Light Truck Clean Diesel Program

Final Public Report

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DOE Project Officer:	John Fairbanks, EE-33, US DOE.
Recipient:	Caterpillar Inc. Technology and Solutions Division P.O. Box 1875 Peoria, IL 61656-1875
Principal Investigator:	Eric Fluga, Global Technical Team Leader Product R&D, TCL-702 Technology and Solutions Division P.O. Box 1875 Peoria, IL 61656-1875 Phone: (309) 578-3065 Fax: (309) 578-3065 Email: Fluga_Eric_C@CAT.com
Program Manager:	Eric Fluga

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Acronyms

CAT3D	3 Dimensional Combustion Simulation Tool
CIDI	Compression Ignition Direct Injection
HCCI	Homogeneous Charge Compression Ignition
HSDI	High Speed Direct Injection
LTCD	Light Truck Clean Diesel
MMI	Mixed Mode Injector
NVH	Noise, Vibration and Harshness
RPAC	Rapid Prototyping for Automatic Controls
ULSD	Ultra Low Sulfur Diesel (less than 15 ppm sulfur)

Executive Summary

The US Department of Energy and Caterpillar entered a Cooperative Agreement to develop compression ignition engine technology suitable for the light truck / SUV market. Caterpillar, in collaboration with a suitable commercialization partner, developed a new Compression Ignition Direct Injection (CIDI) engine technology to dramatically improve the emissions and performance of light truck engines. The overall program objective was to demonstrate engine prototypes by 2004, with an order of magnitude emission reduction while meeting challenging fuel consumption goals.

Program emphasis was placed on developing and incorporating cutting edge technologies that could remove the current impediments to commercialization of CIDI power sources in light truck applications. The major obstacle to commercialization is emissions regulations with secondary concerns of driveability and NVH (noise, vibration and harshness). The target emissions levels were 0.05 g/mile NOx and 0.01 g/mile PM to be compliant with the EPA Tier 2 fleet average requirements of 0.07 g/mile and the CARB LEV 2 of 0.05 g/mile for NOx, both have a PM requirement of 0.01 g/mile.

The program team developed a combustion process that fundamentally shifted the classic NOx vs. PM behavior of CIDI engines. The NOx vs. PM shift was accomplished with a form of Homogeneous Charge Compression Ignition (HCCI). The HCCI concept centers on appropriate mixing of air and fuel in the compression process and controlling the inception and rate of combustion through various means such as variable valve timing, inlet charge temperature and pressure control.

Caterpillar has adapted an existing Caterpillar design of a single injector that: 1) creates the appropriate fuel and air mixture for HCCI, 2) is capable of a more conventional injection to overcome the low power density problems of current HCCI implementations, 3) provides a mixed mode where both the HCCI and conventional combustion are functioning in the same combustion cycle. Figure 1 illustrates the mixed mode injection system. Under the LTCD program Caterpillar developed a mixed mode injector for a multi-cylinder engine system. The mixed mode injection system represents a critical enabling technology for the implementation of HCCI. In addition, Caterpillar implemented variable valve system technology and air system technology on the multi-cylinder engine platform. The valve and air system technology were critical to system control.

Caterpillar developed the combustion system to achieve a 93% reduction in NOx emissions. The resulting NOx emissions were 0.12 gm/mile NOx. The demonstrated emissions level meets the stringent Tier 2 Bin 8 requirement without NOx aftertreatment! However, combustion development alone was not adequate to meet the program goal of 0.05gm/mile NOx. To meet the program goals, an additional 60% NOx reduction technology will be required. Caterpillar evaluated a number of NOx reduction technologies to quantify and understand the NOx reduction potential and system performance implications. The NOx adsorber was the most attractive NOx aftertreatment option based on fuel consumption and NOx reduction potential.

In spite of the breakthrough technology development conducted under the LTCD program there remains many significant challenges associated with the technology configuration. For HCCI, additional effort is needed to develop a robust control strategy, reduce the hydrocarbon emissions at light load condition, and develop a more production viable fuel system. Furthermore, the NOx adsorber suffers from cost, packaging, and durability challenges that must be addressed.

