% fuel efficiency improvement compared to the program target of 10% using the HECC developed technologies with SCR NOx aftertreatment while meeting US EPA 2010 emissions.
- Fuel savings of 590 million gallons of oil per year for Class 8 trucks and fuel savings of 215 million gallons of oil per year for Class 6 & 7 trucks can be achieved based on the efficiency improvements demonstrated once the HECC technology is fully deployed. These estimates are based on Cummins sales data.
- Additional fuel consumption improvements of 2%-3% can be achieved through better integration of the engine with the transmission and vehicle systems (downspeeding the engine, transmission shift pattern, axle ratio, etc.)
- Achieved a 40%-60% reduction in particulate matter emissions with a new combustion system design (piston, fuel injector configuration, intake air swirl level, etc.) along with downsped engine operation. This reduces the amount of fuel consumed to regenerate the diesel particulate filter.
- Completed vehicle drivability assessment with the HECC engine.
- The commercialization assessment of the HECC technologies was completed. Implementation of the technology began with the 2010 engine production and will continue through the next 3-4 years.
- Supplier assessments for all the engine technologies have been completed. All key engine components will be supplied by Cummins Component Business Units.

## Light Duty 6.7L ISB Engine

- US EPA 2010 Tier 2 Bin 8 steady state and transient NOx emissions compliance have been achieved without NOx aftertreatment for the 6.7L ISB engine used in the light duty truck market while exceeding the program target of 10% fuel efficiency improvement. Drive cycle efficiency improvements ranged from 13% to 18%.
- Analysis and design of additional subsystem technology for the 6.7L ISB have been completed to enable an additional 4% improvement in brake thermal efficiency (enabling technologies include variable valve actuation, combustion system optimization, and fuel injection equipment)
- Supplier assessments for all the engine technologies have been completed. All key engine components will be supplied by Cummins Component Business Units.

## Fuels Technology Exploration

- HECC engine technologies developed as part of this program have been shown to be robust for fuel economy and emissions with variations in diesel fuel properties representative of commercially available fuels in the marketplace.
- The development of virtual and real fuel sensing technology is required to maximize the fuel economy benefit associated with the HECC technology when using renewable fuel sources such as biodiesel.
- The fuel economy benefits associated with the HECC engine technologies developed cannot be maintained when using biofuels at constant NOx emissions. However, a reduction of 20% to 40% in particulate matter can be achieved with the use of biofuels.
- Two new fuel virtual sensors have been developed for biofuel content.

## 1. Introduction

Energy use in trucks has been increasing at a faster rate than that of automobiles within the U.S. transportation sector. According to the Energy Information Administration (EIA) Annual Energy Outlook (AEO), a 23% increase in fuel consumption for the U.S. heavy duty truck segment is expected between 2009 to 2020. The heavy duty vehicle oil consumption is projected to grow between 2009 and 2050 while light duty vehicle (LDV) fuel consumption will eventually experience a decrease [1]. By 2050, the oil consumption rate by LDVs is anticipated to decrease below 2009 levels due to CAFE standards and biofuel use. In contrast, the heavy duty oil consumption rate is anticipated to double. The increasing trend in oil consumption for heavy trucks is linked to the vitality, security, and growth of the U.S. economy.

An essential part of a stable and vibrant U.S. economy is a productive U.S. trucking industry. Studies have shown that the U.S. gross domestic product (GDP) is strongly correlated to freight transport [2]. Over 90% of all U.S. freight tonnage is transported by diesel power and over 75% is transported by trucks [2]. Given the vital role that the trucking industry plays in the economy, improving the efficiency of the transportation of goods was a central focus of the Cummins High Efficient Clean Combustion (HECC) program. In a commercial vehicle, the diesel engine remains the largest source of fuel efficiency loss, but remains the greatest opportunity for fuel efficiency improvements. In addition to reducing oil consumption and the dependency on foreign oil, this project will mitigate the impact on the environment by meeting US EPA 2010 emissions regulations.

Innovation is a key element in sustaining a U.S. trucking industry that is competitive in global markets. Unlike passenger vehicles, the trucking industry cannot simply downsize the vehicle and still transport the freight with improved efficiency. The truck manufacturing and supporting industries are faced with numerous challenges to reduce oil consumption and greenhouse gases, meet stringent emissions regulations, provide customer value, and improve safety. The HECC program successfully reduced engine fuel consumption and greenhouse gases while providing greater customer valve.

The US EPA 2010 emissions standard poses a significant challenge for developing clean diesel powertrains that meet the DoE Vehicle Technologies Multi-Year Program Plan (MYPP) for fuel efficiency improvement while remaining affordable. Along with exhaust emissions, an emphasis on heavy duty vehicle fuel efficiency is being driven by increased energy costs as well as the potential regulation of greenhouse gases. An important element of the success of meeting emissions while significantly improving efficiency is leveraging Cummins component technologies such as fuel injection equipment, aftertreatment, turbomahcinery, electronic controls, and combustion systems. Innovation in component technology coupled with system integration is enabling Cummins to move forward with the development of high efficiency clean diesel products with a long term goal of reaching a 55% peak brake thermal efficiency for the engine plus aftertreatment system. The first step in developing high efficiency clean products has been supported by the DoE co-sponsored HECC program. The objectives of the HECC program are:

1. To design and develop advanced diesel engine architectures capable of achieving US EPA 2010 emission regulations while improving the brake thermal efficiency by 10% compared to the baseline (a state of the art 2007 production diesel engine).

2. To design and develop components and subsystems (fuel systems, air handling, controls, etc) to enable construction and development of multi-cylinder engines.

3. To perform an assessment of the commercial viability of the newly developed engine technology.

4. To specify fuel properties conducive to improvements in emissions, reliability, and fuel efficiency for engines using high-efficiency clean combustion (HECC) technologies. To demonstrate the technology is compatible with B20 (biodiesel).

5. To further improve the brake thermal efficiency of the engine as integrated into the vehicle. To demonstrate robustness and commercial viability of the HECC engine technology as integrated into the vehicles.

The Cummins HECC program supported the *Advanced Combustion Engine R&D and Fuels Technology* initiatives of the DoE Vehicle Technologies Multi-Year Program Plan (MYPP). In particular, the HECC project goals enabled the DoE Vehicle Technologies Program (VTP) to meet energy-efficiency improvement targets for advanced combustion engines suitable for passenger and commercial vehicles, as well as addressing technology barriers and R&D needs that are common between passenger and commercial vehicle applications of advanced combustion engines. A peak thermal efficiency goal of 46% (a 10% improvement over diesel engines meeting the US EPA 2007 emissions levels) was demonstrated in 2010 in accordance with the VTP plan. Consequently, the HECC program provided dramatically improved engine combustion efficiency and significantly affected petroleum consumption. Work in this area expanded the fundamental knowledge of engine combustion to new regimes and advanced the knowledge of fuel requirements for these diesel engines to realize their full potential. Fuels Technology activities contributed to the success of energy-efficient advanced combustion regimes as well as identify practical, economic fuels and fuel-blending components that enhanced high efficient clean combustion. The fuel-blending components included biodiesel derived from non-fossil, renewable resources such as biomass, vegetable oils, and waste animal fats.

