Final Report

June 3, 2011

Prepared for:

U. S. Department of Energy

Submitted by:

Cummins, Inc.
Columbus, IN

Light Duty Efficient, Clean Combustion

DoE Program: DE-FC26-07NT43279

Program Duration: October 2007 to December 2010

Prepared by:

Donald W. Stanton, Ph.D.
Principal Investigator

Executive Summary

Cummins has successfully completed the *Light Duty Efficient Clean Combustion* (LDECC) cooperative program with DoE. This program was established in 2007 in support of the Department of Energy's Vehicles Technologies *Advanced Combustion and Emissions Control* initiative to remove critical barriers to the commercialization of advanced, high efficiency, emissions compliant internal combustion (IC) engines for light duty vehicles. 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. All of the following objectives were met with fuel efficiency improvement targets exceeded:

1. Improve light duty vehicle (5000 lb. test weight) fuel efficiency by 10.5% over today's state-of-the-art diesel engine on the FTP city drive cycle
2. Develop & design an advanced combustion system plus aftertreatment system that synergistically meets Tier 2 Bin 5 NOx and PM emissions standards while demonstrating the efficiency improvements.
3. Maintain power density comparable to that of current conventional engines for the applicable vehicle class.
4. Evaluate different fuel components and ensure combustion system compatibility with commercially available biofuels.

Key accomplishments include:

- A 25% improvement in fuel efficiency was achieved with the advanced LDECC engine equipped with a novel SCR aftertreatment system compared to the 10.5% target
- An 11% improvement in fuel efficiency was achieved with the advanced LDECC engine and <u>no</u> NOx aftertreamtent system
- Tier 2 Bin 5 and SFTP II emissions regulations were met with the advanced LDECC engine equipped with a novel SCR aftertreatment system
- Tier 2 Bin 5 emissions regulations were met with the advanced LDECC engine and no NOx aftertreatment, but SFTP II emissions regulations were not met for the US06 test cycle – Additional technical barriers exist for the no NOx aftertreatment engine
- Emissions and efficiency targets were reached with the use of biodiesel. A variety of biofuel feedstocks (soy, rapeseed, etc.) was investigated.
- The advanced LDECC engine with low temperature combustion was compatible with commercially available biofuels as evaluated by engine performance testing and not durability testing.
- The advanced LDECC engine equipped with a novel SCR aftertreatment system is the engine system architecture that is being further developed by the Cummins product development organization. Cost reduction and system robustness activities have been identified for future deployment.
- The new engine and aftertreatment component technologies are being developed by the Cummins Component Business units (e.g. fuel system, turbomachinery, aftertreatment, electronics, etc.) to ensure commercial viability and deployment
- Cummins has demonstrated that the technologies developed for this program are scalable across the complete light duty engine product offerings (2.8L to 6.7L engines)
- Key subsystems developed include – sequential two stage turbo, combustions system for low temperature combustion, novel SCR aftertreatment system with feedback control, and high pressure common rail fuel system

An important element of the success of this project was leveraging Cummins engine component technologies. 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 40% improvement in thermal efficiency for the engine plus aftertreatment system. The 40% improvement is in-line with the current light duty vehicle efficiency targets set by the 2010 DoE Vehicle Technologies MYPP and supported through co-operative projects such as the Cummins *Advanced Technology Powertrains for Light-Duty Vehicles (ATP-LD)* started in 2010.

Introduction

The Cummins Light Duty Efficient Clean Combustion (LDECC) program was established in 2007 in support of the Department of Energy's Vehicles Technologies *Advanced Combustion and Emissions Control* initiative to remove critical barriers to the commercialization of advanced, high efficiency, emissions compliant internal combustion (IC) engines for light duty vehicles (passenger cars, minivans, SUV's, and pickup trucks). Elimination of the technical barriers would enable light duty vehicles with dramatically higher fuel efficiency than current light duty vehicles powered by gasoline engines. In addition, the Cummins LDECC program supported one of the *FreedomCAR and Fuels* goals to enable low emissions, energy efficient vehicles to operate on clean hydrocarbon based fuels powered by IC engine powertrains. Achieving this goal would promote more fuel efficient use of petroleum based fuels, and concurrently, reduce the CO_2 greenhouse gases.

DoE's motivation to focus on the light duty automotive area of the transportation sector is due in part to the estimate that light duty vehicles account for over 60% of all transportation energy consumption in the United States as shown in Figure 1. Reducing petroleum fuel use and greenhouse gas emissions requires limiting the fuel consumed in light duty vehicle engines. Today nearly all light duty vehicles are powered by gasoline engines. Diesel engines have significant efficiency benefits over gasoline engines, and there are opportunities to further improve the diesel combustion system. If 30% of the light truck fleet in the United States were to transition to diesel engines, fuel consumption would be reduced by approximately 90 million barrels of oil per year. When fully implemented, developments achieved in this co-operative project would enable a 10% or greater efficiency improvement, increasing potential fuel savings to 119 million barrels per year. The fuel savings associated with this project would reduce greenhouse gas emissions by eliminating the production of 11 million metric tons of CO_2 per year.

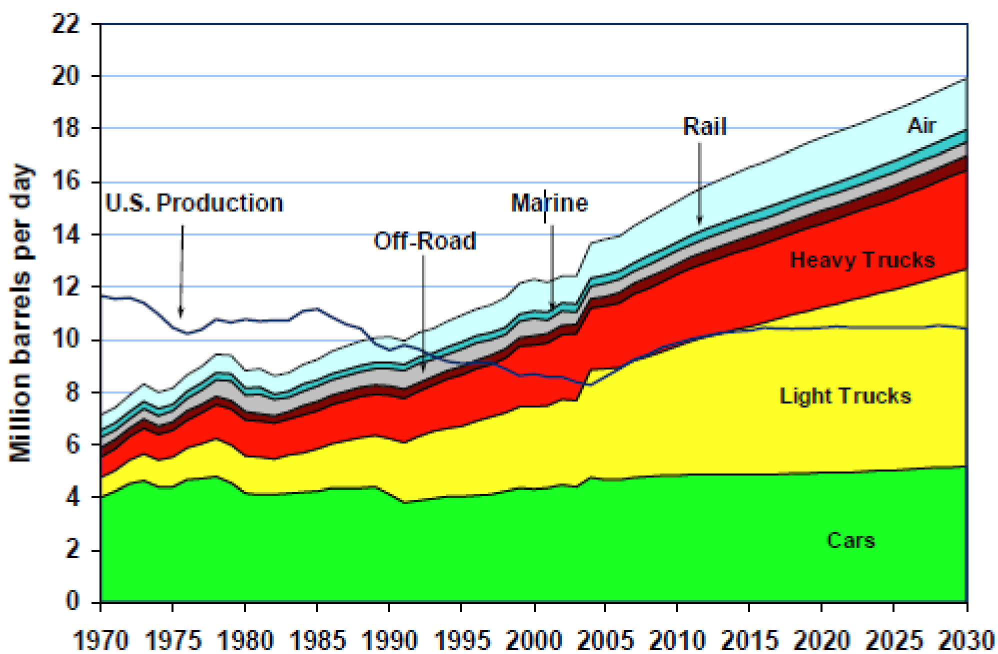


Figure 1: Oil use by transportation segment, from Transportation Energy Data Book: Edition 25 and projections from Annual Energy Outlook 2006.

The US EPA emissions standard for light duty vehicles 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 light duty vehicle fuel efficiency is being driven by increased energy costs as well as the regulation of greenhouse gases. An important element of the success of this project was 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 40% improvement in thermal efficiency for the engine plus aftertreatment system. The 40% improvement is in-line with the current light duty vehicle efficiency targets set by the 2010 DoE Vehicle Technologies MYPP and supported through co-operative projects such as *Advanced Technology Powertrains for Light-Duty Vehicles (ATP-LD)* started in 2010. The first step in developing high efficiency clean products has been supported by this DoE co-sponsored LDECC program. The objectives of the LDECC program were:

5. Improve light duty vehicle (5000 lb. test weight) fuel efficiency by 10.5% over today's state-of-the-art diesel engine on the FTP city drive cycle

6. Develop & design an advanced combustion system plus aftertreatment system that synergistically meets Tier 2 Bin 5 NOx and PM emissions standards while demonstrating the efficiency improvements.

7. Maintain power density comparable to that of current conventional engines for the applicable vehicle class.

8. Evaluate different fuel components and ensure combustion system compatibility with commercially available biofuels.

The LDECC project objectives 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 greater than 10.5% fuel efficiency improvement over current diesel engines and meeting the US EPA Tier 2 Bin 5 emissions levels were demonstrated in 2010 in accordance with the VTP plan shown in Table 1. In particular, for the light duty application, Cummins was able to exceed the 31% part-load brake thermal efficiency target with less than a 4% fuel economy penalty for emissions control via aftertreatment while meeting Tier 2 Bin 5 emissions regulations. Consequently, the LDECC program provided dramatically improved engine efficiency. 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.

Table 1a The status of conventional PFI engines and the best CIDI engines to date and the Combustion and Emission Control program technical goals for advanced, high-efficiency, hydrocarbon-fueled IC engines.

Characteristics	Units	Current Status		Goals by Fiscal Year		
		PFI [a]	CIDI [b]	2007	2010	2013
Engine peak brake thermal efficiency	%	30	41	43	45	46
Engine part-load brake thermal efficiency (2 bar BMEP at 1500 rpm)	%	20	27	29	31	32
Emission control fuel economy penalty [c, d]	%	--	--	<5	<4	<3
Powertrain cost [e, f]	$/kW	20	30	35	30	30
Projected vehicle emissions [g]	Tier 2	<Bin 10	Bin 10	Bin 5	Bin 5	Bin 5

[a] Based on current production port-fuel-injected (PFI) engines.
[b] Values representative of current CIDI engines with passive emission control.
[c] Fuel economy penalty over the combined Federal Test Procedure drive cycle resulting from emission control achieved either by use of LTC combustion strategies or aftertreatment systems. The fuel economy penalty is relative to CIDI engines that meet the 2003 emissions standards.
[d] The "fuel economy penalties" are given in terms of a percentage loss in fuel economy (*e.g.*, a percent reduction in miles per gallon). (If expressed in terms of a cycle average thermal efficiency loss, a 3 to 5% fuel economy loss is equivalent to a 1 to 2% thermal efficiency loss.)
[e] High-volume production: 500,000 units per year.
[f] Constant out-year cost reflect the goal of maintaining powertrain (engine, transmission, and emission control) system cost as the system complexity increases with time.
[g] Projected full-useful-life emissions for a passenger car/light truck using advanced petroleum-based fuels as measured over the Federal Test Procedure and other supplemental test procedures used for certification in those years.

Cummins LDECC Program Met or Exceeded Targets

Table 1: DoE program targets for IC engine efficiency improvements (Source: DoE Vehicle Technologies Multi-Year Program Plan, 2007).

2. Program Layout and Schedule

The LDECC program consisted of three budget periods (phases) as listed in Table 2. Budget Period I contained applied research and exploratory development where an analysis led approach was used to investigate a variety of combustion regimes for diesel engines that demonstrate low emissions and high efficiency. The analysis was verified using single cylinder engine testing. A variety of aftertreament architectures were analyzed based on the engine out emissions achievable with the advanced combustion systems.

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 high efficient, clean combustion. In addition, aftertreatment component technologies were developed to minimize the fuel economy penalty to meet US EPA Tier 2 Bin 5 emissions.

Budget Period III involved engineering development of a multi-cylinder engine with demonstration of 10.5% fuel efficiency improvement while meeting emissions compliance. Additional fuel efficiency improvements associated with integration of the engine and vehicle systems was implemented. 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 simulates a vehicle's dynamic system in order 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 2007 thru December 2008
  - Applied Research & Exploratory Development
  - $834K DoE Funding and $834K Cummins Funding
- Budget Period II – January 2009 – September 2009
  - Advanced Development
  - $735K DoE Funding and $735K Cummins Funding
- Budget Period III – October 2009 – November 2010
  - Engineering Development
  - $820K DoE Funding and $820K Cummins Funding

Table 2: Description and duration of program budget periods.