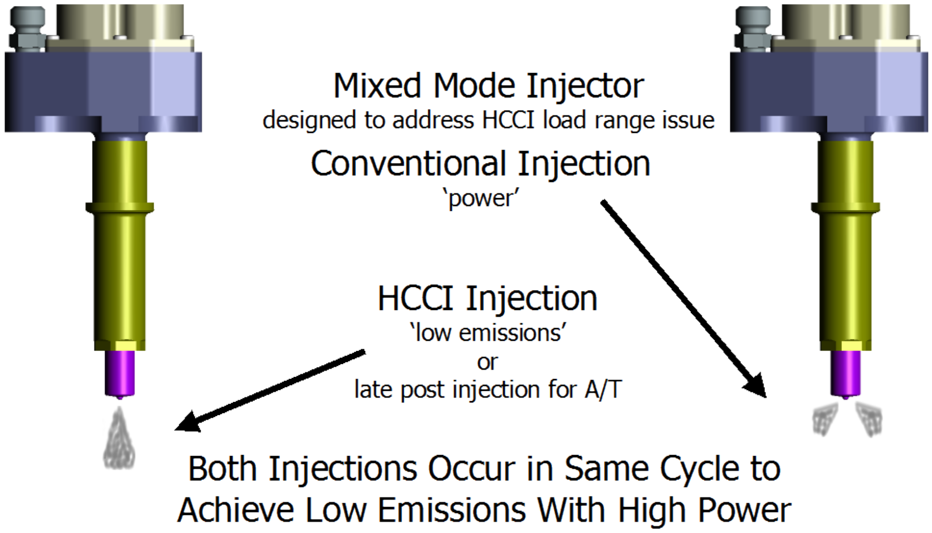

Figure 1: Schematic of Mixed Mode Injector

Results of Work

Approach

The light truck application is an extremely cost sensitive market. To develop compression ignition engine technology for the light truck application will require a dramatic breakthrough in the cost of the emissions system technology. Conventional combustion system technology has the potential of achieving 0.7-0.9 gm/mile NOx and 0.08-0.12 gm/mile PM. The program goal was to demonstrate 0.05 gm/mile NOx and 0.01 gm/mile PM. Conventional lean burn aftertreatment technologies were considered cost prohibitive to the light duty market segment.

To achieve the order of magnitude reduction in emissions, Caterpillar aggressively pursued multiple technologies to identify a suitable alternative. Caterpillar leveraged in house analysis techniques including three dimensional combustion simulation, one dimensional engine system simulation, structural analysis, and full system simulation via Dynasty. Dynasty is Caterpillar's proprietary analysis package that is widely used to predict transient and steady state performance of vehicle, engine, and fuel systems. In addition, Caterpillar leveraged their world-class fuel system and engine development facility to evaluated various emissions system technology options.

Under the LTCD program, Caterpillar focused program attention on developing a low cost combustion system capable of meeting the stringent Tier 2 emissions requirements. The program intent was to minimize or eliminate the need for costly aftertreatment.

Caterpillar concurrently developed advanced aftertreatment technology to facilitate the final integration of the best engine and aftertreatment system.

Results and Discussion

To enable HCCI and the resulting low emissions, Caterpillar focused developing the mixed mode injection system. The development of any fuel system component requires significant hydraulic system level analysis, structural analysis, bench test development and hardware iterations to produce a refined component. After an extended development effort, Caterpillar successfully demonstrated the mixed mode injection system suitable for combustion system development. The first injector was evaluated on a single cylinder engine. Later, more advanced components were evaluated on a multi-cylinder engine platform. Figure 2 is a typical heat release for the mixed mode combustion event. For Figure 2, each of the three heat release curves has approximately 50% of the fuel combusted in a homogeneous fashion. Note the 'cool flame' portion of the early heat release. Figure 2 also demonstrates independent timing control of the conventional injection event.