## 2. Program Layout and Schedule

The HECC program consisted of four budget periods (phases) as listed in Table 1. Budget Period I consisted of applied research were an analysis led approach was used to explore a variety of combustion regimes for diesel engines that demonstrate low emissions and high efficiency. The analysis was verified using single cylinder engine testing. Budget Period II focused on the development of the engine component technologies that were required to achieve the intake manifold conditions, fuel delivery, and exhaust flow conditions for HECC. Budget Period III involved multi-cylinder engine development and demonstration of 10% fuel efficiency improvement while meeting US EPA 2010 emissions compliance. Finally, Budget Period IV identified and implemented additional fuel efficiency improvements associated with integration of the engine and vehicle systems. The demonstration of the vehicle fuel efficiency was done with the aid of the Cummins CyberCell. The Cummins CyberCell is a specialized engine test cell that implements a vehicle dynamic system model to run the engine in real world vehicle drive cycles. The vehicle system model consists of all the powertrain components including the transmission, axles, tires, and control systems. By removing variability associated with vehicle testing, CyberCell can reliably identify changes in fuel economy on drive cycles that would be nearly impossible to resolve in actual vehicle tests. Controlling variability allows evaluation of "noise" factors that affect real world fuel economy. The CyberCell also allows many more vehicle configurations to be evaluated than is possible with real trucks. This approach provided a good balance between program cost and time verses complete installation and engineering associated with full vehicle demonstration.

- Budget Period I – October 2005 thru September 2006
  - Applied Research & Exploratory Development
- Budget Period II – October 2006 – September 2007
  - Component Technology Exploration and Development
- Budget Period III – October 2007 – September 2009
  - Multi-Cylinder Engine System Integration
- Budget Period IV – October 2009 – March 2010
  - Engine and Vehicle Fuel Economy Optimization

**Table 1**: Description and duration of program budget periods.

## 3. Engine Platforms

Two different diesel engines were used to demonstrate the 10% fuel efficiency improvement. First, the heavy duty 15L ISX engine was selected since it is predominately used in Class 8 line-haul applications. The ISX 15L engine powered over 45% of tractors in 2008 and 2009 for the Class 8 line-haul trucks. This engine had to achieve compliance to the US EPA 2010 on-road emissions levels. Certification involved dynamometer testing of engine.

Second, the 6.7L ISB engine was selected since it is used in both personal use vehicles and Class 2b, 3, and 4 commercial vehicles. The 6.7L ISB engine can be purchased in the Dodge Ram 2500, 3500, and 4500 size pickup trucks. This engine is certified at two emissions levels (on-road commercial vehicle and Tier 2 Bin 8 in chassis – both 2010 emissions compliant).

## 4. Collaborations

Cummins collaborated with a combination of industry partners, Purdue University, and Oak Ridge National Laboratory to successfully accomplish the program objectives. Table 2 provides the various partners and the areas of focus for each partner.

- Oak Ridge National Laboratory
  - Fuels research
  - Engine performance analysis
- Purdue University
  - Engine testing with renewable fuels
  - Collaboration on fuel sensing technologies
  - VVA controls
- BP – Global fuels technology
  - Evaluation of future market fuels
  - Fuel supplier
  - Collaboration on the fuel properties conducive to HECC operation
- OEM Partners (Chrysler and Paccar Inc.)
  - Definition of vehicle and power-train requirements
  - Vehicle packaging and performance impact
  - Provide vehicle for demonstration

**Table 2**: Program collaboration and areas of contribution.

## 5. Technical Approach

The combustion strategy employed for the HECC program is illustrated in Fig. 1. The mixed mode combustion strategy relied on extending the early PCCI combustion model to encompass as much of the engine operation as possible while implementing lifted flame diffusion controlled combustion for the remainder of the higher load operation.

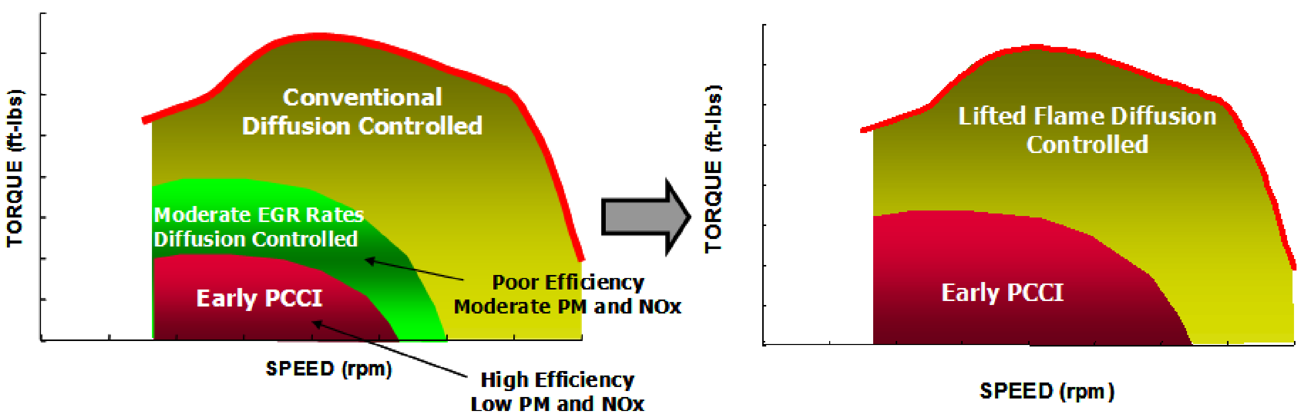


**Figure 1**: Combustion strategy to achieve low emissions, fuel efficient engine operation.

Early PCCI combustion was desirable due to the high thermal efficiency achievable as shown in Fig. 2. Additional desirable attributes included robustness and low NOx and PM emissions. However, early PCCI combustion has challenges including combustion generated noise and high peak cylinder pressures which limit early PCCI combustion to less than full load engine operation in a practical production deployment.

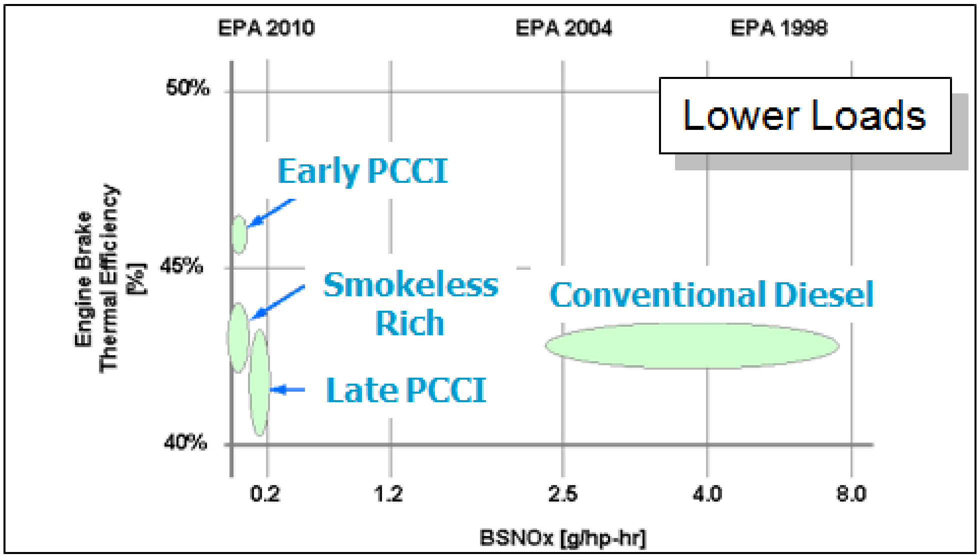


**Figure 2**: Efficiency associated with various combustion regimes.

At higher loads, lifted flame diffusion controlled combustion was used. An illustration of lifted diffusion controlled combustion is given in Fig. 3. The goal of lifted diffusion controlled combustion was to create a lean region near the tip of the liquid fuel where soot precursors are normally formed in conventional diesel combustion. As more cooled exhaust gas recirculation (CEGR) was used to lower NOx, the region near the tip of the spray increased in equivalence ratio (becomes fuel rich) resulting in higher PM production. With the proper combustion, fuel injection, CEGR, and air handling systems; enhanced air entrainment into the combustion plume was achieved resulting in a lifted diffusion flame established farther downstream from the liquid fuel. Creating the lifted flame allowed for high efficient clean combustion to occur at high loads without excessive rates of pressure rise in the cylinder. This characteristic did not demand increasing the cylinder pressure limit of the engine.

