Development of Technologies for a High Efficiency, Very Low Emission, Diesel Engine for Light Trucks and Sport Utility Vehicles

Final Technical Report

Reporting Period

04/01/1997 through 09/30/2005

Principal Author

John H Stang

Report Date

December 2005

Department of Energy
Cooperative Agreement
DE-FC05-97OR22533

Cummins Incorporated
PO Box 3005
Columbus, IN 47202-3005

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ABSTRACT

Cummins Inc., in partnership with the Department of Energy, has developed technology for a new highly efficient, very low emission, diesel engine for light trucks and sport utility vehicles. This work began in April 1997, and started with very aggressive goals for vehicles in the 5751 to 8500 pound GCW weight class. The primary program goals were as follows:

(1) EMISSIONS

NO_x = 0.50 g/mi
PM = 0.05 g/mi
CO = 2.8 g/mi
NMHC = 0.07 g/mi

California decided to issue new and even tougher LEV II light truck regulations late in 1999. EPA also issued its lower Tier 2 regulations late in 2000. The net result was that the targets for this diesel engine project were lowered, and these goals were eventually modified by the publication of Federal Tier 2 emission standards early in 2000 to the following:

NO_x = 0.07 g/mi
PM = 0.01 g/mi

(2) FUEL ECONOMY

The fuel economy goal was 50 percent MPG improvement (combined city/highway) over the 1997 gasoline powered light truck or sport utility vehicle in the vehicle class for which this diesel engine is being designed to replace. The goal for fuel economy remained at 50 percent MPG improvement, even with the emissions goal revisions.

(3) COOPERATIVE DEVELOPMENT

Regular design reviews of the engine program will be conducted with a vehicle manufacturer to insure that the concepts and design specifics are commercially feasible. (DaimlerChrysler has provided Cummins with this design review input.)

Cummins has essentially completed a demonstration of proof-of-principle for a diesel engine platform using advanced combustion and fuel system technologies. Cummins reported very early progress in this project, evidence that new diesel engine technology had been developed that demonstrated the feasibility of the above emissions goals. Emissions levels of NOx = 0.4 g/mi and PM = 0.06 g/mi were demonstrated for a 5250 lb. test weight vehicle with passive aftertreatment only. These results were achieved using the full chassis dynamometer FTP-75 test procedure that allowed compliance with the Tier 2 Interim Bin 10 Standards and would apply to vehicles in MY2004 through MY2007 timeframe.

In further technology development with active aftertreatment management, Cummins has been able to report that the emissions goals for the Tier 2 Bin 5 standards were met on an engine running the full FTP-75 test procedure. The fuel economy on the chassis tests was measured at over 59 percent MPG improvement over the gasoline engines that are offered in typical SUVs and light trucks. The above demonstration used only in-cylinder fueling for management of the aftertreatment system.

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EXECUTIVE SUMMARY

Cummins has studied requirements of the light truck automotive market in the United States and believes that a family of V6 and V8 engine systems can meet these needs. Both engine systems are very complex, since the combined requirements of a fuel-efficient automotive diesel engine as well as the performance and sociability requirements of a gasoline engine are needed. Over the project timeframe, Cummins has essentially completed concept development for many key aspects of light duty automotive diesel technologies required to deliver future engine and aftertreatment systems. The Cummins system concept consists of a V6 or V8 base diesel engine complete with an integrated exhaust aftertreatment system. These future diesel engine technologies, targeted for light duty automotive markets, have the potential to deliver cost effective diesel performance and to meet 2007 gasoline engine emissions requirements. Entire emissions aftertreatment regeneration with in-cylinder management only has been proven to be technically feasible, however these concepts will require a full product development cycle to meet market requirements for a fully developed, commercial product.

Future emission targets will be achieved only through application of technologies including a flexible fuel system with pressure and timing control, outstanding oil control and an optimized combustion system configuration. A critical requirement for future diesel engine systems is a fully integrated exhaust gas recirculation (EGR) system with flexible electronic control capability. In addition, in order to meet the customer expectations for the light duty vehicles, an appropriate design strategy must be developed for these systems that provide a fit to customer-specific vehicle requirements. This engine and aftertreatment system must also have a significant reduction in cost and weight compared to today's diesel engine and exhaust system to be competitive with the gasoline engine.

Research and engineering work at Cummins has been focused on developing low emission solutions and demonstrating these solutions in vehicle chassis testing. This program has emphasized realistic and cost conscience solutions, involving original equipment manufacturers and production intent suppliers. The program has been successful in demonstrating that tailpipe emissions standards are achievable for Tier 2 Bin 5 certified vehicles. In response to the overall objectives of this program, the Cummins project team can report the following technical progress.