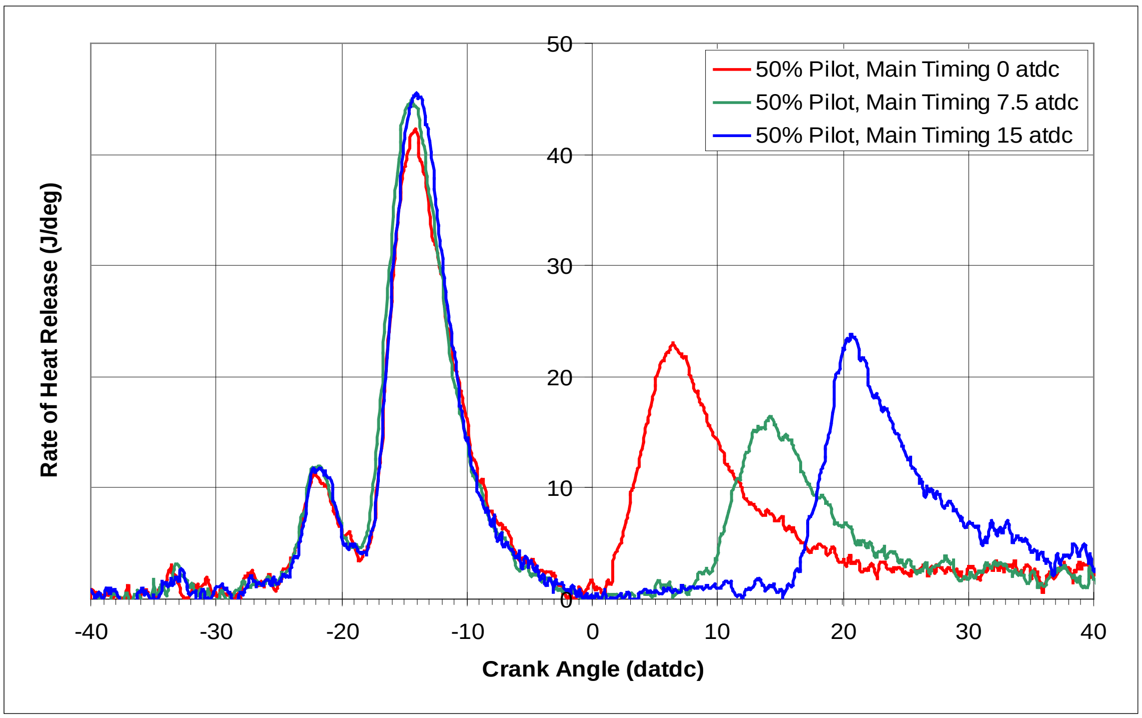

Figure 2: Representative Heat Release from Mixed Mode Injector

Combustion system optimization began after the injection system hardware was developed to a point that the emissions and performance were repeatable. The combustion system optimization was an iterative process relying on Caterpillar's proprietary CAT3D combustion simulation tool, visualization of the fuel injection spray at Caterpillar's spray visualization center, and engine test stand evaluation. CAT3D was instrumental in gaining insight into the fundamental combustion processes that ultimately determine the emissions and performance of the engine. The iterative optimization process investigated various features of the combustion system. Those features included:

injection pressure, combustion bowl shape, compression ratio, valve events, injection timing control and spray pattern of both injection events. Figure 3 illustrates the dramatic improvement in emissions that can be achieved via combustion system optimization. Caterpillar's reliance on simulation to develop the combustion system yielded this dramatic reduction.

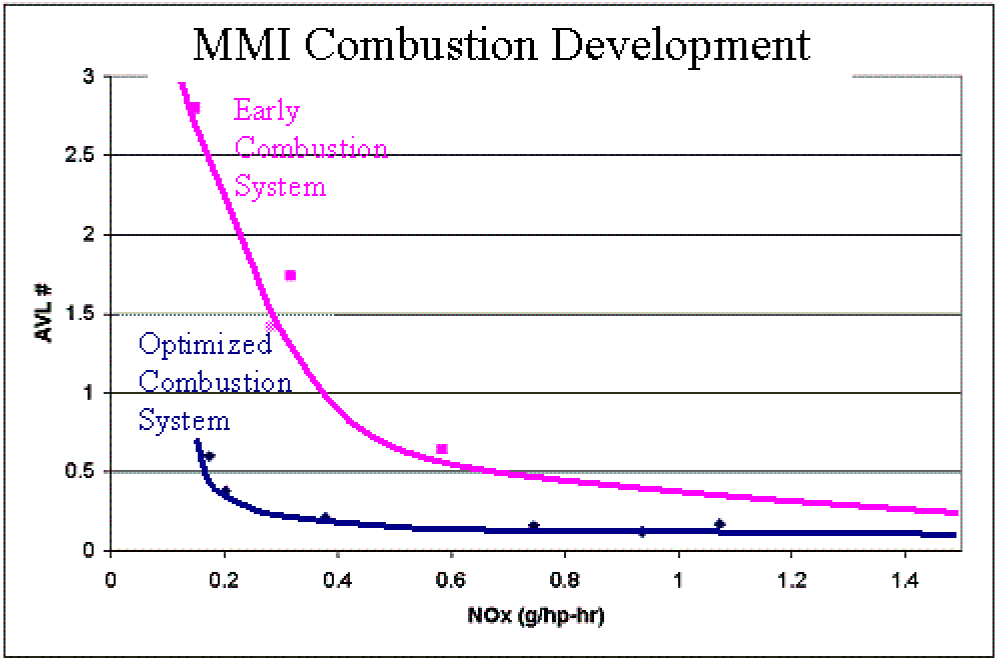

Figure 3: Combustion System Development

After completing the preliminary combustion system optimization illustrated in Figure 3, the development team focused on demonstrating the cycle emissions potential of the combustion system with the mixed mode injector. The technology demonstrated a 0.12 gm/mile NOx vs. the 1.8 gm/mile NOx baseline (non-optimized baseline system). This dramatic reduction fell short of the program target of 0.05 gm/mile. However, it does meet the Tier 2 Bin 8 emissions level of 0.14 gm/mile NOx. Bin 8 is the maximum permanent emissions limit for Tier 2. It is envisioned that the system will require a PM trap to meet the aggressive PM emissions standard.

Conclusion

Under the LTCD program, Caterpillar has made remarkable progress on an advanced low temperature combustion process. The team has developed a fuel injection system that enables the use of HCCI and conventional combustion with the same engine system. Additional development effort would be required prior to production implementation of this technology. The specific development that would be required includes: low temperature hydrocarbon control, improved combustion control, fuel system variability and manufacturability improvements. Future combustion development will be required for the compression ignition engine to maintain and advance its leadership position as an efficient power source for the mobile marketplace.