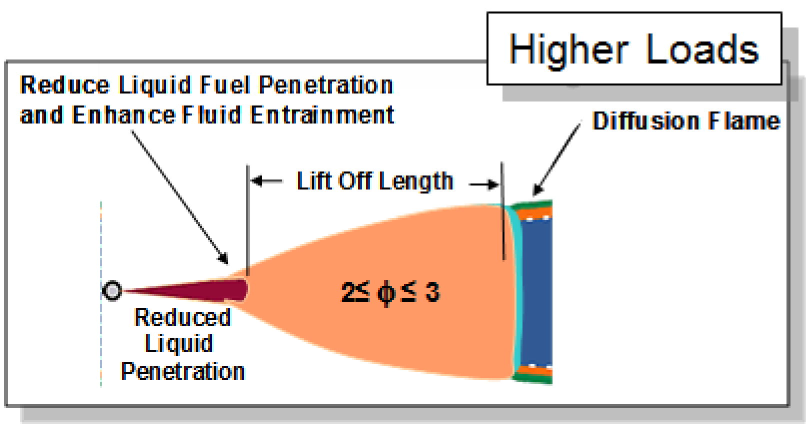


**Figure 3**: Schematic of lifted diffusion controlled combustion used at high engine load conditions.

Employing the various combustion regimes, Cummins developed a global product strategy for diesel powertrain systems to create engine architectures that allow system calibration to achieve a wide range of system out NOx compliance to meet the diversity of future worldwide exhaust emissions standards while providing opportunities to optimize the engine for reduced fuel consumption.

## 6. Heavy Duty 15L ISX Engine Development

A variety of heavy duty, diesel engine architectures has been explored by Cummins as part of the HECC program to meet US EPA 2010 NOx emissions based on two primary strategies to control NOx: cooled EGR (no NOx aftertreatment) and selective catalytic reduction (SCR). Table 3 lists the various technologies developed as part of the HECC program.

| Exploratory (Deselected) | HECC Technology | Selected |
|---|---|---|
| **Combustion**<br>Full Load HCCI<br>Late PCCI Combustion<br>**Air Handling**<br>Electrically Assisted<br>**Base Engine**<br>Increased PCP<br>Exhaust Port Liner | **Combustion**<br>Full Load HCCI<br>Early PCCI Combustion<br>Late PCCI Combustion<br>Lifted Flame Combustion<br>Mixed Mode Combustion<br>Increased CR Piston<br>**Air Handling**<br>2-Stage Turbo w/ Intercooler<br>Electrically Assisted<br>Efficient VGT<br>Variable Valve Actuation<br>**Fuel System**<br>HD XPI >2600 bar<br>Reduced Parasitics<br>**Base Engine**<br>Increased PCP<br>Exhaust Port Liner<br>Friction/ Parasitic Reductions | **Combustion**<br>Early PCCI Combustion<br>Lifted Flame Combustion<br>Mixed Mode Combustion<br>Increased CR Piston<br>**Air Handling**<br>2-Stage Turbo w/intercooler<br>Efficient VGT<br>Variable Valve Actuation<br>**Fuel System**<br>HD XPI >2600 bar<br>Reduced Parasitics<br>**Base Engine**<br>Friction Reduction – Piston, rings, Low viscosity oil, Plasma coated liner<br>Parasitics – Intake port design, Variable flow lube pump |

**Table 3**: Engine technologies developed for the heavy duty 15L ISX engine for Class 8 truck applications.

### 6.1 In-Cylinder Engine Architecture (No NOx Aftertreatment)

An in-cylinder solution for NOx control based on cooled EGR can be achieved with advancements in component technology thus eliminating the need for NOx aftertreatment. The current in-cylinder architecture can achieve compliance with the 2010 NOx regulation along with particulate matter compliance with the use of a diesel particulate filter (see Figure 4 – In-cylinder NOx control). However, obtaining robust PM emission and fuel consumption has been and remains the primary concern for commercial viability. Significant progress has been made to lower the PM levels with less variation. This has been accomplished through downspeeding the engine to allow more time for soot oxidation along with a redesign of the combustion system. Measurements have indicated that a 40% to 60% reduction in PM levels has been obtained. This allows Cummins to meet the 10% fuel consumption reduction target while meeting the US EPA 2010 emissions without NOx aftertreatment. The breakdown of the fuel efficiency improvement of the in-cylinder, no NOx aftertreatment architecture is shown in Figure 5. Variable valve actuation provides additional PM robustness, but involves substantial development to meet the durability demands of the heavy duty trucking market.

Numerous technical barriers still remain in order to develop a commercially viable solution. The primary barriers are:

- Further development of key component technologies

- Variable valve actuation (million mile durability)
  - High fuel injection pressure (mitigate cavitation damage)
  - Engine cooling strategies (large amounts of water condensation)
- Power density
  - In-cylinder NOx control limited to 550 HP
  - Current product highest rating 600 HP
  - Limitations: Vehicle Heat Rejection Capacity
- Fuel consumption robustness
  - Jeopardized by PM robustness
- Unknown transient response
  - Limited Phase 4 vehicle work
  - Concern is turbo lag with moving large amounts of EGR

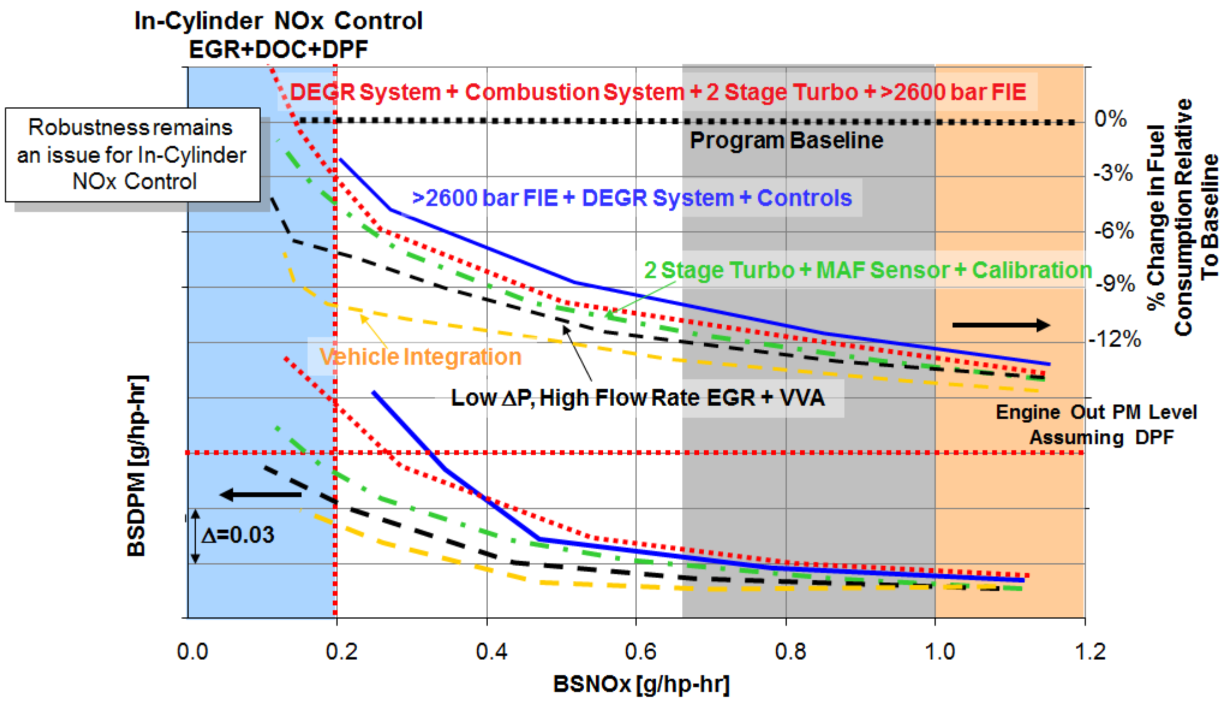


**Figure 4**: Engine out emissions compliance and fuel consumption improvement associated with a variety of HECC engine technologies.