- Developed a clean sheet design for an advanced technology-driven engine platform
- Demonstrated Tier 2 Bin 5 emissions capability through emission testing at sea level and at altitude with 150000-mile-equivalent aged catalyst
- Achieved active aftertreatment regeneration with closed-loop lambda controls
- Completed improved air handling algorithm development to control the variable nozzle turbocharger and to provide air handling compensation at altitude
- Improved intake port flow which has resulted in increased rated power (up to 15 HP or 5% improvement); swirl improvement has further resulted in enhanced mixing and reduced particulate generation.
- Applied variable nozzle turbocharger (VNT) technology which has resulted in a 25% reduction of engine-out NOx and PM while improving fuel economy by 4%; VNT technology has enabled both power and low-end torque increases, from 250 to 275 HP and 1250-RPM torque from 220 to 300 ft-lbs, respectively, and these results have been confirmed under steady state conditions and transient conditions following extensive study of the air handling controls algorithms
- Verified cold start at -30 C with unperceivable wait-to-start time using fast response glow plugs; results have demonstrated key-on to stable-idle within 8 seconds, comparable to today's gasoline engines
- Continued fuel system selection and evaluation process with focus on piezo technology as the system of choice to deliver optimized fuel timing and control (reduced variability)
- Used engine simulation modeling to identify rated power improvements with the implementation of increased valve overlap and increased rail pressure; this engine modeling work also allowed for sensitivity studies of rated power and back pressure to be completed
- Conducted combustion modeling work to identify two combustion bowl designs that have been experimentally verified; model improvements were shown to be needed to explain the differences between analysis and experimental results; these model improvements are the focus of future work
- Tested prototype vehicle system with an aged catalyst at sea level and altitude to demonstrate emission capability and to verify the need for control algorithms to compensate for altitude changes

- Documented the noise and vibration change through the vehicle demonstration as a result of moving between engine lean operation to rich regeneration operation; the magnitude of the measured values demonstrated transparency between the lean and rich operating conditions
- Demonstrated, through durability testing, poor piston scuff susceptibility and robustness; root cause investigations continued with focused areas being piston geometry, fuel system fueling inaccuracies or inconsistencies and control system inaccuracies
- Demonstrated power density of 60.4 WG, 64.3 VNT HP/liter on a 4.2 liter V6

The partnerships with the National Labs have been instrumental to enable continued research in areas of surface chemistry at PNNL, and engine-out emissions under rich conditions and chassis testing for vehicle emissions at ORNL. Continuing these partnerships will further promote our understanding of aftertreatment technologies for increased durability requirements and effectiveness of aftertreatment systems in vehicle applications.

ENGINE DESIGN PROPOSAL

Design of a new engine family that would carefully consider customer needs and trends was undertaken. An outline of this engine family vision is shown in Figure 1. Figure 2 shows a CAD model of the 4.2 liter V6 engine.

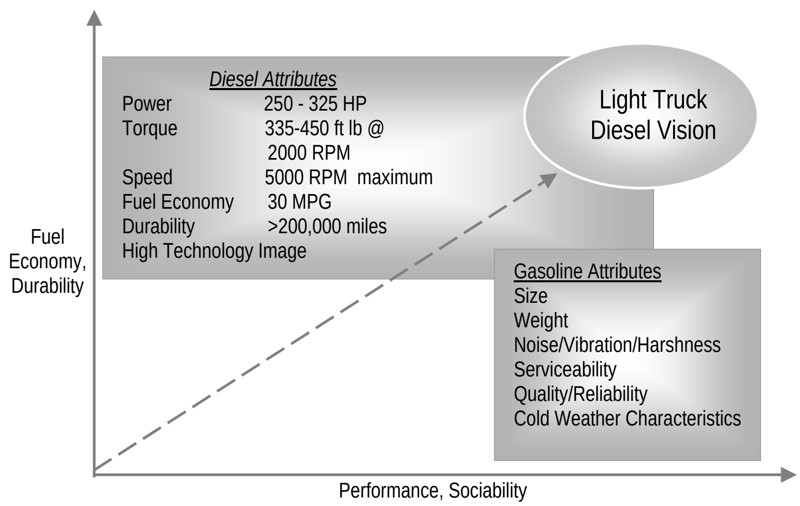

Figure 1. Light Truck Diesel Proposal

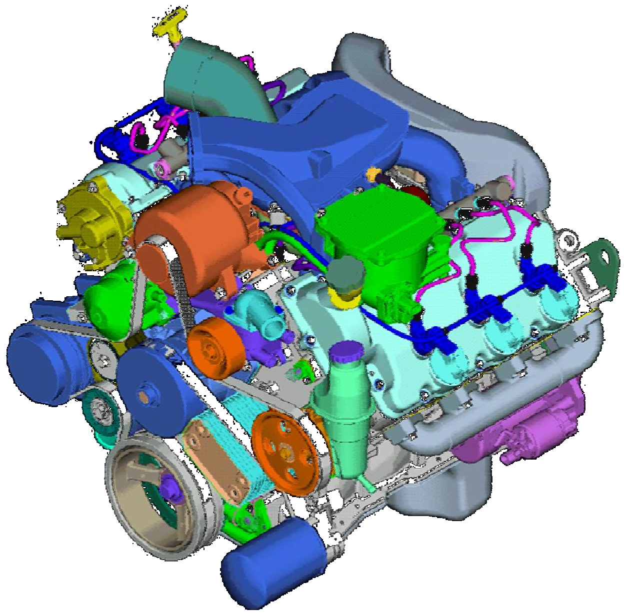

Figure 2. Light Truck Diesel Engine CAD Model

The engine family proposal combines the traditional best features of gasoline and diesel engines. The combined sociability strength of gasoline engines with diesel fuel economy and durability is a win-win scenario! Table 1 shows the relative ranking of high level customer wants used during product design.