Details of the Work

Enabling Technology Development

Advanced Lean NOx Catalyst Development:

As part of the LTCD Program, Caterpillar evaluated the potential of Advanced Lean NOx Catalysis to reduce NOx emissions. By using ultra low sulfur diesel (ULSD; < 15 ppm sulfur) fuel, the catalyst formulations do not need to contain sulfate suppressor additives. As such, the low sulfur fuel allows for a more aggressive catalyst formulation to use exhaust hydrocarbons as a selective catalytic reductant (SCR) for removing NOx. A 300 bhp engine was set up and ten sets of candidate formulations were procured for testing and evaluation.

In addition to testing catalysts from three suppliers, Caterpillar developed formulations were synthesized and coated onto full size substrates. A quick-turnaround of results allowed Caterpillar to make subsequent formulation modifications for evaluation. Late post injection of diesel fuel was utilized to provide a high hydrocarbon to NOx ratio for the catalyst. The testing showed that 30 to 40 % NOx reduction is possible over a medium to high temperature range. Figure 4 shows catalyst performance of several dual brick systems at a low load operating condition (low space velocity). Taking into account the durability of the catalyst, this technology could deliver a 20-25% NOx reduction (or 0.012 gm/mile NOx at the program target).

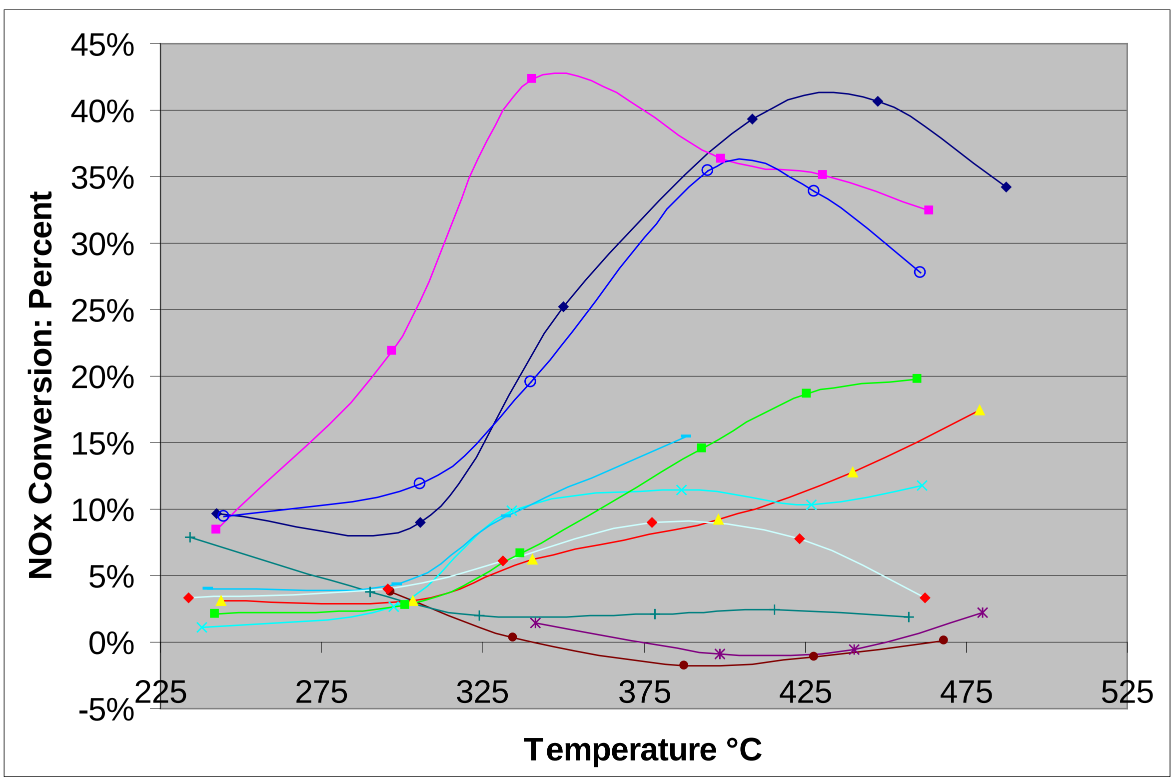

Figure 4: Advanced Lean NOx Catalysis at HC/NOx=6/1 and low Space Velocity: 55,000-80,000 hr^{-1}

<u>NOx Decomposition Catalyst</u>
As part of the LTCD program, NC State University was sub-contracted to evaluate NO decomposition catalyst technology. The focus of this study was to identify new catalyst materials that have the potential to decompose NO efficiently in lean diesel exhaust. Successfully identifying a catalyst of this type is extremely high risk. A successful outcome would be a major breakthrough for the diesel engine industry. The results of this work were inconclusive as to whether an effective NOx decomposition could be created.

<u>NOx Adsorber</u>
As part of the LTCD program, Caterpillar evaluated a single branch (i.e., single branch) NOx adsorber system. The single branch system has the potential of dramatically reducing the cost of the dual branch system. Preliminary development of this system was conducted at TNO in the Netherlands. System development was then transferred to Caterpillar's Technical Center and focused on improving the performance of the TNO developed system. Results indicated an overall NOx reduction of 88% with a fuel consumption penalty of only 4%. This result was very close to the project objective of 90% conversion with 4% (or less) fuel penalty.