3. Program Baseline Performance and Targets

The engine used for this program was the Cummins 4.5L in-line 4 cylinder engine. This engine is one of several light duty diesel engines manufactured by Cummins for worldwide applications (see Figure 2). The technology developed for this engine can be scaled up to the 5L V8 and down to the 2.8L in-line 4 cylinder engine. These engines are suitable for light duty commercial and light duty personal use vehicles as well as off-highway applications. The scalability of the technologies to span the smaller displacement engines improves the commercial viability of the LDECC technologies while facilitating the global deployment of clean, high efficient diesel engines.

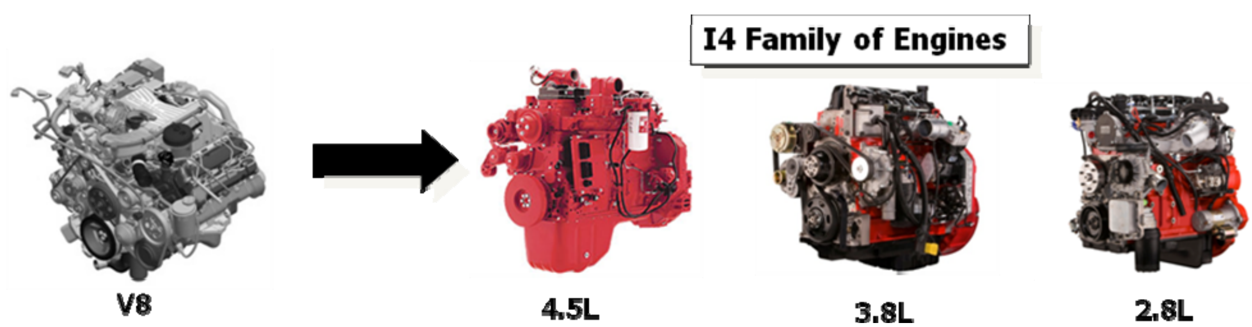


Figure 2: Cummins light duty diesel engines.

For the Cummins diesel engine, the baseline efficiency for a 5000 lb test weight vehicle over the FTP city drive cycle was estimated to be 20.3 mpg. The test vehicle was the Nissan Patrol SUV. The objective of this project was to achieve fuel economy equal to or greater than 22.4 mpg: a 10.5% efficiency improvement over the baseline diesel engine.

For comparison purposes, the Nissan Patrol SUV is marketed as the Infiniti QX56 in the US market. This vehicle has a 5.6L DOHC 32-valve V8 gasoline engine, which produces 315 hp at 5,200 rpm and 385 ft-lb of torque at 3,400 rpm. Based on a 5,500 lb test weight, the EPA fuel economy estimates are 13 city, 17 highway, and 14 combined mpg. The unreformed, unadjusted ratings are 15.4 city, 24.0 highway, and 18.4 combined mpg. The Cummins baseline diesel engine fuel economy of 20.3 mpg city is approximately 50% better than the gasoline engine.

Another objective of the LDECC program was to maintain the power density comparable to that of current conventional engines for the applicable vehicle class. This was achieved by setting the program power density goal of 56 hp/L with 250 hp at 3400 rpm. This type of engine performance places the LDECC 4.5L engine at the top end of the engine performance range for the small pickup, SUV, and cargo van as illustrated in Figure 3. Note, the torque target is limited by the torque capacity of the light duty vehicle driveline.

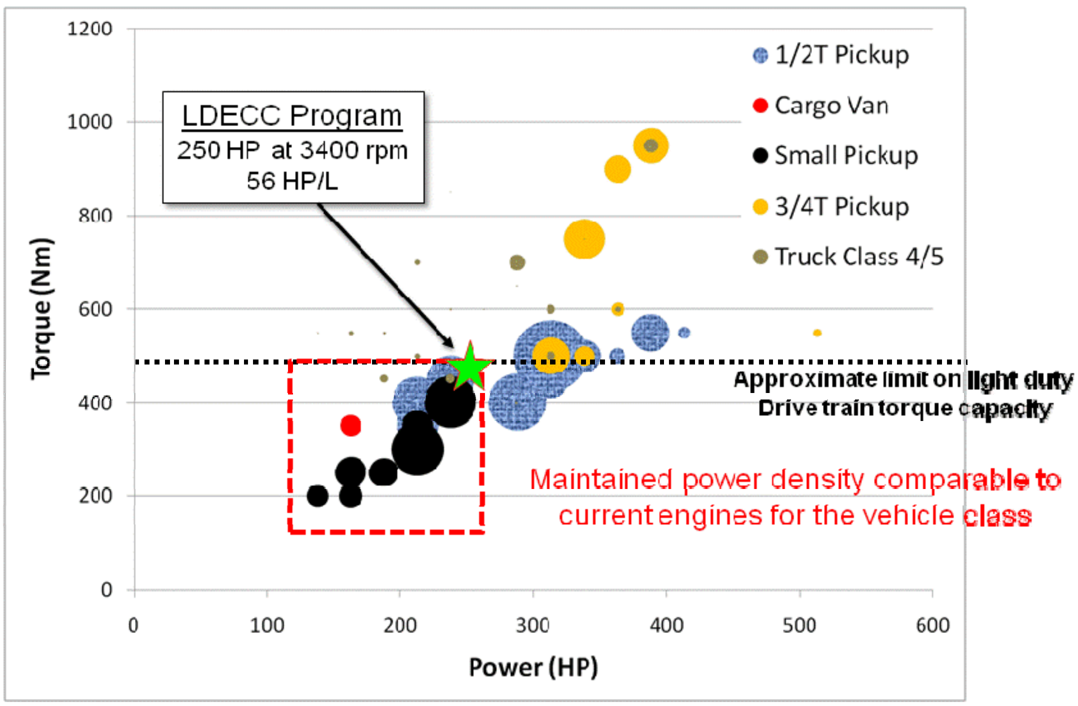


Figure 3: Comparison of the LDECC engine performance targets verses current state-of-the-art engines in the light duty vehicle class.

The Federal Test Procedure 75 (FTP75) is used for emission certification of light duty vehicles. It is comprised of a cold start phase, a transient phase, and a hot start phase. The emissions from each phase are collected separately in a Teflon bag, analyzed and expressed in g/mile. The weighting factors are 0.43 for the cold start, 1.0 for the transient phase and 0.57 for the hot start phase. In addition to this test, the requirement to meet the US06 and SC03 cycles makes the testing more representative of modern drive cycles. The US EPA Tier 2 standards limit vehicle emissions levels based on vehicle weight and require that the vehicle comply at 50,000 miles and meet a more relaxed standard at 120,000 miles as shown in Table 3. For the

LDECC program, Tier 2 Bin 5 emissions levels were established as the program emissions targets and are highlighted in Table 3.

Bin#	Intermediate life (5 years / 50,000 mi)					Full useful life (120k/150k mi)				
	NMOG	CO	NOx	PM	HCHO	NMOG	CO	NOx†	PM	HCHO
	Permanent Bins – all values in (g/mi)									
8	0.100 (0.125)	3.4	0.14	-	0.015	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	-	0.015	0.090	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	-	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	-	0.015	**0.090**	**4.2**	**0.07**	**0.01**	**0.018**
4	-	-	-	-	-	0.070	2.1	0.04	0.01	0.011
3	-	-	-	-	-	0.055	2.1	0.03	0.01	0.011
2	-	-	-	-	-	0.010	2.1	0.02	0.01	0.004
1	-	-	-	-	-	0.000	0.0	0.00	0.00	0.000

Table 3: US EPA light duty emissions requirements with Tier 2 Bin 5 highlighted as the LDECC program targets.

During the course of the LDECC program, new supplemental emissions regulations were established by the California Air Resource Board. The new emissions standards are referred to as SFTP II. For the Tier 2 Bin 5 FTP75 NOx level of 0.7 g/mi target for this program, the SFTP II NOx+NMHC (non-methane hydrocarbons) target is 0.09 g/mi as shown in Table 4. The SFTP II emissions levels are determined by a composite of the FTP75, US06, and SC03 drive cycles. With the advent of the new SFTP II regulations, Cummins had to significantly alter the scope of this project to include exploration of NOx aftertreatment technologies to achieve the fuel economy targets while meeting the Tier 2 Bin 5 FTP75 and the new SFTP II regulations. Cummins recommended this change at the 2009 Vehicle Technologies Annual Merit Review which was supported by peer reviewers and DoE.

Emissions Category	SFTP Weighted Standards (g/mi) NMHC + NOx					
	SULEV		ULEV			LEV
LEVIII FTP	FTP=.02	FTP=.03	FTP=.05	FTP=.07	FTP=.12	FTP=.16
LEVIII SFTP All LDVs (PC-LDT4)	0.040	0.050	0.070	0.090	0.140	0.180

LDECC Target = 0.08 g/mi NOx + NMHC for US06

Table 4: SFTP II emissions targets for the LDECC program.

4. Collaborations

Cummins collaborated with a combination of industry partners to successfully accomplish the program objectives. Two light duty vehicle manufacturers, Chrysler and Nissan (OEMs), provided assistance on the system level requirements of the engine and critical subsystems. Both OEMs supplied information on cooling capabilities, space claims, transmission capabilities and other information required to interface the engine system into the vehicle. Each of these subsystems required its own in-depth engineering analysis/design in the context of engine systems, heat rejection and vehicle integration.

British Petroleum (BP) provided consultation to the project in the area of diesel and biofuels. BP contributed in the following areas:

- Supplied fuels representative of commercially available diesel fuel
- Assisted in the interpretation of test results with any fuel related contributions
- Provided expertise on petroleum replacement energy options (biodiesel)
- Collaborated on the evaluation of fuel sensing technologies

5. Technical Approach

The combustion strategy employed for the LDECC program is illustrated in Figure 4. The mixed mode combustion strategy relied on extending the early PCCI (Premixed Charge Compression Ignition) combustion mode 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.

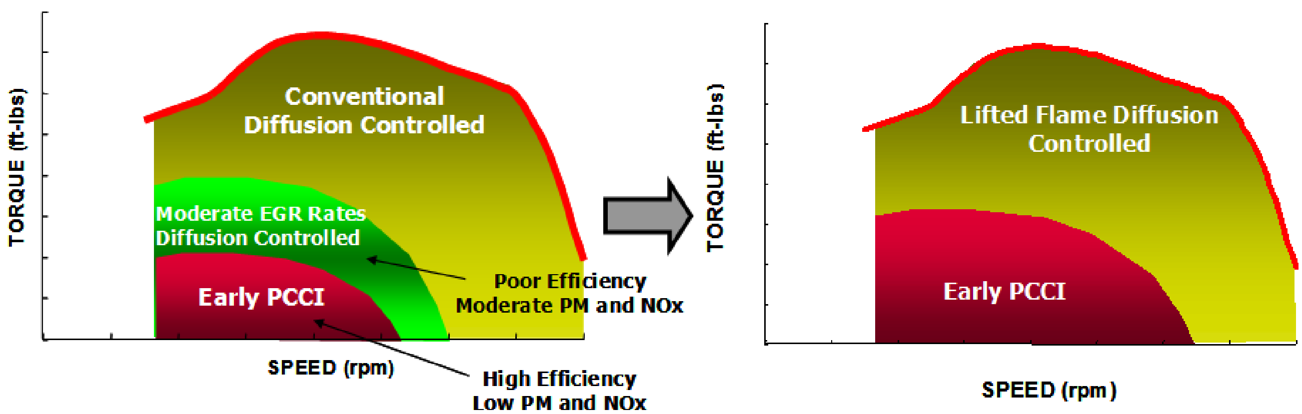


Figure 4: Combustion strategy to achieve low emissions, fuel efficient engine operation.

Early PCCI combustion is a form of low temperature combustion and is desirable due to the high thermal efficiency achievable as shown in Figure 5. 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.