Description	V6 Target Value	V8	Importance (10 High)
Customer Cost	Market Driven		10
Emissions	EPA Tier 2 & CA LEV II		9
Size (mm)	L641, W688, H755	L784, W688, H775	9
Noise	69 dBa Hood Open		8
Vibration	Equal to Gas		8
Fuel Economy	50% Better than Gas		8
Quality/Reliability	Equal to Gas		8
Rated Speed	4000 rpm (5000 maximum)		7
Useful Life	B10 > 325,000 km (200,000 mi)		7
Performance	Gasoline-Like		6
Displacement (liter)	4.2	5.6	6
Power, kW (Hp)	190 (250)	240 (325)	5
Torque Peak	Gasoline-Like Powertrain		5
N-m (ft-lb)	455 (335)	600 (440)	5
Warm-Up	75 C (167 F) Coolant in 10 min. @ -30 C (-22 F), road load		4
Serviceability	Equal to Gasoline		4
Cold Start	< 20 sec. @ -30 C (-22 F)		3
Weight, kg	275	320	3

Table 1. Light Truck Engine Proposal

The overall architecture and description of the major subsystems of the engine are described in Table 2 below.

Table 2. Light Truck Diesel Subsystem Description

Subsystem	Description
Configuration	90 deg Vee
Displacement	4.2L V6 5.6L V8
Bore and Stroke	94 x 100 mm
Valvetrain and drive	Single overhead cam, chain driven
Valve system	Four valves per cylinder with hydraulic lash adjustment
Fuel system	High pressure common rail
Control system	Full authority electronic
Emission control	Modulated cooled EGR with NOx adsorber and particulate filter
Aspiration	Variable geometry turbocharger
Intercooling	Vehicle mounted air to air cooler
Block	Cast iron
Head	High temperature aluminum alloy
Accessories	Common automotive gasoline components
Accessory drive	Single serpentine belt, self adjusting

The design philosophy behind the family of engines is to reduce engineering and manufacturing resource needs by capitalizing on common parts, modularity and integrated functions. The design features are similar to high-volume gasoline engines. The mounting location and layout for accessories are very similar to modern gasoline engines, allowing direct application of gasoline components at vehicle plant engine trim lines. The layout also provides opportunity for vehicle specific trim options without driving the need for major capital investment or retooling. Sourcing and manufacturing strategies have targeted high volume, automotive gasoline operations in order to facilitate the design philosophy.

The cylinder head module is a complete, tested sub-assembly and can be installed on the engine as a complete system as shown in Figure 3. The cylinder head incorporates an exhaust transfer passage at the rear; this passage transfers exhaust gas to a crossover manifold which mounts the turbocharger. The cylinder head incorporates the exhaust gas recirculation (EGR) cooler as a cast feature. The intake manifold integrates ports to transport the cooled EGR gas to the EGR valve. This integrated design eliminates the need for external plumbing, reduces weight and complexity, and reduces the potential for exhaust leaks.

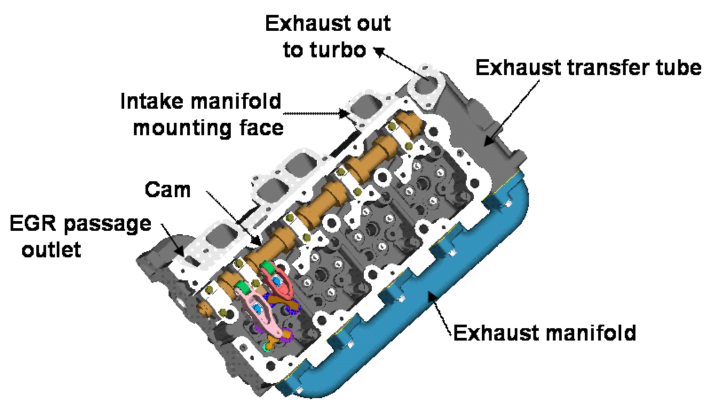

Figure 3. V8 Cylinder Head

The valve train incorporates hydraulic lash adjustment and a single overhead, chain-driven cam. The overhead system is designed to accommodate full overhead assembly, including valves, rockers, lash adjusters and cams, prior to cylinder head installation on the engine. Each V6 head is fastened with eight, M14 x 1.5, grade 12.9 cap screws; the V8 uses ten.

The cylinder block shown in Figure 4 is cast iron with a 4 bolt main cap. The cylinders are parent bored and require standard manufacturing processes used for diesel components. A bedplate connects the oil pan flange to the main bearing outer capscrew providing increase bulkhead rigidity and sideload reinforcement at a lower cost than side bolted main caps. The V6 engine design includes a primary balance shaft located in the center of the vee, below the fuel pump.