<u>Nox Adsorber regeneration</u>
Caterpillar evaluated an in-pipe enrichment approach to NOx adsorber regeneration. The exhaust flowing through the catalyst was enriched with fuel injected in the exhaust pipe up stream of the catalyst. This injection system was tested in combination with a dual branch catalyst approach. The purpose of this testing was to evaluate the effectiveness of NOx adsorber regeneration with an in-pipe injection dual branch system and compare that to the previously tested in-cylinder injection single branch system.

Results showed at higher exhaust temperature conditions (exhaust gas > 300 °C) in-pipe injection performs comparable to and sometimes even better than the previously tested in-cylinder enrichment. At lower exhaust temperatures, the in-pipe injection system suffers from fuel vaporization issues and less effective reductant species (diesel fuel instead of CO/H_2) yielding an excessive fuel consumption penalty (> 10%). This will be particularly problematic for light duty applications, where catalyst temperatures during the certification cycle and real life application are relatively low. As such, preliminary results indicate that for light duty applications, in-cylinder enrichment may be a better option. Improved noise, drivability, exhaust temperatures and smoke are other key advantages of the in-pipe injection system. The in-pipe injection system does impose different control strategies, making it harder for optimization.

Initial steady-state tests with in-pipe enrichment showed very poor regeneration performance at low exhaust gas temperatures (below 300°C). In addition, this injector demonstrated very poor atomization at higher fuel flows. An alternate injector was procured to investigate the effect of atomization. Visual testing showed improved atomization and spray pattern. The radial distribution of emissions was measured, showing that fuel is evenly distributed over the face of the catalyst.

Subsequent testing indicated similar performance with respect to NOx conversion and BSFC penalty for both in-pipe fuel systems. At low temperatures (<300°C), the performance with the alternate injector was slightly better. After additional data analysis, it was concluded that the method to determine the required regeneration fuel quantity was producing inconsistent results. One of the challenges for in-pipe fuel systems is to determine how much fuel is needed to fully regenerate the NOx adsorber. A model was developed to better understand the mechanisms during storage and regeneration of the NOx adsorber using in-pipe enrichment. After studying the data and model, a more consistent fuel quantity optimization method was developed. The optimized method in general showed small differences between the injection systems, but showed that depending on the operating condition the original injector or the alternate injector performed better. The alternate injection system was considered more robust and selected as the system of choice.

Most of the NOx adsorber system development has been conducted with the same catalyst formulation. This approach has allowed Caterpillar to develop a more fundamental understanding of the NOx adsorber system performance. A catalyst screening method was developed to assess the performance of various catalyst formulations. This method was used to test 7 different formulations from 4 different suppliers. The testing focused on 3 areas:

- NOx storage efficiency
- In-cylinder regeneration efficiency
- In-pipe regeneration efficiency

The testing showed that a wide range of formulations with varying performance characteristics is available. The temperature range for efficient NOx conversion was the primary difference between various catalyst formulations. Catalysts that have good low temperature performance are usually not capable of performing at higher temperatures. Similarly, catalysts that have good high temperature performance are usually not capable of performing at lower temperatures. The amount of NOx that can be stored on a catalyst at a 10% NOx slip (90% of NOx is stored on catalyst) is an important parameter of a catalyst, since it is an indication of the required catalyst size. A higher storage capacity with 10% slip means that a smaller catalyst would be sufficient to meet the regulatory requirements.

Transient regeneration strategies utilizing in-cylinder late cycle fuel injection (i.e., single branch) were developed to understand the transient performance capability of the system. Control software was developed for the steady state test cell to simulate the transient test cycle. In addition, preliminary engine system transient control strategies have been developed. Two main conclusions were drawn:

1. The NOx adsorber does not store NOx very well under low temperature conditions. More importantly, it is very hard to regenerate the NOx adsorber at lower temperatures. This means that if a NOx adsorber needs to be regenerated in these conditions, the storage capability after the regeneration has decreased even

further. The catalyst does not begin to operate efficiently until the catalyst temperature has reached 250°C. Fast heat up strategies will be necessary to improve the performance over the cycle.

2. In-cylinder enrichment is only possible at engine operating conditions above 25% load. Below this load, the engine needs to be throttled significantly to reduce lambda resulting in poor combustion and misfire. Because of the limited regeneration operating range, a triggered regeneration might need to be aborted too early because of a sudden drop in load. This happened a number of times during transient testing, resulting in a high fuel penalty and lower NOx conversion. Extension of the operating range is necessary to prevent aborted regenerations and the resulting higher fuel penalties.