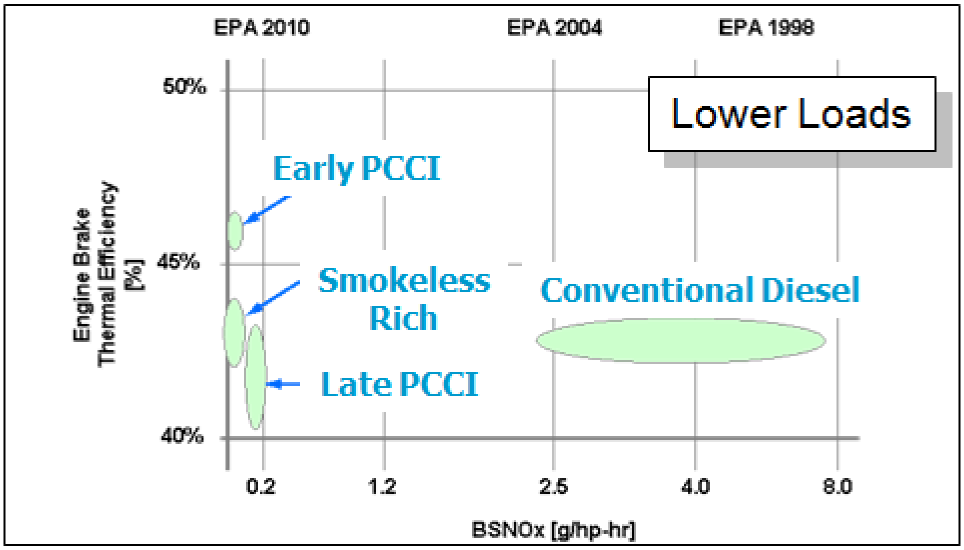


Figure 5: Efficiency associated with various combustion regimes.

At higher loads, lifted flame diffusion controlled combustion was used. An illustration of lifted diffusion controlled combustion is given in Figure 6. The goal of lifted diffusion controlled combustion was to create a lean region near the tip of the liquid fuel to suppress soot precursors that are normally formed in this region 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. The lifted flame established farther downstream from the liquid fuel. Creating the lifted flame allowed for 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.

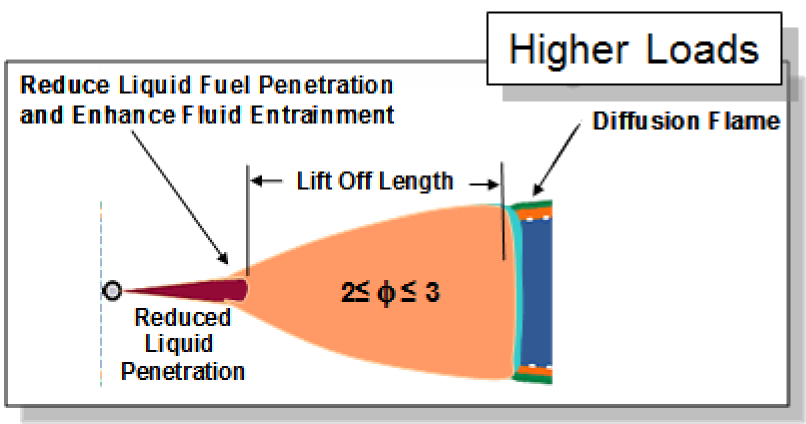


Figure 6: Schematic of lifted diffusion controlled combustion used at high engine load conditions.

Employing the various combustion regimes, Cummins developed a product strategy for light duty diesel powertrain systems. Engine architectures were created that allow system calibration to achieve a wide range of system out NOx compliance while providing opportunities to optimize the engine for reduced fuel consumption. A variety of diesel engine architectures were explored by Cummins as part of the LDECC program to meet US EPA NOx emissions regulations based on two primary strategies to control NOx: cooled EGR (no NOx aftertreatment) and selective catalytic reduction (SCR) NOx aftertreatment.

The program fuel efficiency roadmap, which leads to the 10.5% target, is shown in Figure 7 and applies to the two primary engine architectures to control NOx emissions (e.g. CEGR with no NOx aftertreatment and SCR NOx aftertreatment). The roadmap has been divided into five technical areas:

- closed cycle efficiency improvement
- expansion of early PCCI
- air handling system
- control system
- combustion optimization with advanced drive train design

For the first area, the closed cycle is defined as the portion of the cycle from intake valve closing to exhaust valve opening during which combustion occurs. The closed cycle efficiency improvement was achieved via two options. The first option was a new combustion system designed to tolerate high levels of CEGR. The CEGR was used to control NOx emissions as fuel injection timing was advanced for improved thermal efficiency without high levels of engine out particulate matter (PM). The second option explored was SCR NOx aftertreatment. Obtaining high SCR NOx conversion efficiency decoupled the NOx emissions control from the closed cycle efficiency of the engine. Combustion phasing was selected based on the location for maximum efficiency and not NOx reduction.

Additional fuel efficiency improvement shown in Figure 7 was gained from the expansion of early PCCI combustion. Expansion of the operating range of this form of low temperature combustion required development and optimization of a variety of systems including the combustion system, fuel system, air handling system, and control system. These systems were integrated to provide the desired intake manifold conditions and fuel injection characteristics to promote early PCCI combustion as the engine power output increased.

Advancements in the air handling component design further contributed to efficiency improvements shown in Figure 7. In addition, the control system development provided efficiency gains by managing the transition between modes of combustion shown in Figure 4. For the engine architecture with SCR aftertreatment, the control system was also extremely important for thermal management of the aftertreatment system and urea injection strategy.

Also shown in Figure 7 is the efficiency enhancement achieved through an optimization of the engine that includes a consideration of the complete driveline. A highly integrated powertrain system has achieved additional improvements in fuel economy by enabling further expansion of the early PCCI combustion region as well as improved operation of the NOx aftertreatment system. Cummins investigated powertrain optimization as part of the LDECC program using analysis and test cell activities. Note, the additional engine optimization with advanced driveline components was not part of the technology development required to reach the 10.5% efficiency target. Limited work in this area was included to provide guidance for future product development activities that would involve deployment of the LDECC technologies in vehicle demonstrations.

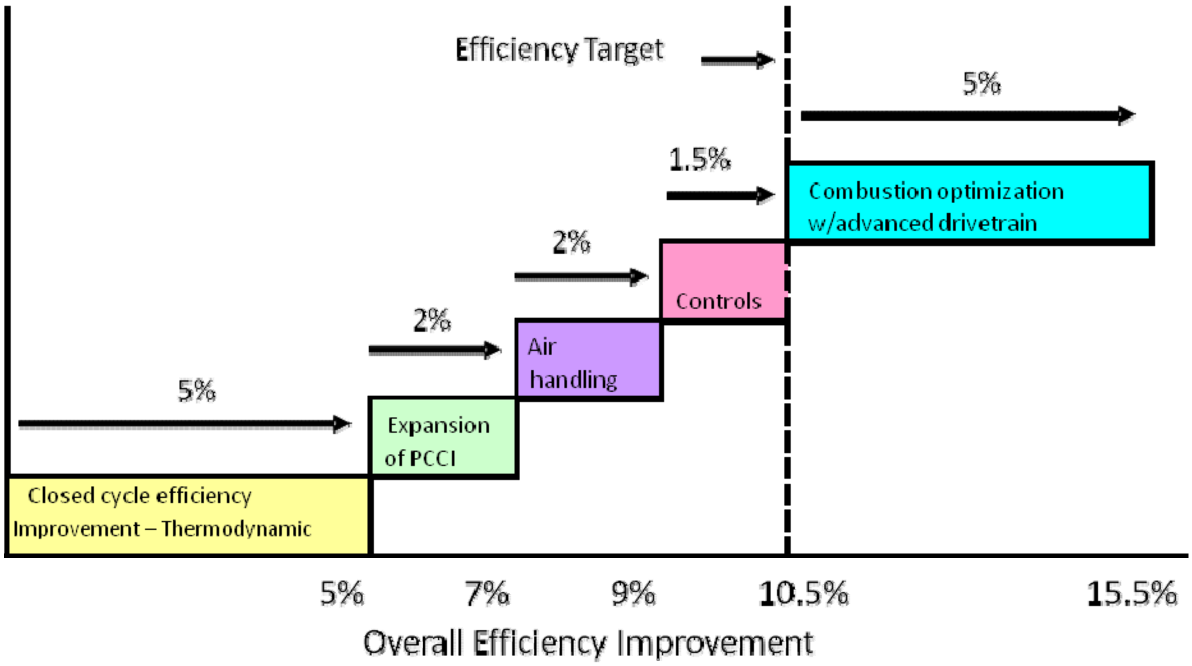


Figure 7: Fuel efficiency roadmap for the LDECC program.

6. Engine Development

A variety of light duty diesel engine architectures has been explored as part of the LDECC program to meet US EPA Tier 2 Bin 5 emissions based on two primary strategies to control NOx: cooled EGR (no NOx aftertreatment) and selective catalytic reduction (SCR). Table 4 and 5 list the various technologies developed as part of this program. The middle column of Tables 4 and 5 contains the specific technologies listed under each engine subsystem that were evaluated during Budget Period I (Applied Research and Exploratory Development). The right column contains technologies that were selected for further development in Budget Periods II and III while technologies that were not selected for future exploration are shown in the left column.

Deselected technologies during Budget Period I include:

- Full load HCCI (excessive cylinder pressure and poor controllability)
- Late PCCI combustion (poor fuel efficiency and poor controllability)
- Variable intake swirl (not enough benefit vs. the cost)
- Piezo actuated fuel system (provides reduced noise and lower unburned hydrocarbons but cost and durability are not competitive with a solenoid actuated fuel system)
- Electrically assisted turbo (extremely expensive with power electronics)
- Increased peak cylinder pressure capability (no benefit for light duty applications)
- Exhaust port liner for reduced heat loss (manufacturing process problems)
- Dual EGR coolers (packaging issues and excessive cost)
- Closed loop combustion (cost vs benefit tradeoff not acceptable)
- Fuel quality censor (market demand is not present)
- Dow Mullite, NGK, and Ibedin DPF Substrates (excessive pressure drop)

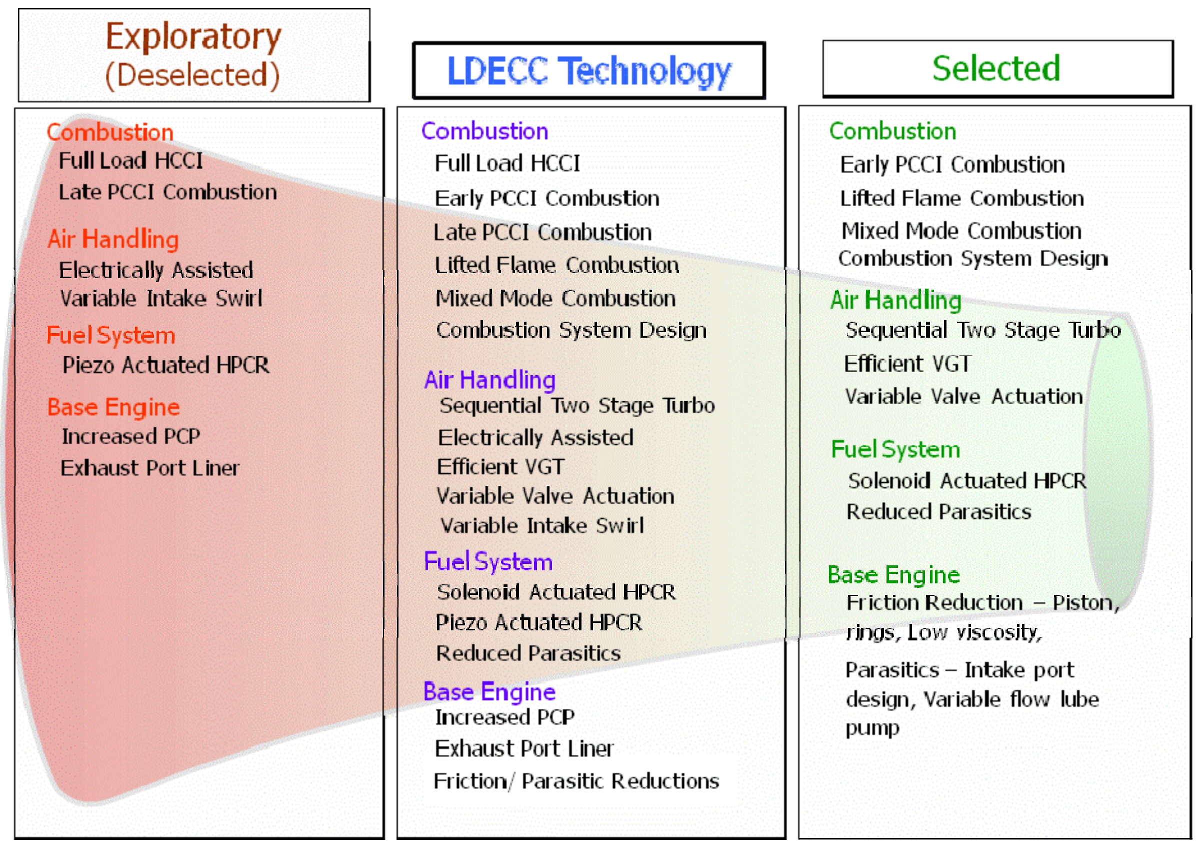


Table 4: Engine technologies evaluated during Budget Period I.