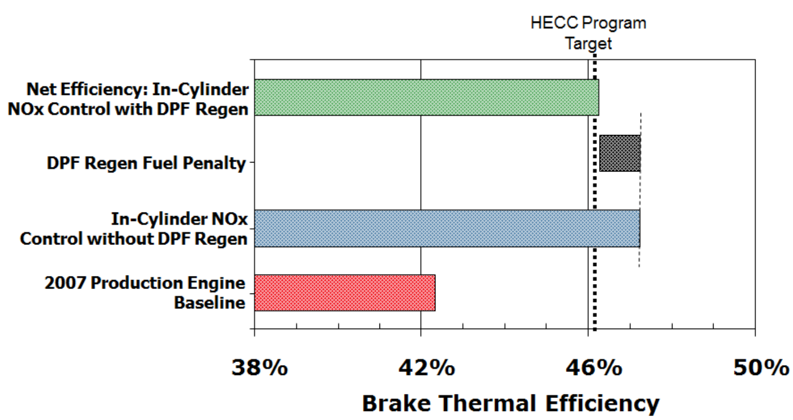


**Figure 5**: Summary of the fuel efficiency improvement associated with the in-cylinder, no NOx aftertreatment engine architecture.

## 6.2 HECC Engine Architecture with SCR Aftertreatment

Much of the enabling technology listed in Table 3 for in-cylinder NOx control was used to provide additional fuel economy improvements for SCR related architectures as shown in Fig. 6. There remained a greater than 5% fuel economy benefit associated with the SCR architectures compared to the in-cylinder NOx control architecture using the same HECC component technologies. Additionally, the aftertreatment size can be reduced compared to SCR systems that are currently in production. This is attributed in part to the HECC engine technologies that provide a system that is robust to engine out emissions variation and provides up to a 15% improvement in fuel efficiency. Also, the HECC engine can achieve a wide range of engine out emissions that provide robustness.

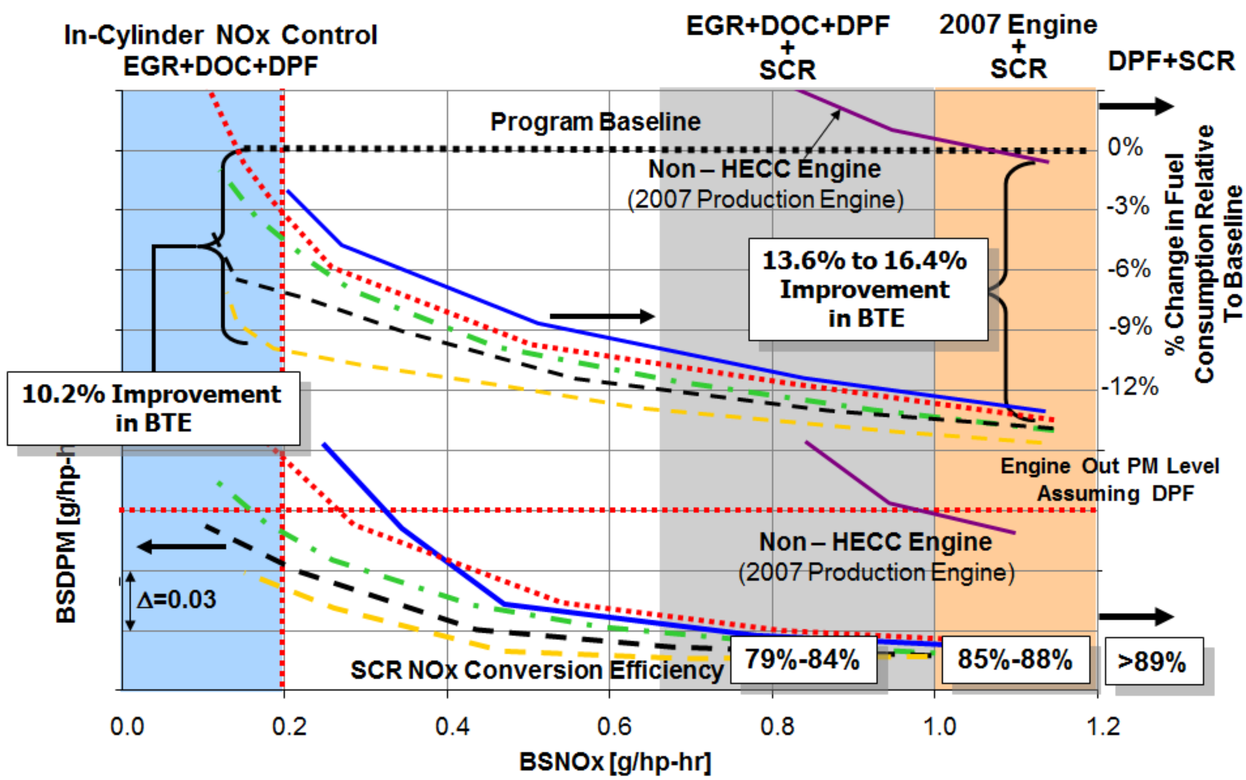


**Figure 6**: Comparison of HECC technologies for a variety of engine out NOx levels indicative of a no NOx aftertreatment (in-cylinder) engine architecture and a SCR NOx aftertreatment engine architecture.

Significant fuel economy improvements were achieved using the HECC base engine integrated with the Cummins high NOx conversion efficiency SCR aftertreatment system. The HECC engine is ideally suited for integration with a high efficiency SCR system. The base engine is capable of achieving a wide range of engine out NOx levels that allow the engine and aftertreatment system to be tuned to achieve US EPA 2010 emissions while exceeding the 10% efficiency target. Thermal management of the aftertreatment system is achieved over a wide variety of ambient conditions. The combined system is robust with reduced variation. A summary of the efficiency improvement of the HECC engine coupled with SCR aftertreatment is shown in Fig. 7.