The main results of the transient testing are shown in Table 1:

	NOx conversion	Fuel penalty
Run 1	75%	3%
Run 2	90%	10%

Table 1: NOx conversion & Fuel Penalty

Desulfation

One of the key challenges for NOx adsorber catalysts is that the catalyst will also trap sulfur (in the form of SOx). The trapped sulfur reduces the NOx reduction capability of the catalyst. As such, a strategy for removing the sulfur (desulfation) is required for this technology to become viable. A successful desulfation strategy will require a tightly controlled catalyst temperature (i.e. 690 – 710 degrees C). Lower temperatures will not facilitate the desulfation process. Exceeding the temperature range will cause irreversible thermal degradation of the catalyst material. A typical desulfation strategy will rapidly cycle the exhaust stream between fuel lean and fuel rich (lambda < 0.85). An extended rich hold will produce H_2S (unacceptable due to odor and toxicity). The lean/rich cycling prevents the formation of hydrogen sulfide. The lean/rich cycling makes tight temperature control especially challenging. Desulfation strategies were investigated with the NOx adsorber equipped engine. An in-pipe diesel fuel injection system was utilized for this study.

To gain a fundamental understanding of NOx adsorber catalyst behavior, the team utilized a test bench in the Advanced Materials Technology (AMT) Division of Caterpillar. The bench test was also used to investigate desulfation behavior of a NOx adsorber catalyst.

High Speed Direct Injection (HSDI) Development

The Isuzu 4JX1 platform was selected as the single cylinder HSDI engine for implementation of the enabling technology. The Isuzu 4JX1 engine is a four cycle, water-cooled, dual overhead cam diesel engine. It is equipped with a Caterpillar HEUI® fuel system. The 160 hp 4-cylinder engine has a 19:1 compression ratio, a 95.4mm bore and 104.9mm stroke (3.0 L total displacement). To facilitate the development of the combustion system and new Caterpillar developed HEUI based mixed mode injector, a single cylinder version of this engine was developed. Testing during this reporting period focused on identifying the optimum injector tip geometry to facilitate HCCI with a HSDI combustion system

Multi-cylinder Engine Development

To develop a robust injector design, the development team constructed a fully functioning analytical model of the injector utilizing Caterpillar's proprietary Dynasty software package. Dynasty is a Caterpillar proprietary simulation and analysis program that is widely used to predict the transient and steady state behavior of hydraulic systems. The model was used to predict and evaluate fuel system performance. Based on Dynasty modeling, the electronic and hydraulic design was improved to enhance the system performance. In addition, structural FEA of critical injection system components was completed. Based on FEA analysis, design modifications were implemented to address key structural issues.

Caterpillar developed a variable valve system for a production, multi-cylinder HSDI platform. The system was an adaptation of an internally developed system. The variable valve system was needed to control the start of combustion for HCCI. A Dynasty model was constructed to refine and improve the system performance. In addition, structural analysis of key components was completed. The design was modified to eliminate structural and performance issues identified in the pre-build analysis. After the design modifications were complete, the hardware was procured.

Caterpillar developed a high-pressure ratio (high efficiency) capable turbocharger for the HSDI platform. The high-pressure ratio was required to supply the airflow while operating the engine with the VVT system. The high efficiency device was required to achieve the aggressive fuel consumption targets for the LTCD program. Caterpillar developed this turbocharger with its internal turbine engine expertise.

The turbocharger was evaluated on the HSDI engine platform. Test data indicated that the compressor performance met all performance specifications. However, the performance of the supplier provided turbine did not meet performance expectations. Additional turbocharger development work will be required to achieve acceptable turbine performance. In addition, an enhanced EGR system utilizing fast acting electronic EGR valves and enhanced EGR cooling was evaluated during this reporting period. The enhanced EGR system met all performance expectations.

A “Virtual Transient Test Cell” model was created for the HSDI engine. The “Virtual Transient Test Cell” uses Dynasty to simulate the engine, transient torque controller, command module, and the engine Rapid Prototyping for Automatic Controls (RPAC) controller. Dynasty is a Caterpillar proprietary simulation and analysis program that is widely used to predict the transient and steady state behavior of vehicle systems. Extensive work was done on turbocharger maps to allow the simulation of the idle condition, which is a significant portion of transient cycles. The actual RPAC engine control logic was added the Dynasty simulation model. The model was used to test and develop software control strategies in advance of the actual transient tests.

CAT3D, the Caterpillar 3-dimensional combustion simulation tool, was used to model the HSDI engine to computationally evaluate a number of combustion system concepts. Initially, the accuracy of the model was validated against engine data at three steady-state operating conditions (1500 rpm/25% load; 1990 rpm/100% load and 2400 rpm/50% load). The model was calibrated and determined to accurately predict cylinder pressure, NOx emissions, and soot. The calibrated model was then utilized to evaluate a number of conventional combustion system options.

The second phase of the CAT3D modeling work focused on analyzing Homogeneous Charge Compression Ignition (HCCI) combustion and the Mixed Mode Injector (MMI) with the goal of achieving the mandated 2007 tier 2 emissions levels. While validation of the spray, combustion and emissions predictions for HCCI was on going, CAT3D was being used to give directionally correct combustion system configurations. For example, CAT3D was used for visualizing the spray penetration and thereby the wall impingement locations when early injections (-115 DATDC) were used. Previous testing on the Isuzu single-cylinder engine suggested that minimization of spray to liner wall interaction is favorable for the reduction of unburned-hydrocarbon emissions.