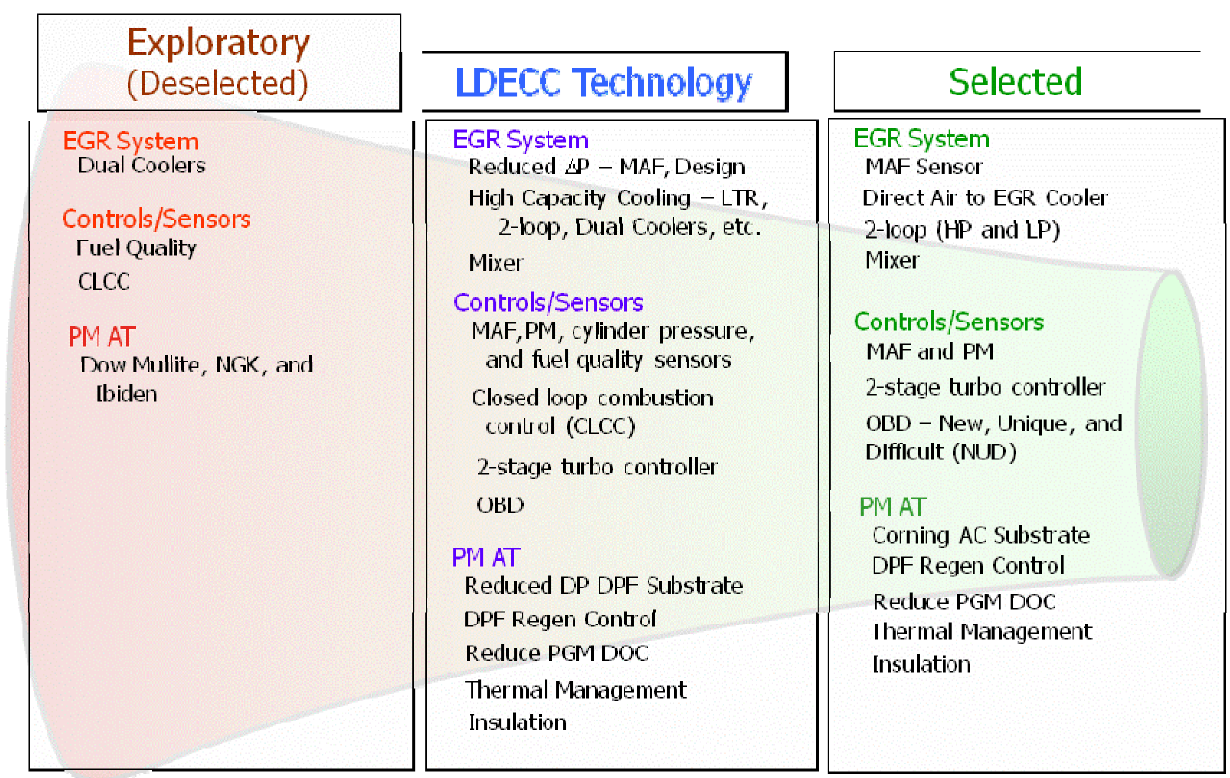


Table 5: Additional engine and aftertreatment technologies evaluated during Budget Period I.

7. LDECC Engine Architecture with SCR NOx Aftertreatment

During Budget Periods II and III, the technologies selected for further evaluation as shown in Tables 4 and 5 were integrated with SCR NOx aftertreatment. A schematic of the final SCR engine architecture is shown in Figure 8.The feature content includes:

- New combustion system design to tolerate high levels of CEGR
- Solenoid actuated HPCR fuel system with <1800 bar injection pressure
- Single loop, high pressure EGR system with EGR cooler bypass
- Sequential two stage turbo with a high pressure stage compressor bypass valve, a high pressure stage turbine bypass valve, and a low pressure stage turbine bypass valve
- Interstage diesel oxidation catalyst (DOC) between the low pressure and high pressure stages of the turbines
- Aftertreatment system with DOC+SCR+DPF configuration
- Cylinder deactivation for aftertreatment thermal management

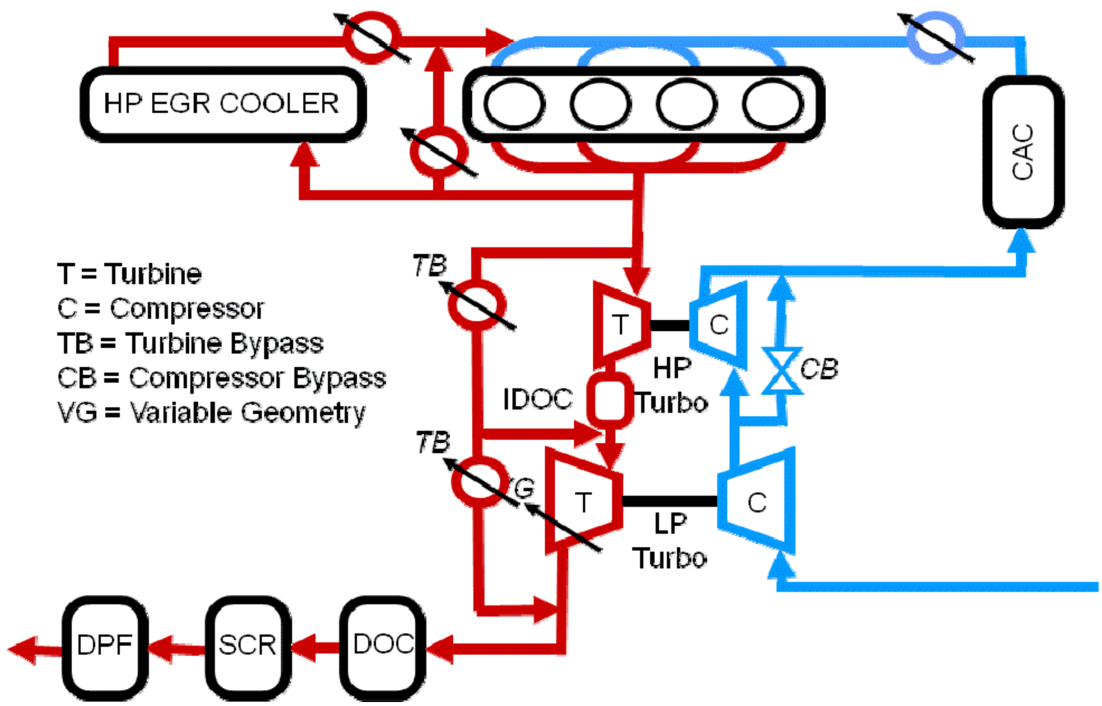


Figure 8: The LDECC engine architecture with SCR NOx aftertreatment.

Notable technologies there were **not** required for the SCR engine architecture included:

- Variable valve actuation (VVA)
- Piezo actuated fuel system
- Two loop EGR system (no low pressure loop EGR system needed)
- Variable intake swirl

- Cylinder pressure sensors for closed loop combustion control

The fuel economy results for this architecture are shown in Figure 9 for the FTP city drive cycle. The SCR architecture greatly exceeded the fuel economy improvement target of 10.5% while meeting the Tier 2 Bin 5 emissions standards. A 20.5% fuel economy improvement was achieved without cylinder deactivation, while a 25% fuel economy improvement was achieved with the use of cylinder deactivation. The cylinder deactivation improved the fuel economy by providing a better fuel efficient aftertreatment thermal management strategy. With less air flow moving through the engine due to cylinder deactivation, the exhaust temperature of the active cylinders increased faster, thus providing the energy to get the aftertreatment warm in less time. In either case, the SCR architecture as shown in Figure 8 doubled the targeted fuel economy improvement.

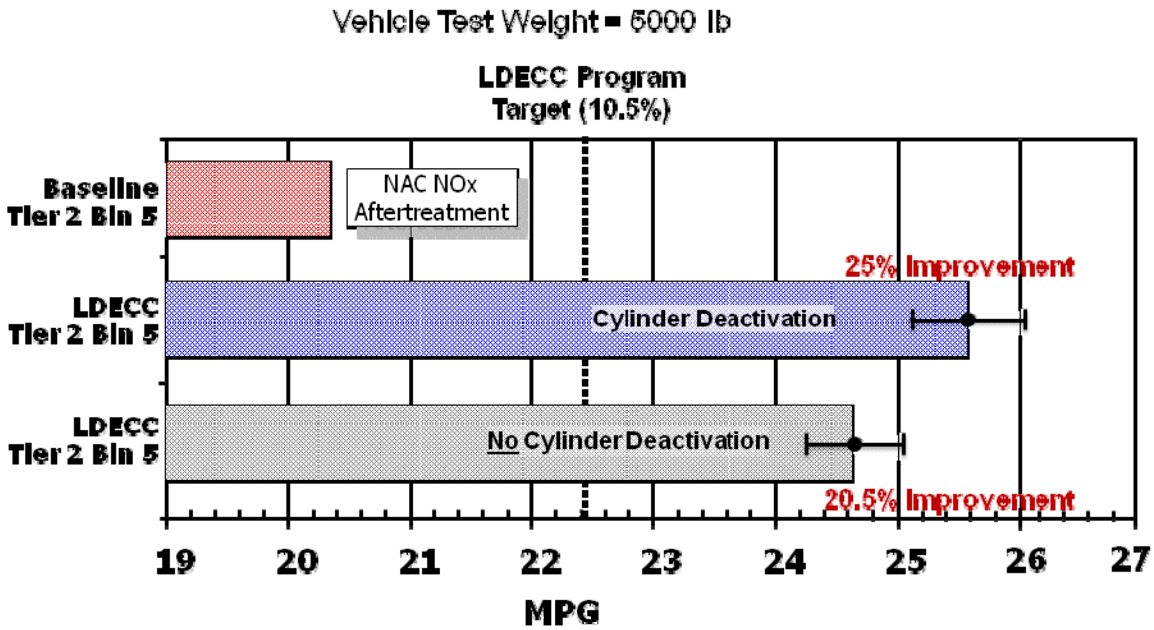
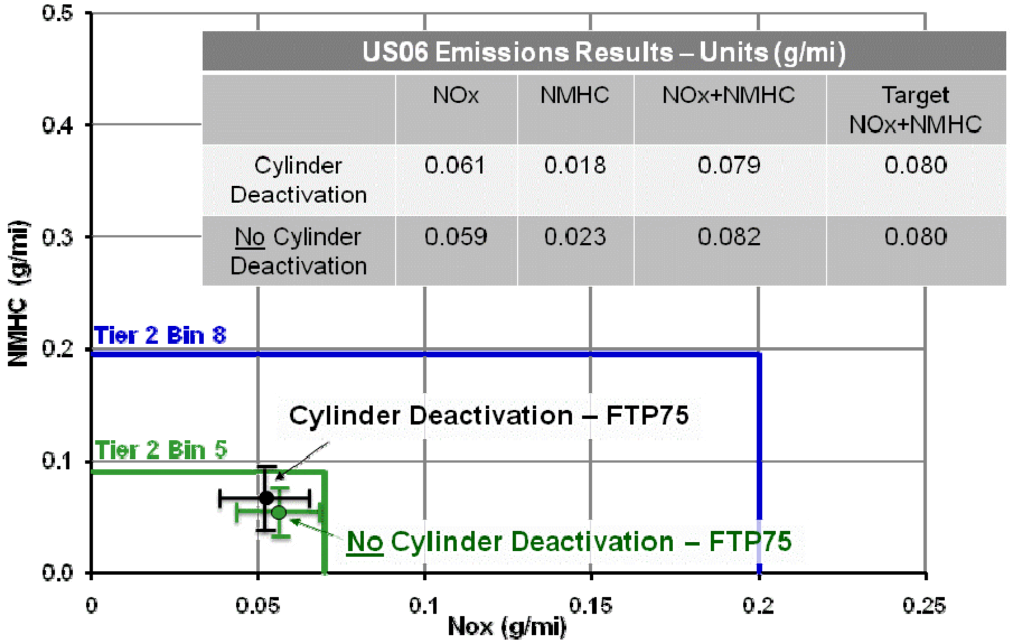