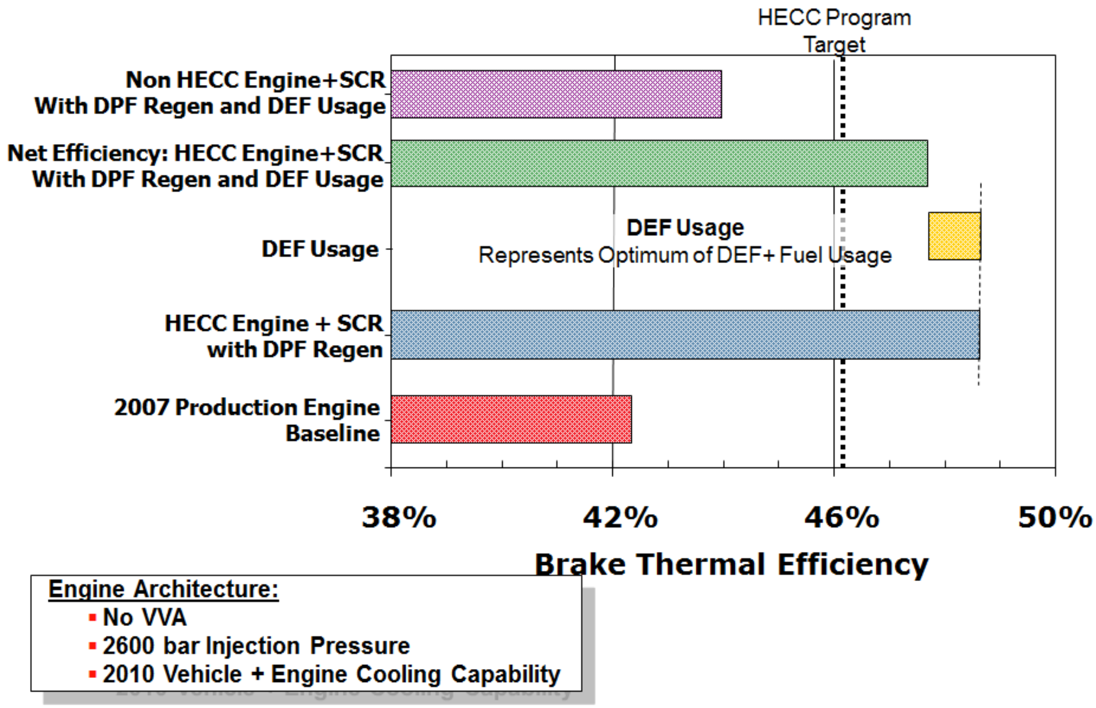


**Figure 7**: Fuel efficiency improvements that exceed the program target of 10% using the HECC engine with SCR aftertreatment.

The SCR and HECC engine feedback control provides the attributes shown in Figure 8. The system can reach high SCR NOx conversion efficiencies while minimizing the variation via feedback control. With reduced variation, this system can be diagnosed to insure emissions compliance in accordance with the EPA OBD (on-board diagnostic) regulations. Based on engine system tests, the HECC engine and the high efficient SCR system with feedback control can meet the stringent 2013 OBD requirements.

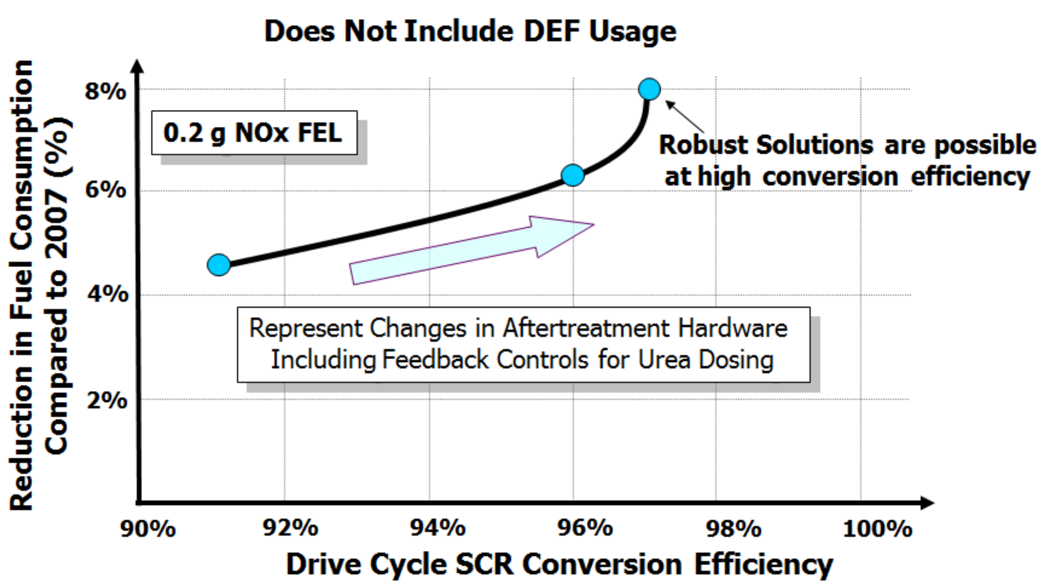


**Figure 8**: Relationship between SCR NOx conversion efficiency and fuel consumption improvement. The fuel consumption improvement is relative to the program baseline while the SCR conversion efficiency improvement is relative to the current production SCR systems for the ISX engine.

The HECC engine has the ability to provide adequate thermal management of the aftertreatment system to achieve catalyst temperatures for peak conversion efficiency over a wide range of ambient operating and drive cycles. Key base engine technologies for thermal management include a VGT turbo, EGR cooler bypass valve, and insulation via thermal barrier coatings of exhaust system components (exhaust ports, manifold, etc.).

Besides improved fuel efficiency, the HECC engine with SCR NOx aftertreatment eliminates some of the important barriers associated with the in-cylinder NOx control architecture. With the addition of SCR, the power density can be maintained or increased. Vehicle heat rejection can be maintained or decreased compared to the 2007 engine and vehicle baseline. Acceptable vehicle transient response has been demonstrated. However, some technical challenges remain for the HECC engine with SCR NOx aftertreatment. The primary challenges are:

- Conversion of DEF to NH3 (eliminate DEF derived deposits)
    - Off-line decomposition
- Packaging
- Weight
    - Alternative sources for NH3
    - Reduce catalyst sizes
- Fuel efficiency thermal management

## 6.3 Commercial Viability of the Heavy Duty 15L Engine Technology

Cummins has a long history of product development with a proven ability and commitment to bring new and innovative technologies to market. Commercialization of the HECC technologies requires sound economics based on acceptable payback periods for the customer, acceptable capital investments, and acceptable return-on-investment.

To insure that the HECC technology development remained focused on commercial implementation, Cummins applied mature six-sigma product development processes and business case development. The six-sigma process is a disciplined Phase-Gate process by which technology development proceeds from Invention/Innovation through Development, Optimization and Certification (robustness). Some technologies developed under this agreement have been subsequently transition into the Cummins product development groups for production implementation. This effort was a cross-functional and corporate-wide process to productionize and commercialize new technologies. Cummins focused on making the HECC technologies a value proposition with an acceptable customer payback. The key technologies demonstrating potential commercialization are shown in Table 4. These technologies enabled meeting and exceeding the fuel efficiency target of 10%. The trucking industry operates on small margins (<3%), and fuel cost is a significant fraction of the cost of ownership. Lower fuel use engines and trucks represent an easier business case.

| Exploratory (Deselected) | HECC Technology | Selected |
|---|---|---|
| **EGR System**<br>2-loop | **EGR System**<br>Reduced ΔP<br>High Capacity Cooling – LTR, 2-loop, Dual Coolers, etc.<br>Mixer | **EGR System**<br>Direct Air to EGR Cooler<br>Dual Coolers<br>Mixer |
| **Controls/Sensors**<br>Fuel Quality<br>CLCC | **Controls/Sensors**<br>MAF, PM, cylinder pressure, and fuel quality sensors<br>Closed loop combustion control (CLCC)<br>2-stage turbo controller | **Controls/Sensors**<br>MAF and PM<br>2-stage turbo controller |
| | **PM AT**<br>Reduced DP DPF Substrate<br>DPF Regen Control<br>Reduce PGM DOC<br>Thermal Management<br>Insulation | **PM AT**<br>Reduced DP DPF Substrate<br>DPF Regen Control<br>Reduce PGM DOC<br>Thermal Management<br>Insulation |

**Table 4**: Technology selected based on commercial viability assessment.

## 7. Light Duty 6.7L ISB Engine Technology

The objective of this portion of the program was to improve the fuel consumption of the 6.7L ISB engine that is used in the Dodge Ram pick-up truck. This pick-up truck application is much different than the heavy duty 15L application. The 6.7L ISB engine is chassis certified to meet the Tier 2 Bin 8 US EPA 2010 emissions for light truck applications. The baseline for this effort was the Cummins 6.7L engine that met the Tier 2 Bin 8 US EPA 2010 emissions regulations ahead of schedule in 2007. The 2007 Cummins engine, used as the baseline, employed an aftertreatment system consisting of a closed-coupled catalyst (CCC), NOx adsorber catalyst (NAC), and diesel particulate filter (DPF).