With planned HCCI injection timings ~ -75 DATDC, the narrower spray angle achieved the objective of keeping the spray off the liner wall. Based on this analysis, the downward spray pattern and nozzle design appeared acceptable.

Baseline engine-only dynamometer testing was completed by Perkins technology. A steady state test cycle was used to simulate the FTP75 chassis dyno requirement. This 8-mode test was run and results yielded 6.19g/mile NOx. For comparison, previous FTP75 in chassis testing on the HSDI engine resulted in 5.79 g/mile. In addition to the steady state baseline, Perkins Technology developed and ran a transient test cycle to mimic the FTP75. Initial testing on this cycle resulted in measured NOx of 4.98g/mile. This newly developed transient cycle and data was utilized to calibrate the Dynasty model for control system development.

In addition to the baseline work at Perkins, a second HSDI engine was installed in a Caterpillar Technical Center test cell and used for initial controls system development. The capability of controlling the engine was removed from the original ECM and given to the Caterpillar RPAC (Rapid Prototyping for Automatic Controls) system. The controller allows complete engine governing, fuel system and air system control. After an initial debug, the development team focused on using the control to evaluate the emissions potential of the baseline hardware.

The Variable Valve Timing (VVT) system was installed and tested on the HSDI engine platform. The VVT system was utilized to actively control the effective compression ratio and appropriately phase HCCI combustion

The re-designed Phase 2 air system was installed and tested. Optimized 8-mode emissions (simulated FTP75) with this combination resulted in 0.50g/mile NOx level with acceptable smoke as shown in Table 2. Further steady state emissions optimization of the Phase 2 air system yielded slightly lower NOx emission results (0.43 g/mile).

	NOX g/mile	HC g/mile	PM g/mile	Fuel Burn MPG
Baseline	5.38	0.43	--	17.0
Optimized Stock Hardware	1.79	0.77	0.12	16.7
VGT with Stock EGR	1.00	0.57	--	16.0
Phase2 Air System	0.50	1.19	--	16.1

Table 2 8-Mode Cycle Results

Figures 5, 6, and 7 illustrate the basic emissions trade-offs that were demonstrated with the mixed mode combustion system. Figure 7 shows the dramatic reduction in smoke emissions as the combustion system development occurred. This dramatic reduction was made possible by the guidance of CAT3D.