Figure 9: Fuel economy improvement for the LDECC engine architecture with SCR NOx aftertreatment. FTP city drive cycle.

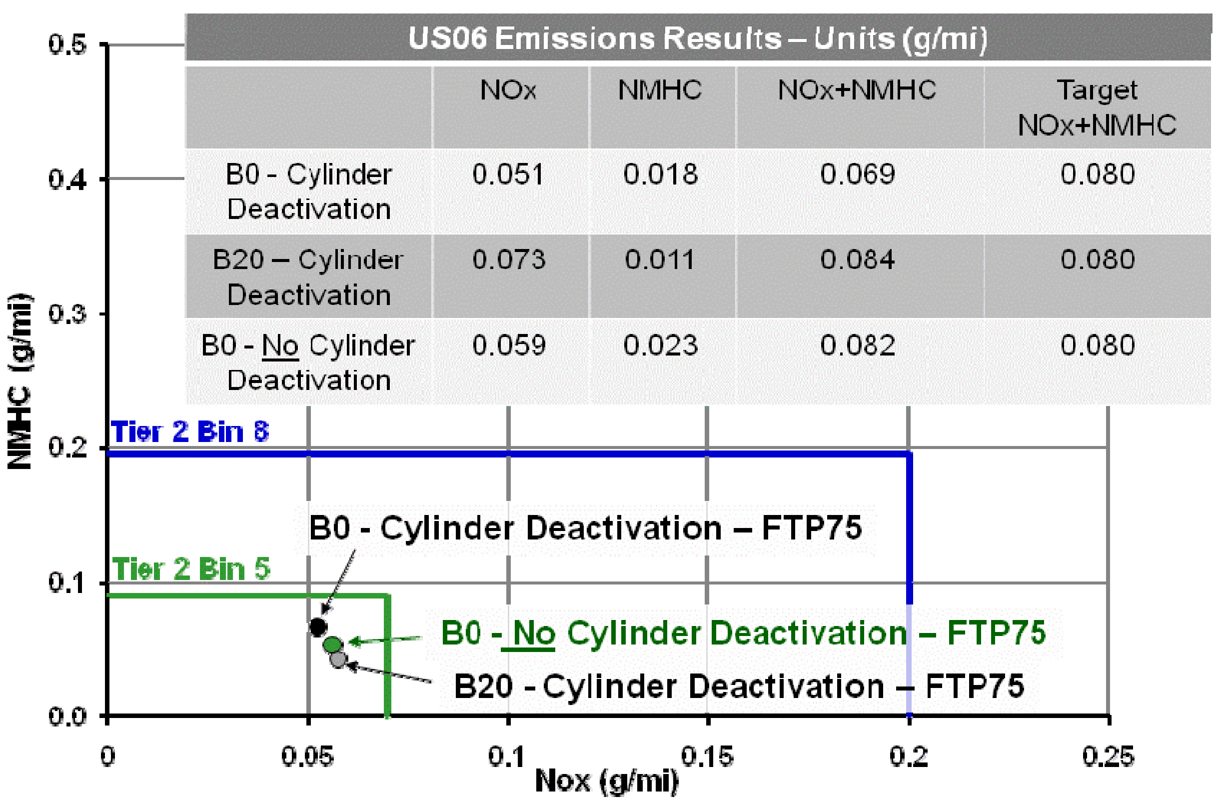
Compliance to Tier 2 Bin 5 emissions regulations were achieved with and without cylinder deactivation as shown in Figure 10. The error bars represent the 95% confidence interval for the measurements. Also shown in Figure 10 are the emissions results for the US06 test cycle which is part of the SFTP II emissions regulation as described in Section 3. The SCR architecture met the US06 emissions targets with and without cylinder deactivation.



US06 Emissions Results – Units (g/mi)				
	NOx	NMHC	NOx+NMHC	Target NOx+NMHC
Cylinder Deactivation	0.061	0.018	0.079	0.080
No Cylinder Deactivation	0.059	0.023	0.082	0.080

Figure 10: Tier 2 Bin 5 and US06 emissions results for the SCR engine architecture.

The emissions certification tests were repeated for the SCR architecture using a B20 biodiesel (a blend of 20% soy based biofuel and 80% diesel). All emissions standards were met with the biodiesel blend as shown in Figure 11.



US06 Emissions Results – Units (g/mi)				
	NOx	NMHC	NOx+NMHC	Target NOx+NMHC
B0 - Cylinder Deactivation	0.051	0.018	0.069	0.080
B20 – Cylinder Deactivation	0.073	0.011	0.084	0.080
B0 - No Cylinder Deactivation	0.059	0.023	0.082	0.080

Figure 11: Emissions results of the SCR engine architecture with B20 biodiesel blend.

7.1 Combustion System Design

The final combustion system was designed for the unique challenges of meeting stringent emissions and fuel consumption. A combustion system is defined as the piston bowl profile, fuel injector nozzle configuration, and intake swirl level associated with the design of the intake ports of the cylinder head. The system design was successful due to the ability to operating the engine using low temperature combustion with high levels of CEGR to lower NOx without excessive production of PM emissions. Computational Fluid Dynamics (CFD) was used to evaluate over 1500 different configurations to explore a wide design space before hardware was procured and tested. Three different combustion systems (configurations) are shown in Figure 12 at one selected engine operating condition where PCCI combustion is utilized. Each curve represents emissions results as CEGR rates are increased from right to left.

Three different combustion systems were tested on the multi-cylinder engine to validate the CFD analysis. From Figure 12, good agreement was achieved between the CFD analysis (right side) and experimental data (left side). The final combustion system design, denoted as configuration #3, provided low PM emissions as CEGR was increased. This was a significant achievement that PM emissions were maintained at low levels as CEGR was increased. Increasing levels of CEGR controlled NOx emissions as the fuel injection timing was advanced to find the optimal placement of the combustion event for best fuel efficiency. The final combustion system design was used for both engine architectures: cooled EGR (no NOx aftertreatment) and selective catalytic reduction (SCR).

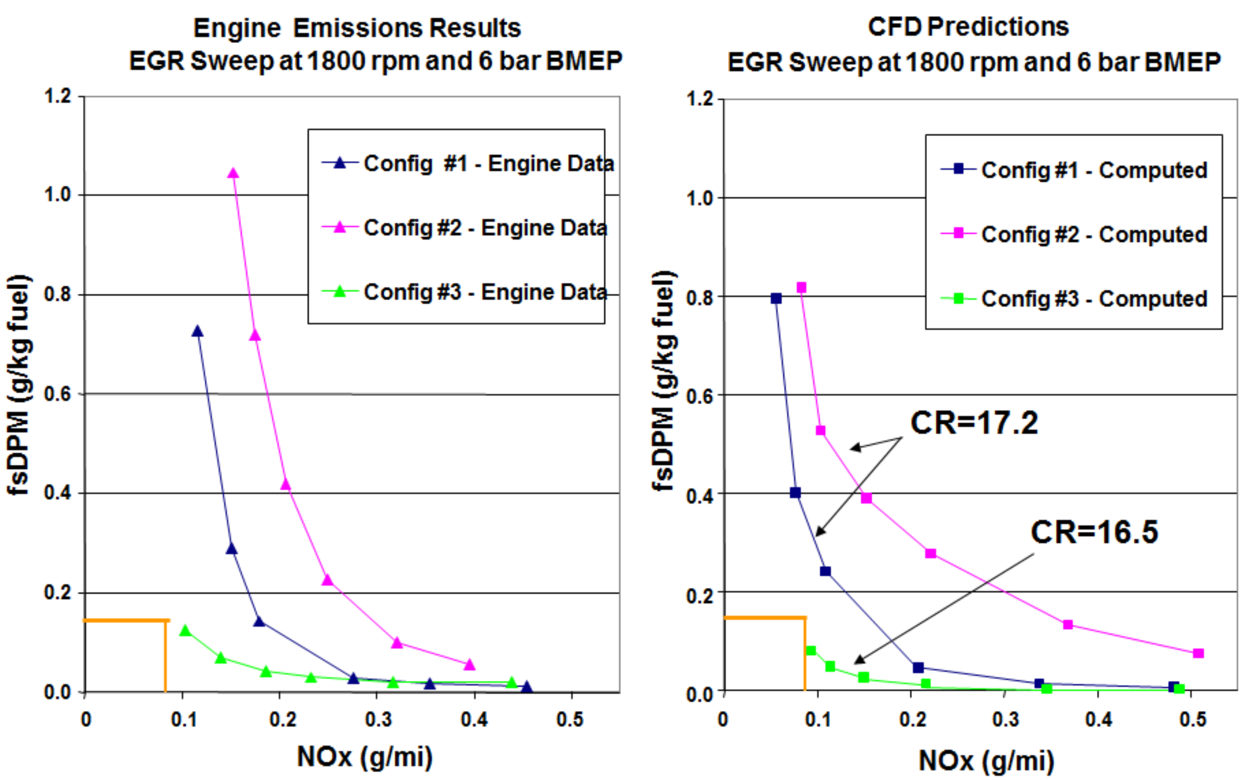


Figure 12: Emissions results for the new combustion system designs demonstrating the emissions robustness as EGR levels are increased.

7.2 Turbomachinery Design

A two stage turbo was developed for the LDECC engine. A schematic of the engine architecture with the two stage turbo is shown in Figure 8. Two turbines and two compressors are used. The turbo was designed to operate in a sequential manner. At low engine load (or low air flow), the exhaust gas moves through the high pressure (HP) turbine which is the smaller of the two turbines. The small turbine provides higher boosting of the air flow to provide sufficient fresh air flow into the engine while flowing high rates of CEGR at the low load operating conditions. High levels of CEGR and sufficient fresh air flow were required to achieve PCCI combustion over a large portion of the light duty drive cycle. Typically, the air then passes through the second turbine. The second turbine is larger and is referred to as the low pressure (LP) turbine. At the engine's low load operation, the LP turbine does not incur any significant pressure drop and does not provide any significant power for boosting. The majority of the power extraction (or boosting) is provided by the HP turbine.

At higher load (or higher air flow), the small HP turbine had to be by-passed. A HP stage turbine and compressor by-pass valve had to be incorporated into the two stage turbo as shown in Figure 13. Below is a list of the acronyms used in Figure 13 to describe the components.