Figure 4. V6 Cylinder Block

The front cover module shown in Figure 5 is a complete sub-assembled module that is designed to mount both custom and common gasoline engine components. The front cover is common for the V6 and V8, incorporating the water pump, vacuum pump, oil filter and lube pump. An aluminum stacked plate oil cooler is mounted on the front cover face, bridging oil and water over the chain drive, as well as serving the basic function of oil cooling. The die cast front cover includes oil channels which transfer oil from the oil filter to oil cooler then to main oil rifle and vacuum pump. The front cover mounts all accessories without the use of brackets. All accessory mountings such as the alternator, A/C compressor, and power steering pump are integrated into the front cover casting, engine block, and/or cylinder head, thereby lowering cost and improving reliability.

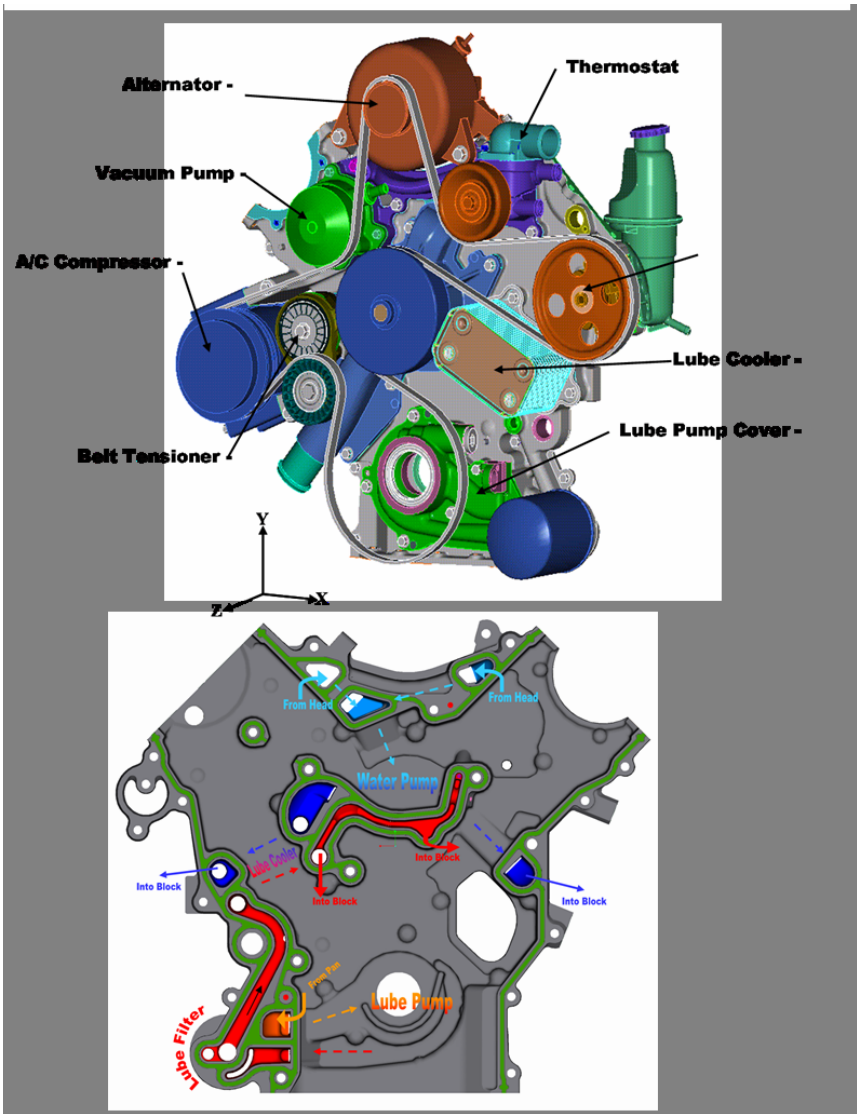

Figure 5. Front Cover and Accessory Drive System

The chain drive system on the front of the engine, shown in Figure 6, is a two-row bushed roller chain, with hydraulic tensioner. The chain drives both cams and the fuel pump in the center position. The left bank cam sprocket integrates the engine position signal generation teeth, while the right bank cam sprocket provides rotation for the centrifugal crankcase ventilation filter system.

Figure 6. Front Chain Drive System

The fuel system evaluated for this engine family is a high-pressure common rail system. The system includes injectors, high pressure rail and a high pressure pump. The pump and injectors are connected to the rail with high pressure tubing. The design of the engine is flexible, allowing for the application of all current commercially-available HPCR systems offered by major fuel system suppliers.

The fuel system requires a clean and water free source of fuel. A thermostatically controlled fuel heater is integrated into a common housing with the fuel filter/water separation element. The housing provides mounting for a water removal valve. The filter is located forward for easy access but rearward and inward of the block and head castings for compactness.

The family of engines is turbocharged using a single variable-geometry turbocharger. The turbocharger is located centrally in the valley of the V, as shown in Figure 7. The designs use the exhaust crossover as the mounting base. The post turbine exhaust down pipe, incorporating an oxidation catalyst, is designed to facilitate packaging space requirements of the vehicle application.