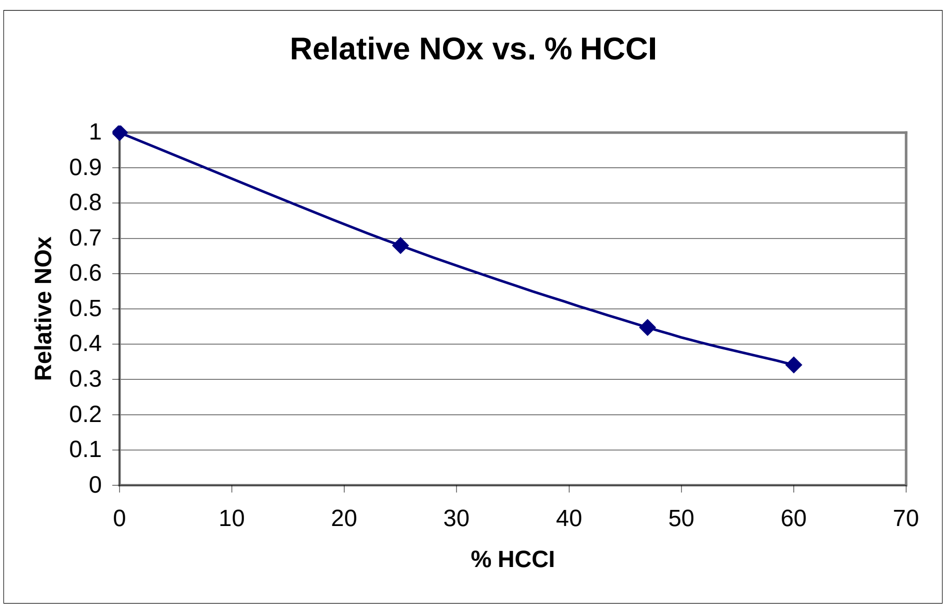

Figure 5: NOx vs. % HCCI

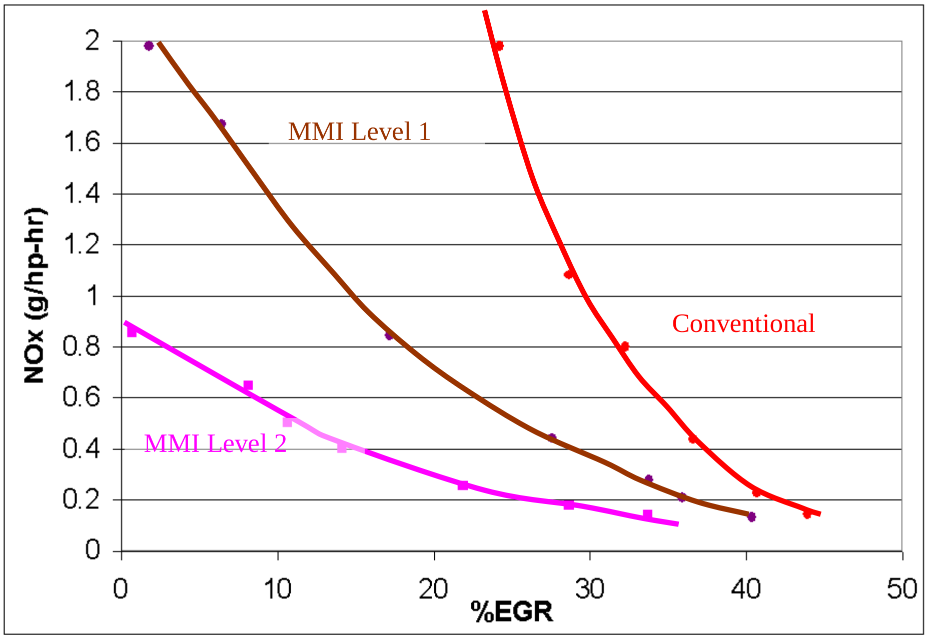

Figure 6: NOx vs. %EGR

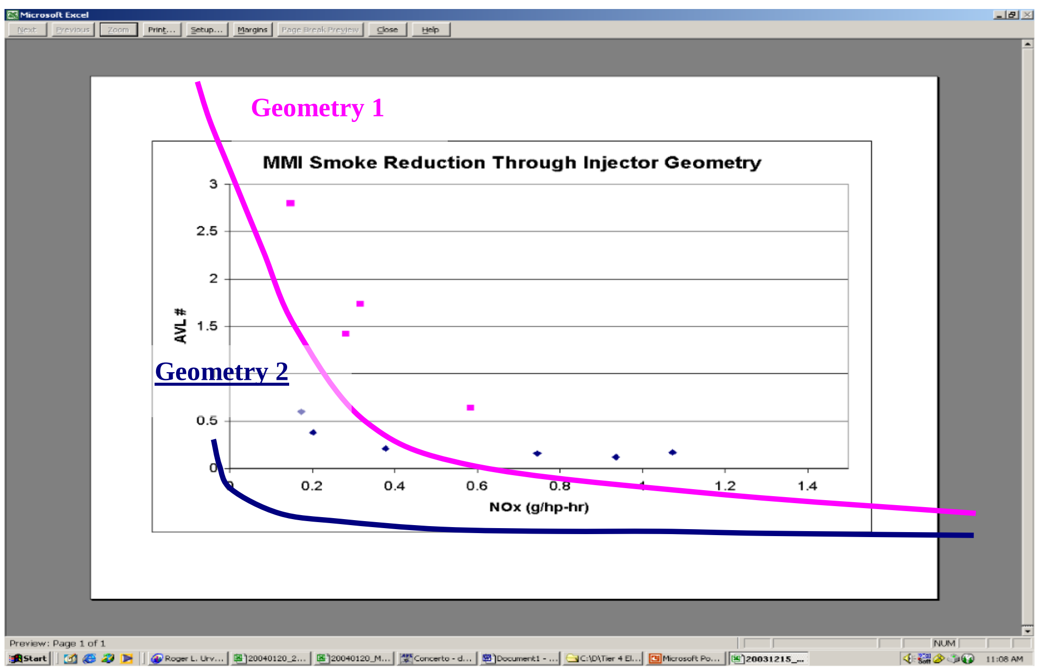

Figure 7: AVL Smoke vs. NOx

The Mixed mode combustion system successfully demonstrated the Tier2 Bin emissions levels. Unfortunately, the Mixed Mode Injection system was not capable of meeting the program goals of 0.05 gm/mile NOx. To achieve the program goals, a combined NOx Adsorber and Mixed Mode system would be required. It is unclear if the cost and complexity of this system would be acceptable in the Light Duty Market. A more likely scenario is the continued development of the basic combustion system for commercial implementation.

Vehicle Development

The HSDI chassis was baselined on the FTP75 cycle and reported during the previous reporting period (LTCD1). The cycle results were utilized to develop a transient dynamometer test for the loose engine. This test was utilized to ensure a more robust engine prior to in-chassis testing. Vehicle integration design work was delayed due to delays in the multi-cylinder development effort. The multi-cylinder development was delayed due to unforeseen challenges with the injection system. As a result, the vehicle technology integration was not conducted as part of the LTCD program.

Program Management

Detailed project plans were created and maintained for the life of the project. Weekly status meetings were held to monitor, update and report on the progress. Plans included resources and costs and were the basis for the budgets submitted to DOE.