- CBV – compressor by-pass valve for the HP stage compressor
- EBV – EGR by-pass valve
- HP turbo – high pressure turbo
- IDOC – interstage diesel oxidation catalyst
- LP turbo – low pressure turbo
- TBV – turbine by-pass valve for the HP stage turbine

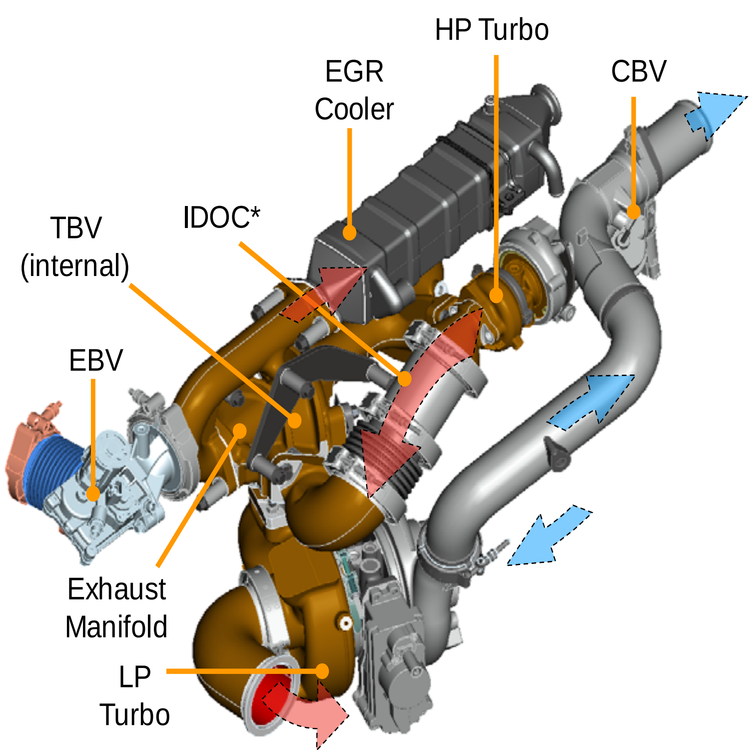


Figure 13: Schematic of the sequential two-stage turbo.

The sequential two stage turbo provided the right level of boosting at high load and low load operation of the engine. This turbo had the following requirements and challenges that were met with the final design:

- Compact design to fit into the vehicle
- Low pressure drop for the compact design
- Optimal sizing of the compressors and turbines
- Compressor and turbine by-pass valve designs for no leakage and low inertia for transient response

An important design feature of the turbo was the integration of a diesel oxidation catalyst between the LP and HP turbines. This DOC is referred to as the IDOC (interstage diesel oxidation catalyst). The IDOC provided the necessary reduction in unburned hydrocarbon (UHC) emissions that was required to meet the Tier 2 Bin 5 emissions regulation. By placing the IDOC between the LP and HP turbines, the thermal management of this device was enhanced. Shortly after engine start-up, the engine calibration was optimized to reach the desired operating temperature of the IDOC to reduce UHC as quickly as possible. The IDOC added an additional level of robustness for the early PCCI combustion regime. Under a wide variety of ambient conditions (temperature, pressure, and humidity), occasionally unacceptable levels of UHC and carbon monoxide were created from the engine. The IDOC reduced these emissions levels sufficiently.

The development and design of the sequential two stage turbo was a key component to allow low temperature combustion (early PCCI) operation over a large portion of the light duty drive cycles. The same turbo design was used for both engine architectures: cooled EGR (no NOx aftertreatment) and SCR NOx aftertreatment.

7.3 High NOx Conversion Efficiency SCR System

A new aftertreatment system was designed for the needs of this light duty application. Unlike a larger diesel engine used for heavy duty commercial vehicle applications, the light duty engine operates at lower loads with high levels of CEGR. Increasing and maintaining aftertreatment temperatures were significant challenges. In addition, the FTP75 emissions certification cycle for Tier 2 Bin 5 emissions has more emphasis on controlling cold start emissions during engine start-up and warm up periods.

To address these challenges, a novel, patent pending aftertreatment design was developed with a closed coupled catalyst (CCC) followed by an SCR NOx reduction catalyst, and a diesel particulate filter (DPF) (see Figure 8). This combination and order of aftertreatment components was chosen to provide fast warm up of the aftertreatment components to control emissions. The CCC was placed close to the turbo to minimize heat loss. The SCR catalyst was placed upstream of the DPF to provide hotter exhaust temperatures for warm up and to prevent accelerated aging of the SCR catalyst as the DPF was regenerated at high temperatures.

A closed loop feedback system was developed to specify the urea dosing for the SCR system to achieve extremely high NOx conversion efficiencies with reduced variation and low ammonia emissions from the tailpipe. The importance of the SCR system with feedback control is shown in Figure 14. To reach the aggressive fuel efficiency goal for this program, the Cummins engineering team targeted a FTP75 drive cycle NOx conversion efficiency of 90% with closed loop feedback control. This would result in an 8% improvement in fuel efficiency over the baseline engine due to the ability to separate the optimal placement of combustion from NOx emissions control. The closed loop feedback system provided the targeted conversion efficiency with acceptable variation compared to the open loop system as indicated by the error bars in Figure 14. This technology break-through was a major enabler for the success of this program.

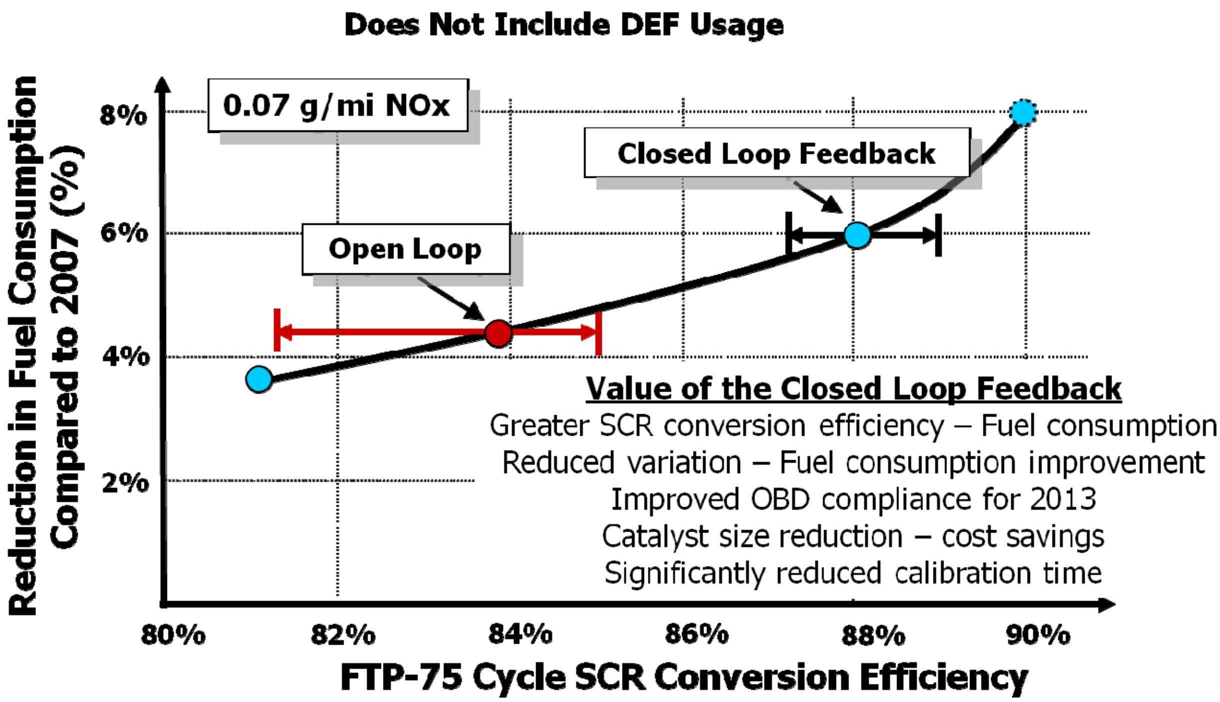


Figure 14: Performance of the LDECC SCR aftertreatment system.

7.4 Thermal Management of the Aftertreatment System

Once the performance capability of the novel SCR aftertreatment system was demonstrated, the calibration of the system became a major focus for Cummins. As demonstrated in Figure 14, the SCR aftertreatment system can provide high NOx conversion efficiency with reduced variation if the system can reach an acceptable operating temperature. Reaching the acceptable operating temperature is referred to as thermal management.

The challenge associated with thermal management is demonstrated in Figure 15. The FTP75 emissions cycle consists of a cold engine start-up phase followed by a highly transient phase with significant engine idling and concluding with a hot start phase with less engine idling. Also shown in Figure 15 are the catalyst components warm up requirements. During the first 60 seconds, the IDOC (interstage diesel oxidation catalyst placed between the two stages of the turbo) needs to light-off. This will create an exotherm to subsequently heat up the CCC (closed coupled DOC) and SCR catalyst within 120 seconds. The remaining portion of the drive cycle only requires active thermal management when the engine idles.

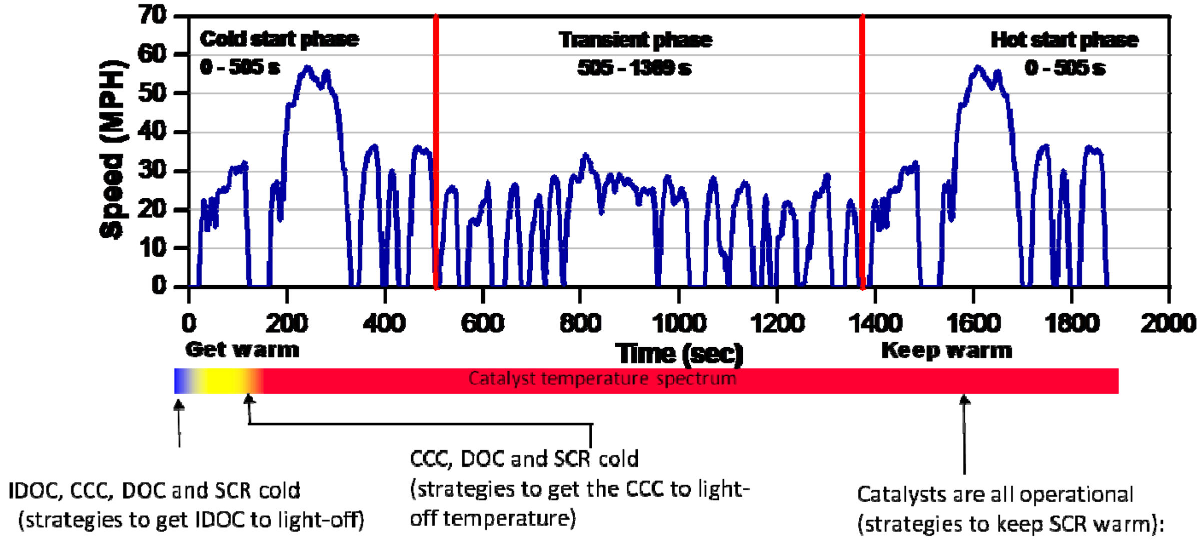


Figure 15: FTP75 emission cycle showing the various aftertreatment thermal management regions and the corresponding objectives that must be met for successful AT operation.

The following options were explored to provide thermal management:

- Intake Throttle
- EGR By-Pass Valve (EBV)
- Turbine By-Pass Valve (TBV)
- Low Pressure VGT
- Low Pressure VGT By-Pass Valve
- Idle Speed
- Fuel Injection Parameters – Late Cycle Fuel Injections
- Closed Couple Catalyst (CCC) Formulation
- Aftertreatment Insulation
- Cylinder Deactivation
- Fuel Reformer

The objective was to find the right combination of these aftertreatment thermal management levers that provided the desired operating temperature in the most fuel efficient manner. For example, a typical light duty diesel engine can use approximately 9% to 12% of the FTP75 drive cycle total fuel consumed for thermal management of the aftertreatment. The objective of this effort was to reduce the fuel consumption penalty from 8% - 12% to 4% - 5%.