Figure 9 shows the pathway used to achieve the 10% efficiency improvement. The first area of efficiency improvement was associated with eliminating the NOx aftertreatment (NAC) along with the fuel consumption required to maintain this device. The second area of efficiency improvement was closed cycle efficiency improvement with the use of low temperature, early PCCI combustion. The technologies used to meet and exceed the fuel efficiency target of 10% while meeting Tier 2 Bin 8 US EPA emissions are shown in Fig. 10. Key technologies include a new combustion recipe (piston bowl, injector nozzle configuration, and intake swirl), a two stage sequential turbo, and controls.

The emissions compliance was achieved without NOx aftertreatment. Results for two vehicle weight classes (85K to 10K and 10K to 14K) are shown in Fig. 11 for manual and automatic transmissions. The fuel consumption target of 10% was exceeded for each vehicle with both the manual and automatic transmissions. The average fuel consumption improvement for all the vehicle configurations and weights was 14% as shown in Fig. 12.

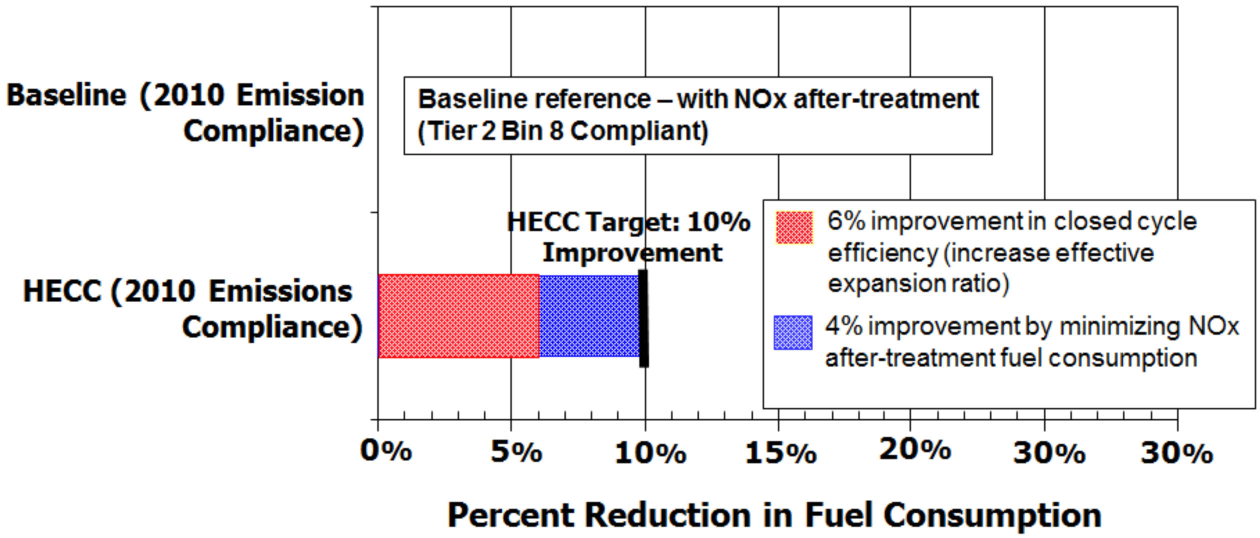


**Figure 9**: Roadmap for efficiency improvement for the 6.7L ISB engine while meeting Tier 2 Bin 8 emissions without NOx aftertreatment.

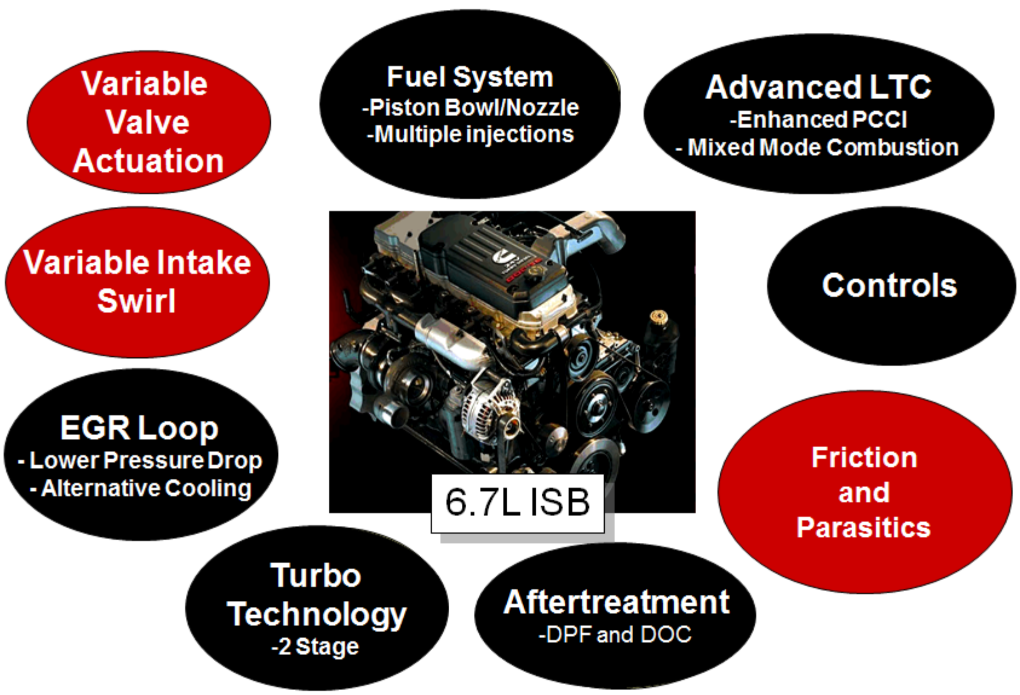


**Figure 10**: Technology used to meet and exceed the fuel efficiency target of 10% for the 6.7L ISB engine while meeting the Tier 2 Bin 8 US EPA 2010 emissions regulations.