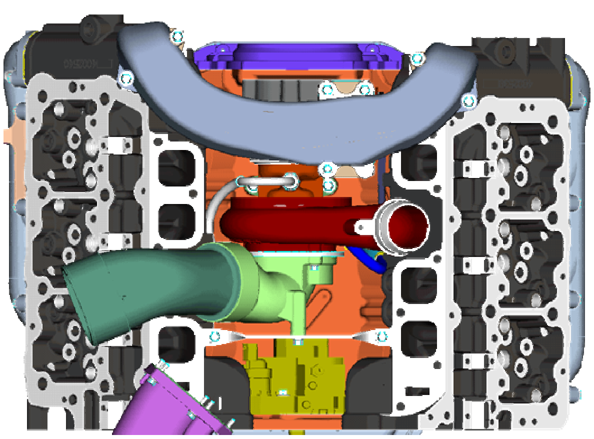

Figure 7. Turbocharger Location

ENGINE EMISSIONS DEVELOPMENT

Emissions development of the light truck diesel engine started with a benchmarking activity. A 4.2 L engine, sold in Europe for 1997 automotive use, was procured. The engine was brought to the U.S. and tested on the light duty EPA FTP cycle.

Testing of the above engine yielded emissions results of NOx=1.8 g/mi and PM= 0.30 g/mi at a test weight of 4900 lb. This was far from the standards that it would need to meet from 1997-2003 at a test weight below that of a target vehicle.

Development of the engine emissions control system then started, beginning with the removal of the stock, non-cooled, step-controlled EGR system, and VE-vintage fuel system. The air handling system including a Holset wastegated turbocharger and cooled, modulated EGR system. The results were very encouraging with Tier 1 requirements achieved at NOx=0.9 g/mi and PM= 0.06 g/mi.

Continued development and refinement of the combustion system and the control system showed significant progress toward the original DOE target. The results are shown in Figure 8.

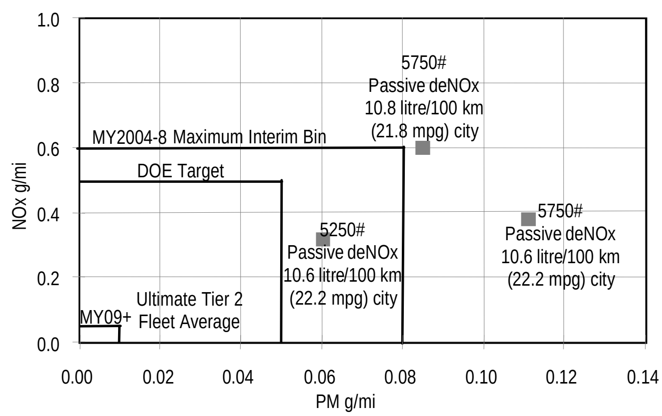

Figure 8. Interim Tier 2 Emissions Results with Development Mule

The first series of results are shown at test weight of 5750 lb. Two data points are presented: first NOx=0.6 g/mi and PM=0.09 g/mi; and second NOx=0.4 g/mi and PM=0.11 g/mi. Control system calibration was changed to establish the tradeoff.

A simple deNOx catalyst was used in all cases. The exact effectiveness was not measured but was generally estimated to be less than 10 percent.

The second test was run at a test weight of 5250 lb. This case more closely approximates typical medium weight SUV's. The results were very encouraging with NOx=0.4 g/mi and PM=0.06 g/mi. For comparison the Maximum Interim Bin for MY 2004-2008 is shown in Figure 8. The data clearly shows that the emissions are within the requirements through MY 2008.

Starting with this engine tune as baseline, further development toward the Tier 2 goal focused on the aftertreatment system. For reference, the ultimate Tier 2 fleet average requirement is NOx=0.07 g/mi and PM=0.01 g/mi .

Demonstration of the ultimate Tier 2 goal was achieved through the use of advanced aftertreatment devices. NOx emissions were reduced with the use of a NOx adsorber and particulate emissions removed with a downstream soot filter. Work toward this goal was done in a two stage process; proof of concept and reduction to practical use.

The proof of concept stage consisted of addition of the aftertreatment devices (NAC, DPF), reductant dosing system, and related controls. Diesel fuel was used as the reducing agent. Initial testing included reductant introduced after the turbine, external to the base engine.

This initial demonstration did not include the effects of deterioration or contamination due to sulfur poisoning. No attempt was made to desulfate during any of the prescribed driving cycles. Therefore, these devices required the use of ultra low sulfur fuel in order to maintain performance over the several documented cycles.

The laboratory setup consisted of a non-mobile engine controller, coupled with all other systems, in standard component locations. The emission measurement equipment used had the following accuracy (considering all components): NOx +/- 0.025 g/mi and PM +/- 0.005 g/mi.

The fuel used in this demonstration was a petroleum-based Phillips, ultra low sulfur diesel, with measured sulfur content of less than 4 ppm. The fuel had a cetane number of 48.

Results presented are from chassis dynamometer testing using the Urban Dynamometer Drive Schedule (UDDS). No attempt was made to run a true FTP-75 with a cold bag. A test sequence consisting of a 505 sec (bag 1) cycle, followed by three sets of back-to-back Highway-Fuel-Economy-Test-then-UDDS cycles was used. The multiple cycles were used to ensure that regeneration of both devices, not just accumulation, was actually occurring. The results are shown in Figure 9, with values as low as NOx = 0.05 g/mi and PM = 0.005 g/mi measured.