This objective was achieved through a systematic assessment of the levers listed above. A summary of the specific devices that were chosen for each portion of the FTP75 drive cycle is shown in Figure 16. The red dots beside each technology indicate the specific technologies that were not chosen as part of the solution to achieve the desired temperature during that portion of the FT75 emissions drive cycle. The green dots indicate technologies that were successful.

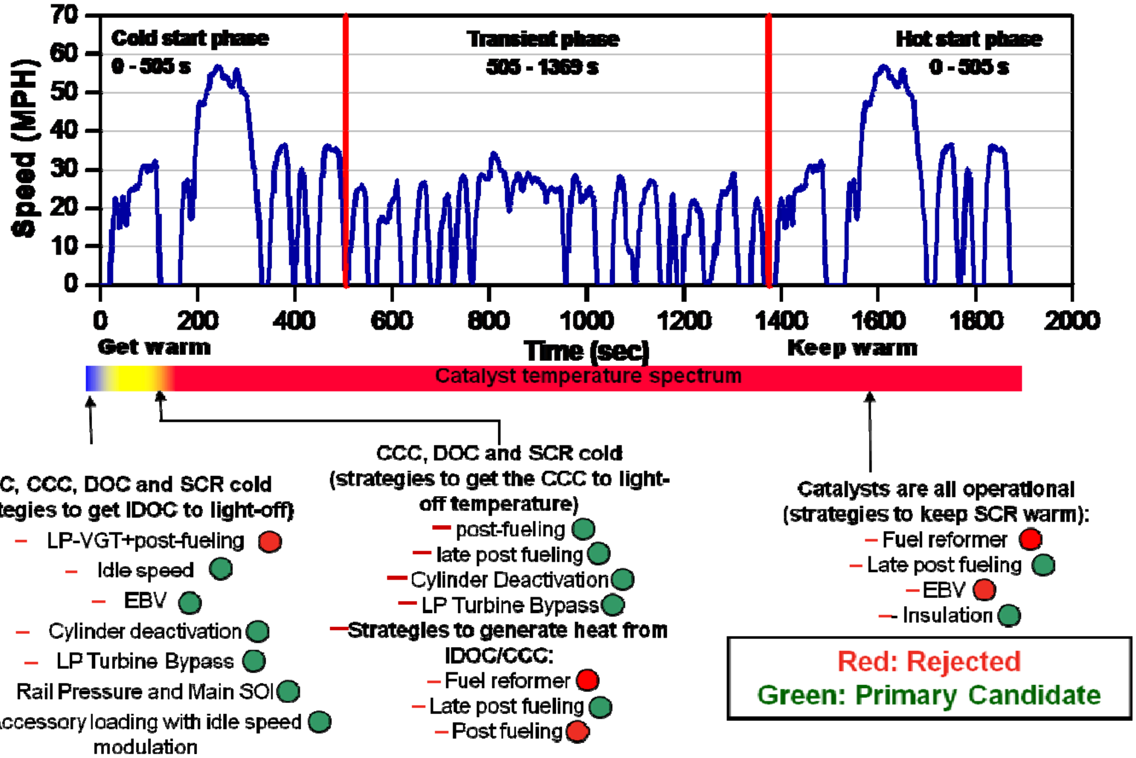


Figure 16: Summary of the thermal management levers used to achieve adequate aftertreatment temperatures to reach the NOx conversion efficiency targets.

A variety of solutions shown in Figure 16 were identified to provide fuel efficient thermal management of the aftertreatment system. An assessment of the commercial viability of each of the levers is shown in Table 6. Justification for the commercial viability is given. A few highlights from the assessment are:

- The sequential two stage turbo is a complex device that incorporates the various by-pass valves and is a key enabler for thermal management
- More work is required to reduce the cost and complexity of the turbo, but Cummins Turbo Technologies (CTT) is moving forward with the commercialization of this technology with cost reduction refinements scheduled
- Cylinder deactivation is an effective, fuel efficient thermal management technology, but it has significant technical challenges before production implementation is possible
- Fuel reformers need significant development to improve fuel efficiency, reduce cost, and reduce vehicle integration complexity

Cylinder deactivation can be done without the use of a complex variable valve actuation system (VVA). An increasing number of V gasoline engines use a form of cylinder deactivation in production. Unlike many gasoline engines that use cylinder deactivation to avoid using the intake throttle at low loads, the Cummins LDECC program demonstrated that cylinder deactivation is an effective thermal management lever for the aftertreatment system, but it is not ready to move into product development.

The biggest challenge is incorporating a form of cylinder deactivation for an in-line engine. The natural vibration, noise, and harshness of an in-line 4 cylinder engine can be excessive when various cylinders are deactivated. More research and development is required to implement cylinder deactivation for an in-line 4 cylinder engine. Cylinder deactivation was not required to meet the program objectives, but it is a technology that deserves further exploration and development for additional efficiency improvements.

Technology	Status	Commercial Viability Justification
Intake Throttle	Rejected	Poor fuel efficiency
EGR by-pass valve	Accepted	In current production
Turbine by-pass valve (high pressure stage)	Accepted	High viability – leakage is a watch out
Low Pressure Stage VGT	Rejected	Too expensive for benefit
Low pressure stage VGT by-pass valve	Accepted	High viability – leakage is a watch out
Idle speed increase	Accepted	In current production
Fuel injection parameters	Accepted	In current production
Closed coupled catalyst formulation	Accepted	High viability – refine precious metal loading
Aftertreatment insulation	Accepted	In current production
Cylinder deactivation	**Rejected**	**More research needed – technical issues to resolve**
Fuel reformer	Rejected	Low fuel efficiency and high cost

Table 6: Summary of the commercial viability of the aftertreatment thermal management technologies.

8. No NOx Aftertreatment Engine Architecture (In-Cylinder NOx Control)

The second type of engine architecture explored as part of the Cummins LDECC program involved the elimination of NOx aftertreatment. NOx emissions control was provided by much higher levels of CEGR compared to the SCR NOx aftertreatment architecture. The CEGR, no NOx aftertreatment architecture relied on extending the low temperature combustion regime to cover the emissions certification cycles as described in *Section 5 – Technical Approach*. The motivation for exploring this second architecture was to compare it to the SCR aftertreatment architecture to determine which architecture provides the most fuel efficiency and the best commercial viable solution.

A schematic of the final CEGR engine architecture with no NOx aftertreatment is shown in Figure 17. The feature content includes:

- New combustion system design to tolerate high levels of CEGR

- Piezo actuated HPCR fuel system with <2200 bar injection pressure
- Variable valve actuation
- Dual loop, high pressure EGR and low pressure EGR systems with EGR cooler bypass on the high pressure loop
- Sequential two stage turbo with a high pressure stage compressor bypass valve, a high pressure stage turbine bypass valve, and a low pressure stage turbine bypass valve
- Interstage diesel oxidation catalyst (DOC) between the low pressure and high pressure stages of the turbines
- Aftertreatment system with DOC+DPF to control UHC and PM emissions respectively.
- Cylinder deactivation for aftertreatment thermal management

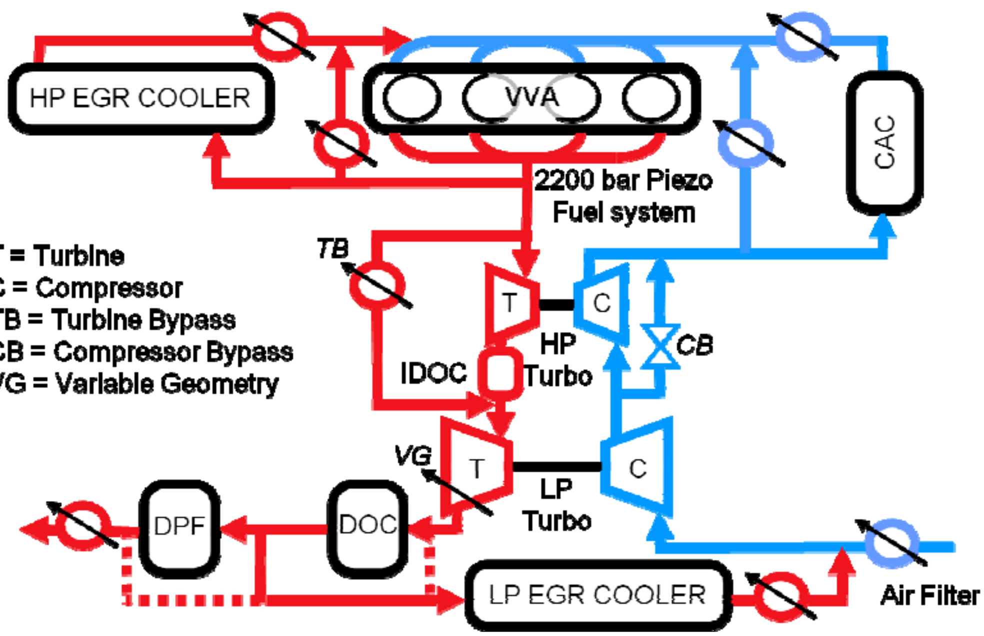


Figure 17: Engine architecture for CEGR and no NOx aftertreatment.

This engine architecture without SCR NOx aftertreatment (Figure 17) is considerably different than the SCR engine architecture shown in Figure 8. The fuel system chosen for the CEGR, no NOx aftertreatment architecture was the piezo actuated high pressure common rail (HPCR) fuel system. This fuel system provided greater control of the quantity and timing of the injection events compared to a solenoid actuated fuel system. Greater control of the fuel injection events allowed the fuel, fresh air, and CEGR to mixed to promote early PCCI combustion without excessive UHC, carbon monoxide, and PM emissions. The piezo fuel system provided more robustness in the low temperature combustion operation of the engine.

In addition, the maximum injection pressure of the piezo fuel system was increased from 1800 bar to 2200 bar. The additional injection pressure was used to control smoke levels (or PM emissions) as the engine transitioned to high load operation. Under the high load operation, the amount of fresh air that could be introduced into the cylinder was limited by the turbomachinery. The increased injection pressure was another engine calibration parameter to control excessive smoke.

Another technology employed on the CEGR, no NOx aftertreatment engine was VVA. The VVA design and procurement were the outcomes of the collaboration between Mechadyne LLC and Cummins and was used for multi-cylinder engine testing. The various functions, or capabilities, of the VVA system included in the design are summarized in Figure 18. The features outlined in green were determined to provide important benefits for this engine architecture. All these features contributed to the ability to expand the low temperature combustion regime, referred to as early PCCI, to encompass the majority of the light duty FTP75 emission cycle. The acronyms for the features listed in Figure 18 are:

- LIVC – late intake valve closing, known as Miller cycle
- I-EGR (2nd Bump) – internal EGR created from a 2nd movement of the intake valve
- I-EGR (EEVC) – internal EGR created from early exhaust valve closing
- Variable Swirl – modulation of the intake swirl motion
- Cylinder deactivation – do not actuate the intake and exhaust valves for a cylinder
- EEVO – exhaust valve opening
- EIVC – early intake valve closing

EEVO was not deemed to be a significant enabling feature. This feature would be more important for thermal management of NOx aftertreatment and not expanding the low temperature combustion operating regime. At the conclusion of this program, there were insufficient data to determine if cylinder deactivation and EIVC was a significant benefit for the CEGR, no NOx aftertreatment architecture and does require more exploration.