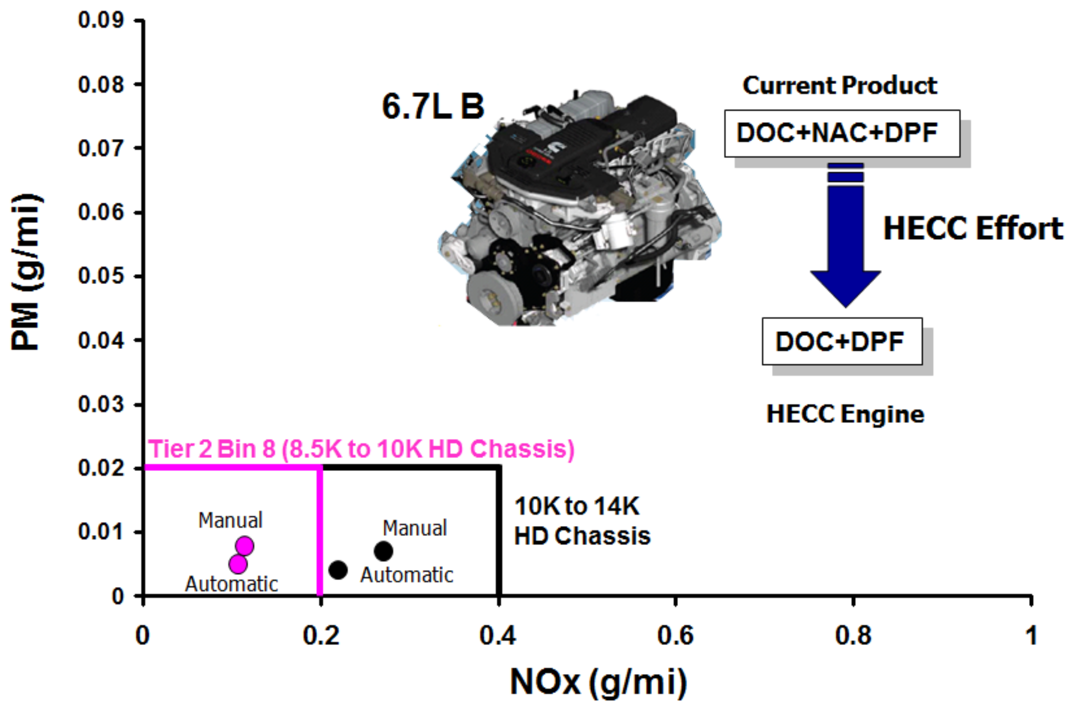


**Figure 11**: Emissions compliance results of the HECC 6.7L ISB engine. Emission compliance achieved without NOx aftertreatment.

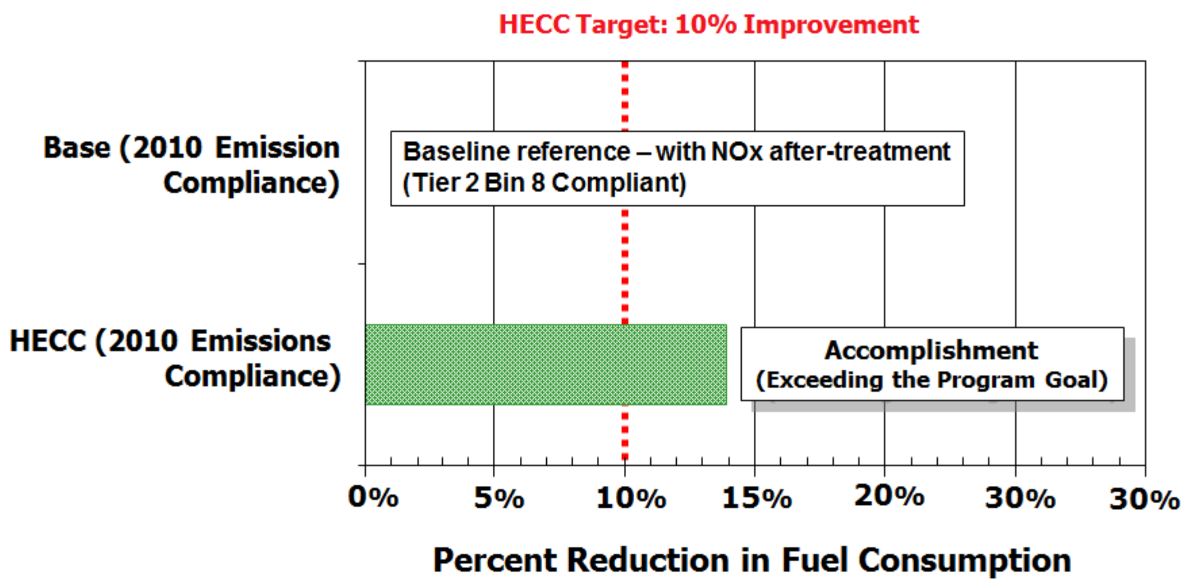


**Figure 12**: Average fuel consumption improvement for the 6.7L ISB engine exceeding the program target of 10%.

## 8. Fuels Research – Impact on HECC Technology

A substantial amount of fuel related research was completed as part of the Cummins HECC program that involved the collaboration of Cummins, BP, ORNL, and Purdue University. Key questions addressed were:

1. What is the impact of diesel fuel variation on HECC engine performance?
2. What fuel properties are important to promote HECC?
3. Does an optimal petroleum based fuel blend exist for HECC?
4. How does biodiesel impact HECC operation?
5. Can the HECC engine be optimized to operate on biodiesel with acceptable NOx emissions and preserve the fuel efficiency improvement demonstrated using commercially available diesel fuel?

A detailed study of petroleum based fuel properties was conducted at Cummins using the 6.7L ISB engine. Fuel properties and engine parameters were varied for this study. Fuel properties investigated included distillation temperature, cetane, and aromatics. The goal was to study the fuel consumption and emissions for the ISB engine operating under low temperature PCCI combustion. This pickup truck engine and application reflected the successful use of low temperature PCCI combustion over the majority of the vehicle duty cycle.

The fuels blended for this effort are similar to the FACE fuels. The engine data were used to development regression models where engine performance parameters are a function of the engine calibration parameters and fuel properties. A detailed investigation of the variation of the fuel consumption and emissions is obtained for fuel property variations. An example of how emissions and fuel consumption change with variation in cetane number is shown in Fig. 13. The regression models were used to derive the following conclusions:

- A blend of diesel and gasoline is best suited for HECC operation over real world drive cycles
- The blend percentage of diesel and gasoline varies primarily with engine load
- The HECC engine technology used on the 15L ISX and 6.7L ISB is robust to the typical variation in commercially available diesel fuel – fuel consumption and emissions compliance variation is manageable
- It is important to explore transient engine operation when quantifying the impact of fuel properties on engine emissions and fuel efficiency since most engines operate in mixed mode combustion (see Fig. 1)