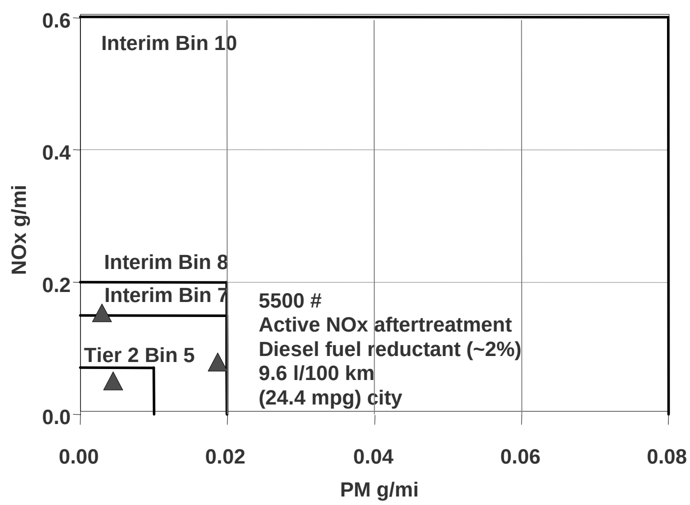

Figure 9. Initial NOx Adsorber Emissions Results

The NOx adsorber did not appear to show any accumulation effect in that performance did not deteriorate during the entire test sequence of over 50 miles. In fact, the highest NOx emissions were recorded during the second cycle of the test.

Likewise, the soot filter appeared to regenerate during this test sequence. Measurements indicate the back pressure stabilized and recovered at least once during the sequence.

Following the proof of concept demonstration, a program was put in place to take the learning from the mule engine and laboratory set up to a practical system that could be applied to a running vehicle with a concept engine.

For the practical system to be cost effective and fit the intended vehicle application, in-cylinder injections were used for delivering the reductant. The common rail fuel system approach was ideal for this situation.

The requirements to meet all aspects for certification meant inclusion of warm up, de-NOx, desulfation, and active PM filter control. All of these functions were coded into the on-board engine control module. In-cylinder dosing was used in developing a practical application for the aftertreatment technology to reach Tier 2 Bin 5.

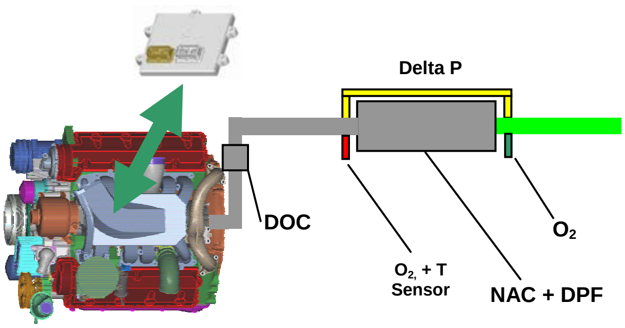

Figure 10. Engine and Aftertreatment Setup

A vehicle with an electronic automatic transmission was procured and fitted with a concept V6 engine and aftertreatment system, shown diagrammatically in Figure 10. The vehicle was tested over the FTP-75, including the cold cycle. The testing was completed with the aftertreatment system in the new and de-greened state, as well as after 150,000 mile equivalent aging. The 150,000 mile test was completed at Environment Test Labs, in Aurora, CO at 5400 ft. altitude. The results for the FTP-75 are listed in Table 3.

The vehicle testing was conducted at 5000 lb inertia test weight, with a 50 mph power setting of 14.4 hp. These values were chosen to represent a medium sized SUV of current market availability in the United States.

Test	CO [g/mi]	CO2 [g/mi]	NOx [g/mi]	NMHC [g/mi]	FE [mpg]	PM [g/mi]
FTP-75 FUL limits	4.2	-	0.07	0.090	-	0.01
FTP-75	0.399	480.27	0.033	0.089	21.12	0.006
FTP-75	0.367	491.67	0.038	0.056	20.32	-
	0.241	519.18	0.074	0.043	19.16	-
bag 1	0.971	547.87	0.141	0.222	18.47	0.008
	1.051	583.44	0.181	0.269	17.08	-
	1.121	578.14	0.243	0.207	17.15	-
bag 2	0.272	475.03	0.003	0.057	21.37	0.004
	0.200	475.27	0.000	0.000	21.04	-
	0.060	517.34	0.002	0.001	19.24	-
bag 3	0.207	439.17	0.009	0.049	23.11	0.007
	0.166	453.40	0.003	0.000	22.05	-
	0.018	478.05	0.080	0.000	20.83	-

Table 3. Emissions Test Results for Practical System

FUEL ECONOMY RESULTS

Fuel economy was measured using two vehicles, a current SUV with a 4.7 liter gasoline engine and a light truck with a 5.7 liter gasoline engine. After testing with the gasoline engines was complete, both vehicles were fitted with a 4.2L V6 and 5.6L V8 in the SUV and light truck respectively. Results as measured are shown in Figure 11.