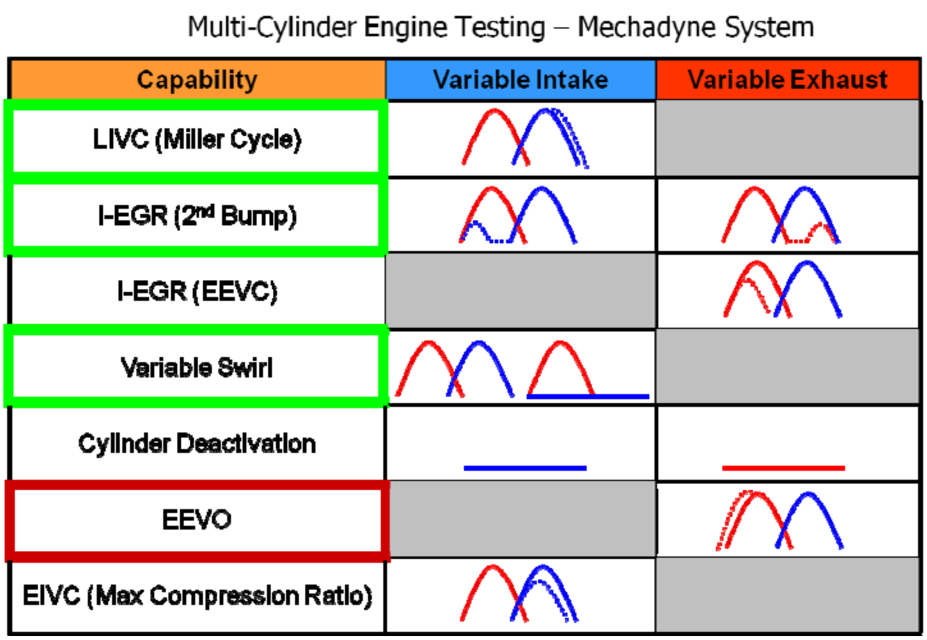


Figure 18: VVA functionality for the CEGR, no NOx aftertreatment engine architecture.

A dual loop, or two loop, EGR system was used to provide the necessary cooling of the high EGR rates required to meet the Tier 2 Bin 5 NOx emission level without the use of NOx aftertreatment. The high pressure loop moved EGR directly from the exhaust manifold to the intake manifold. The low pressure loop moved EGR downstream of the DPF catalyst to the inlet of the compressor.

The same combustion system, sequential two-stage turbo, and IDOC that was used on the SCR engine architecture was used on the CEGR, no NOx aftertreatment architecture. The fuel economy result for CEGR architecture is shown in Figure 19 for the FTP city drive cycle. Cummins successfully demonstrated an 11% fuel economy improvement verses the 10.5% target.

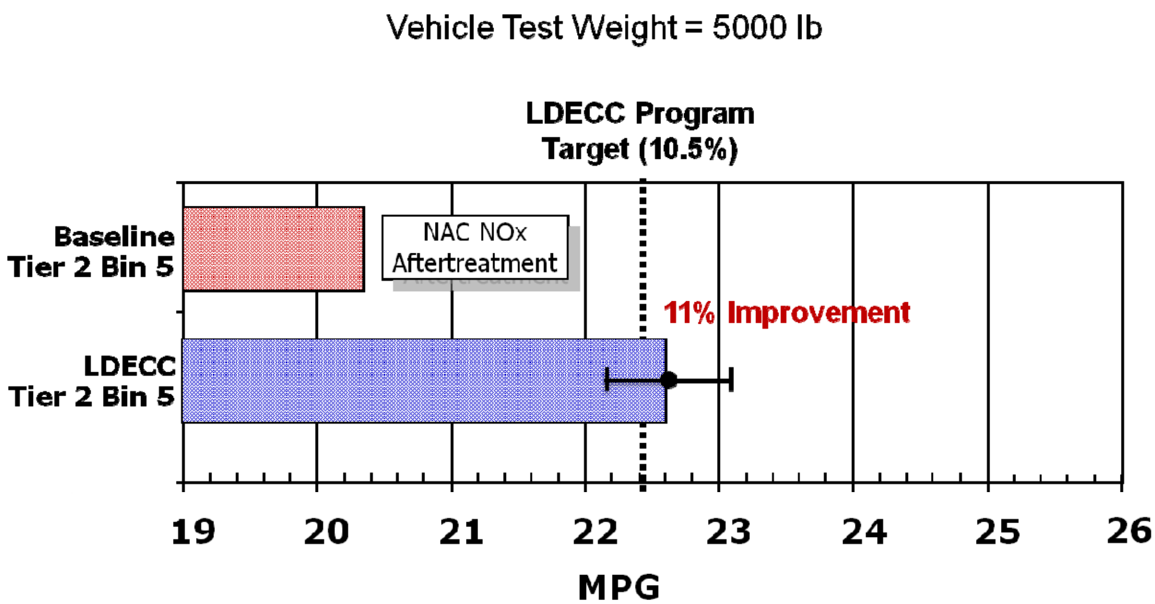


Figure 19: Fuel economy results for the CEGR, no NOx aftertreatment engine architecture.

The Tier 2 Bin 5 emissions were achieved as shown in Figure 20. The error bars represent the 95% confidence interval for the measurements. Additional work would be required to obtain robust compliance to emissions. This would typically be done during a product development program and was beyond the scope of the LDECC program. Also shown in Figure 20 are the emissions results for the US06 test cycle which is part of the SFTP II emissions regulation as described in Section 3. US06 NOx emissions could **not** be met without the use of NOx aftertreatment. Meeting the US06 NOx emissions was not part of the original scope of work for the LDECC program, but was an emissions change that occurred during the course of this program as explained in Section 3. In order to get a good assessment of the commercial viability of the CEGR, no NOx aftertreatment architecture, the US06 test was conducted. This remains a significant limitation of this architecture.

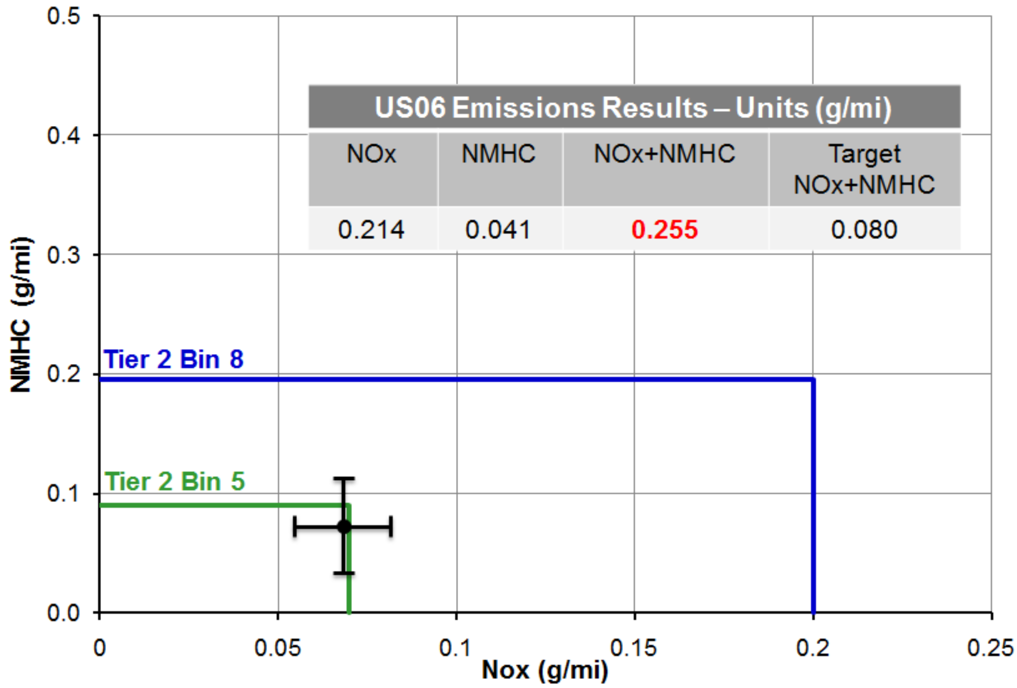


Figure 20: Emissions results for the CEGR, no NOx aftertreatment engine architecture.

9. Commercial Viability

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 LDECC technologies requires sound economics based on acceptable payback periods for the customer, acceptable capital investments, and acceptable return-on-investment.

To insure that the LDECC 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 LDECC technologies a value proposition with an acceptable customer payback. Based on the emissions and fuel economy results, Cummins is focusing on the SCR engine architecture as the best pathway forward. The technologies described in Section 7 - *LDECC Engine Architecture with SCR NOx Aftertreatment* enabled a 20% improvement in fuel economy thus exceeding the program fuel efficiency target of 10.5% as well as exceeding the Café standards for light duty vehicles in the 2013 to 2016 timeframe. As the technology transitions from research to production development, a few areas for further development include:

- Reducing the complexity of the turbomachinery
- Reduce cost of the aftertreatment system
    - Lower DOC precious metal loading

  - Reduce PGM loading of the AMOx (NH_3 slip catalyst)
  - Reduce volume of SCR catalyst
- Additional work required to refine formulation of DOCs
- Reduce thermal mass in the exhaust manifold, turbo, and exhaust piping

All the necessary component technologies (turbo, aftertreatment, combustion system, etc.) are being developed through the various Cummins Component Business units. This helps insure that the integrated solution can be deployed across the complete light duty engines manufactured worldwide by Cummins.

10. Summary

Cummins has successfully completed the *Light Duty Efficient Clean Combustion* (LDECC) cooperative program with DoE. This program was established in 2007 in support of the Department of Energy's Vehicles Technologies *Advanced Combustion and Emissions Control* initiative to remove critical barriers to the commercialization of advanced, high efficiency, emissions compliant internal combustion (IC) engines for light duty vehicles. 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. All of the following objectives were met with fuel efficiency improvement targets exceeded:

9. Improve light duty vehicle (5000 lb. test weight) fuel efficiency by 10.5% over today's state-of-the-art diesel engine on the FTP city drive cycle
10. Develop & design an advanced combustion system plus aftertreatment system that synergistically meets Tier 2 Bin 5 NOx and PM emissions standards while demonstrating the efficiency improvements.
11. Maintain power density comparable to that of current conventional engines for the applicable vehicle class.
12. Evaluate different fuel components and ensure combustion system compatibility with commercially available biofuels.

Key accomplishments include:

- A 25% improvement in fuel efficiency was achieved with the advanced LDECC engine equipped with a novel SCR aftertreatment system compared to the 10.5% target
- An 11% improvement in fuel efficiency was achieved with the advanced LDECC engine and <u>no</u> NOx aftertreamtent system
- Tier 2 Bin 5 and SFTP II emissions regulations were met with the advanced LDECC engine equipped with a novel SCR aftertreatment system
- Tier 2 Bin 5 emissions regulations were met with the advanced LDECC engine and no NOx aftertreatment, but SFTP II emissions regulations were not met for the US06 test cycle – Additional technical barriers exist for the no NOx aftertreatment engine
- Emissions and efficiency targets were reached with the use of biodiesel. A variety of biofuel feedstocks (soy, rapeseed, etc.) was investigated.
- The advanced LDECC engine with low temperature combustion was compatible with commercially available biofuels as evaluated by engine performance testing and not durability testing.
- The advanced LDECC engine equipped with a novel SCR aftertreatment system is the engine system architecture that is being further developed by the Cummins product development organization. Cost reduction and system robustness activities have been identified for future deployment.
- The new engine and aftertreatment component technologies are being developed by the Cummins Component Business units (e.g. fuel system, turbomachinery, aftertreatment, electronics, etc.) to ensure commercial viability and deployment
- Cummins has demonstrated that the technologies developed for this program are scalable across the complete light duty engine product offerings (2.8L to 6.7L engines)

- Key subsystems developed include – sequential two stage turbo, combustions system for low temperature combustion, novel SCR aftertreatment system with feedback control, and high pressure common rail fuel system

An important element of the success of this project was leveraging Cummins engine component technologies. 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 40% improvement in thermal efficiency for the engine plus aftertreatment system. The 40% improvement is in-line with the current light duty vehicle efficiency targets set by the 2010 DoE Vehicle Technologies MYPP and supported through co-operative projects such as the Cummins *Advanced Technology Powertrains for Light-Duty Vehicles (ATP-LD)* started in 2010.