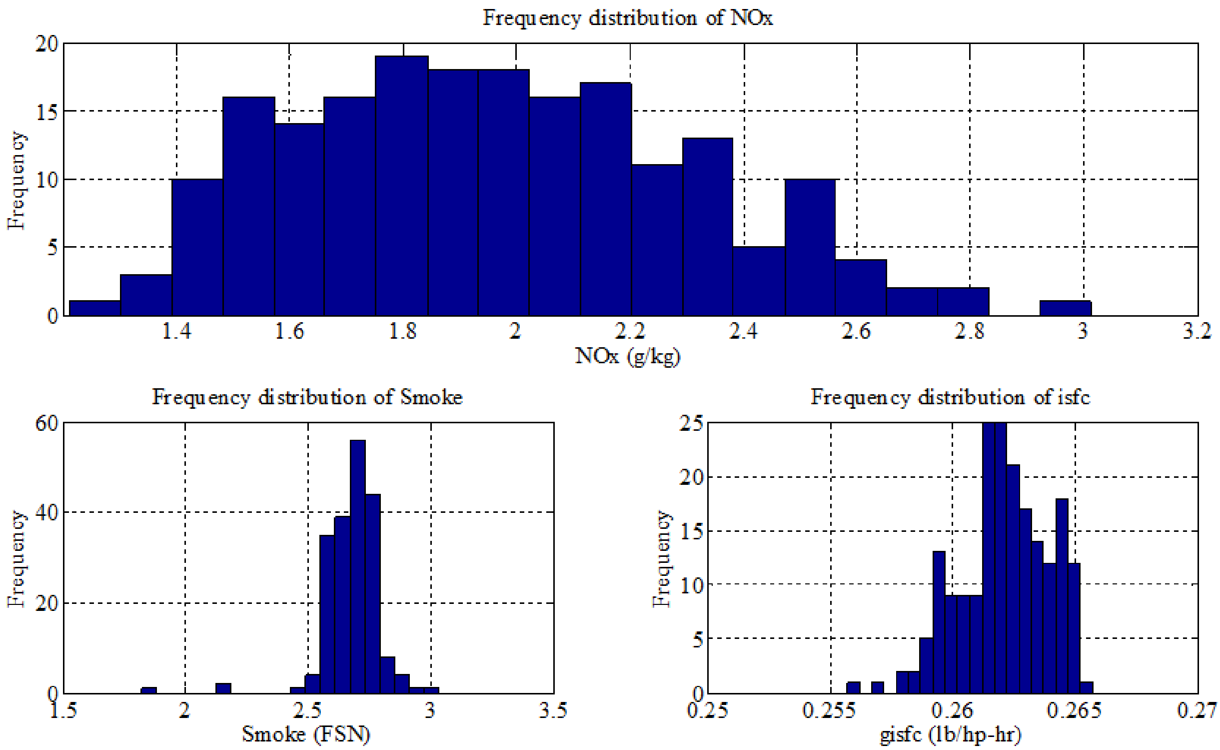


**Figure 13**: Variation in NOx, smoke, and fuel consumption (gisfc) as cetane varies.

The fuels research was extended to include biofuels derived from renewable sources such as soy, palm, rapeseed, etc. The main objective of this effort was to determine if the engine could be calibrated to offset the negative impact of biodiesel on increasing NOx and increasing fuel consumption. The fuel consumption increase associated with biodiesel is due to the lower energy content of biodiesel compared to commercially available diesel fuel. A secondary objective was to determine if a virtual or real sensor could be used to detect the blend level of biofuel. If a sensor could be developed, the engine control system could respond to information on the blend level to help change the engine operation to reduce the impact of biofuels on NOx emissions and preserve fuel consumption benefits. Engine testing as part of this program demonstrated a 1% to 6% increase in fuel consumed with using B20 with the standard engine calibration.

The 6.7L ISB engine was used to develop regression models based on engine calibration parameters and biodiesel fuel type and fuel blend. This extensive effort involved the collaboration of Purdue University to study soy based biodiesel, ORNL to study biofuel type, BP to provide fuel, and Cummins to study the optimization and development of engine control strategies. A virtual sensor based on exhaust oxygen fraction was developed and demonstrated as a way to detect biodiesel blend level. In conjunction with the virtual sensor development, Cummins successfully tested a real sensor with capability to provide blend level. Finally, Cummins was able to demonstrate that the engine could be optimized to offset any NOx increase with biodiesel up to a 20% blend (the study did not extend beyond B20). During this study, fuel consumption was optimized while meeting 2010 emissions regulations. However, the study showed that the fuel consumption improvements could not be fully preserved when operating the engine on B20 compared to standard ultra-low sulfur diesel (ULSD). The fuel consumption difference between B20 and ULSD was reduced to less than 2%.

The important outcomes of the biofuels work were:

- Drive cycle optimization with a variety of biodiesel blends was completed with excellent regression model development and accuracy
- Difficult to maintain fuel efficiency at desired emissions levels with biodiesel given the lower energy content of the biofuel
- Two ways to sense the percentage of biofuel blended with diesel were successfully employed
    - Virtual and real sensors
    - Study includes variations in biofuel feedstock
- Established cost effective ways to develop engine control strategies for variation in biodiesel blends
    - Cannot develop unique engine calibrations for biodiesel blends

It is important to note that the commercial viability of biodiesel fuel sensing technology is uncertain. At the conclusion of this program, the US market drivers for developing the biodiesel sensors and the corresponding control algorithms were not sufficient to incorporate this technology in the standard diesel product. Once the market need and business case is established for biodiesel sensing, new control strategies can be implemented based on the accomplishments from this work. However, additional development is needed before the sensors and controls systems are ready for production.

## 9. Summary

The Cummins High Efficiency, Clean Combustion (HECC) program was completed in March 2010. All program objectives were met, and the engine efficiency targets were exceeded. The commercial viability of the technology was established. Highlights of the accomplishments are summarized:

**<u>Heavy Duty – 15L ISX Engine</u>**

- Can meet the 10% fuel efficiency improvement target using no NOx aftertreatment while compliant with the US EPA 2010 emissions for Class 8 commercial vehicles.
- Achieved greater than 15% fuel efficiency improvement compared to the program target of 10% using the HECC developed technologies with SCR NOx aftertreatment while meeting US EPA 2010 emissions.
- Fuel savings of 590 million gallons of oil per year for Class 8 trucks and fuel savings of 215 million gallons of oil per year for Class 6 & 7 trucks can be achieved based on the efficiency improvements demonstrated once the HECC technology is fully deployed. These estimates are based on Cummins sales data.
- Additional fuel consumption improvements of 2%-3% can be achieved through better integration of the engine with the transmission and vehicle systems (downspeeding the engine, transmission shift pattern, axle ratio, etc.)
- Achieved a 40%-60% reduction in particulate matter emissions with a new combustion system design (piston, fuel injector configuration, intake air swirl level, etc.) along with downsped engine operation. This reduces the amount of fuel consumed to regenerate the diesel particulate filter.
- Completed vehicle drivability assessment with the HECC engine.

- The commercialization assessment of the HECC technologies was completed. Implementation of the technology began with the 2010 engine production and will continue through the next 3-4 years.
- Supplier assessments for all the engine technologies have been completed. All key engine components will be supplied by Cummins Component Business Units.

**Light Duty 6.7L ISB Engine**

- US EPA 2010 Tier 2 Bin 8 steady state and transient NOx emissions compliance have been achieved without NOx aftertreatment for the 6.7L ISB engine used in the light duty truck market while exceeding the program target of 10% fuel efficiency improvement. Drive cycle efficiency improvements ranged from 13% to 18%.
- Analysis and design of additional subsystem technology for the 6.7L ISB have been completed to enable an additional 4% improvement in brake thermal efficiency (enabling technologies include variable valve actuation, combustion system optimization, and fuel injection equipment)
- Supplier assessments for all the engine technologies have been completed. All key engine components will be supplied by Cummins Component Business Units.

**Fuels Technology Exploration**

- HECC engine technologies developed as part of this program have been shown to be robust for fuel economy and emissions with variations in diesel fuel properties representative of commercially available fuels in the marketplace.
- The development of virtual and real fuel sensing technology is required to maximize the fuel economy benefit associated with the HECC technology when using renewable fuel sources such as biodiesel.
- The fuel economy benefits associated with the HECC engine technologies developed cannot be maintained when using biofuels at constant NOx emissions. However, a reduction of 20% to 40% in particulate matter can be achieved with the use of biofuels.
- Two new fuel virtual sensors have been developed for biofuel content.

## 10. References


1. Ward, Jacob. “Vehicle Technologies Analysis Portfolio,” Energy Efficiency and Renewable Energy Presentation, U.S. Department of Energy, Presentation to 21CTP, Feb. 2009.

2. National Academy of Science Presentation, 21st Century Truck Partnership, 2007.

3. Stanton, Donald. “High Efficient Clean Combustion,” DEER conference presentation, 2008.

4. Nelson, Christopher. “Exhaust Energy Recovery,” DEER conference presentation, 2008.

5. The Technology and Maintenance Council of the American Trucking Association (ATA), *Lightweight Components Effect on Fuel Economy, Recommended Practice*, RP 1112.