The resulting combined mpg improvement versus gasoline for the SUV test weight is 44 percent, whereas the light truck was 49%.

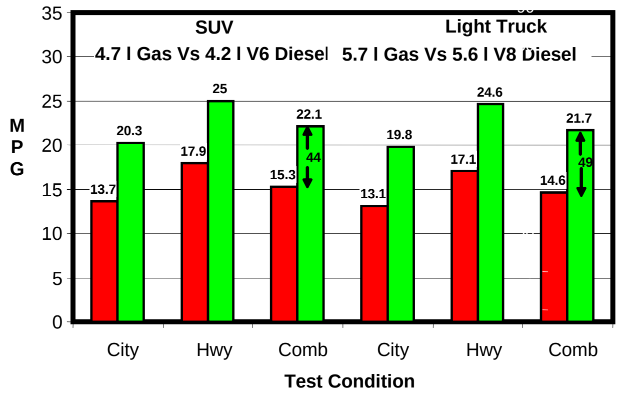

Figure 11. Measured Fuel Economy Results

ENGINE PERFORMANCE

Performance curves for the light truck diesel V8 are shown in Figure 12. The data shows the engine achieving its torque goal at 2000 rpm and power goal at 4000 rpm.

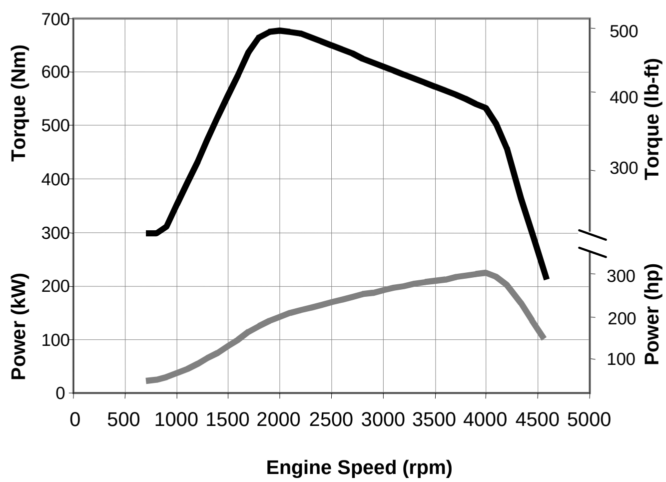

Figure 12. V8 Performance Curves

NOISE TEST RESULTS

Noise results for the light truck diesel are shown in Figure 13. Testing was conducted on an engineering prototype, model year 2003 Dodge Ram pickup truck as the base case. The production vehicle did not have any special noise abatement equipment added for diesel engine noise attenuation. The results reflect early engine calibrations without EGR. Four test conditions are reported: exterior noise at park, interior noise at idle, 60 mph cruise, and exterior at 3 ft with the hood open.

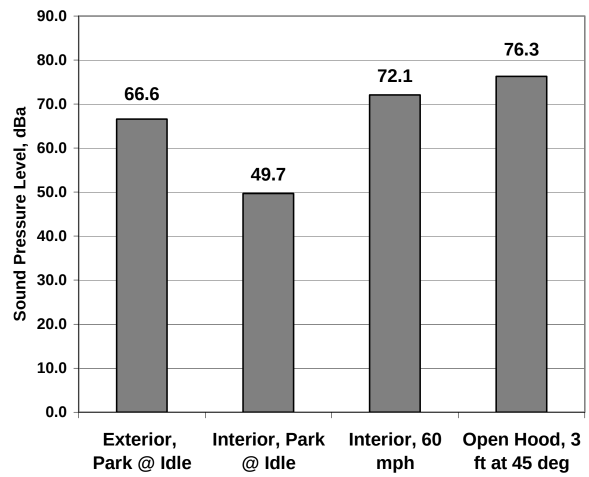

Figure 13. V8 Vehicle Noise

PERFORMANCE TEST RESULTS

Performance test results, comparing the light truck diesel with a current production gasoline V-8 engine, are shown in Figure 14. Testing was conducted on the prototype Ram pickup vehicle discussed above. Again, the 5.7 liter V8 gasoline powered vehicle was used as the base case. Both vehicles used the same automatic transmission. A third case is also presented which used an improved vehicle powertrain match.

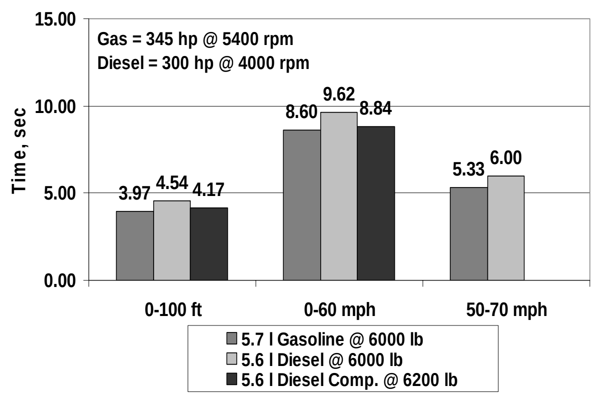

Figure 14. V8 Acceleration Test Results

SUMMARY AND CONCLUSIONS

During this last decade, the North American light-duty full size pickup truck and full size sport utility vehicle (SUV) markets have continued to become increasingly crowded with innovative products from an increasing number of OEMs. This crowded market necessitates increased product differentiation by OEMs with complex vehicle systems that comply with future emissions regulations. In addition, the average horsepower of vehicles sold in the North American markets has been rising significantly for more than a decade.

In a trend that is consistent with the ever-increasing diesel engine penetration seen in European passenger vehicles, a trend driven primarily by superior fuel economy, it is likely that more than one North American OEM will offer diesel power in the light duty vehicle markets to capitalize on the increased combustion efficiency and fuel economy advantage of the diesel engine. These light truck and sport utility vehicle markets have traditionally been dominated by gasoline engines with ever increasing horsepower and driver refinement characteristics. With a new diesel-based powertrain offering, it is essential that these OEM's offer a superior diesel engine in order to break through previous diesel ownership paradigms that are prevalent in these markets, as well as to provide customers with the driveability and socialbility expectations that they have become accustomed to with gasoline engines.

In response to consumer expectations for improved fuel economy in addition to traditional power, driveability and vehicle refinement expectations, Cummins has proposed a diesel engine and aftertreatment system concept which delivers a cost effective, light weight powertrain alternative to both traditional diesel engines and less fuel efficient gasoline engines. The most recent refinement to this platform is focused on a family architecture which has been refined and demonstrated during the concept development phase. The engine system, when combined with aftertreatment and combustion control systems, meets tough U.S. EPA Tier 2 Bin 5 and CARB ULEV II standards while delivering EPA label fuel economy of 22 mpg combined city and highway. This fuel economy advantage over gasoline engines is clear. Depending on driving conditions, 60 percent improvement over gasoline should be regularly reported by customers.

The early development results for this new light truck family of diesel engines show much promise for fuel economy and emissions management. There is also great potential for improvements in areas of performance and emissions sociability. The same statement can be made in the area of noise, where again, the diesel is noisier but by only a small noise level. It is believed that these differences can also be overcome by final calibration optimization work on the product. Emissions results show that diesel powered SUV's and light trucks (6000-8500 lb GVW) can meet the interim Tier 2 Light Truck emission standards. With the addition of advanced aftertreatment devices, these diesel-powered SUV's and light trucks can meet the full Tier 2 Light Truck emission requirements.

Cummins believes that there definitely exists a path to market for the Light Truck Diesel. However, there are several areas that the program has not addressed that are very suitable for the future work to further the development already completed. These areas include the technologies supporting high efficiency, clean combustion system approaches including closed loop combustion controls. The following areas should be considered as proposed future topics to advance the development of these early technologies.

Low Temperature Combustion Zone Expansion

The demonstrations conducted under the previous programs were narrowly focused on the emission control zone for one specific engine and test condition. Controls robustness and engine-to-engine variation were not addressed in those programs. Low emission operating conditions are typically unstable, both cylinder-to-cylinder and cycle-to-cycle, and are influenced by engine operating conditions. An investigation will need to be conducted to determine how closed loop controls can be placed on all possible controlled inputs to the combustion event to minimize both cylinder-to-cylinder and cycle-to-cycle variability, with an air handling strategy defined to support even lower engine out emissions levels.

Closed Loop Controls Development

Closed loop combustion control will provide the maximum thermal efficiency while maintaining limits on peak cylinder pressure, noise, combustion stability and emissions. Closed loop EGR and oxygen management controls will be required as the emissions targets continue to get tighter and tighter, and as system variation becomes a larger part of the overall budget. This is especially true over the useful life of the system. An investigation will need to be conducted to understand sources of variation in the control system, fuel system and air system. With that understanding, algorithms can be developed to compensate the various systems to maintain tighter tolerances over time, and from system to system.

Aftertreatment System Optimization

A low cost, low energy aftertreatment system with particulate filtration will be required to meet the emission standards. All efforts mentioned above seek to reduce the reliance and size of these components, but none are intended to completely obsolete either function in the aftertreatment system. Further emphasis will need to be placed on development of low cost, low energy aftertreatment systems. The filtration substrate size has, in the past, been the limiting cost factor due to the rated engine power density. Alternative substrate materials will need to be investigated.

Systems Integration

The future emission targets will be achieved only through application of technologies including a flexible fuel system with pressure and timing control, outstanding oil control and optimized combustion system configuration. A critical requirement for future diesel engines is a fully integrated exhaust gas recirculation (EGR) system with flexible electronic control capability. In order to meet the customer expectations for the light duty vehicles, an appropriate design strategy must be developed for future diesel engines that provide a fit to specific customer requirements. This engine must also have a significant reduction in cost and weight compared to today’s diesel engines to be competitive with the gasoline engine. This can be achieved through parts commonality with high volume automotive gasoline engine technology (where applicable), reduced part numbers through design integration, high power density for reduced displacement and optimized use of materials through duty cycle and test cycle analysis.