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ABSTRACT

Cummins has studied requirements of the Light Truck Automotive market in the United States and believes that the proposed V-family of engines meets those needs. Design and development of the V-family engine system continues and has expanded. The engine system is a difficult one, since the combined requirements of a very fuel-efficient commercial diesel, and the performance and sociability requirements of a gasoline engine are needed. Results of testing show that the engine can meet requirements for fuel economy and emissions in the Tier 2 interim period from 2004 to 2008. Advanced results show that the full Tier 2 results for 2008 and beyond can be achieved on a laboratory basis.

INTRODUCTION

Cummins Inc. and the Department of Energy have started the "Development of Technologies for a High Efficiency, Very Low Emissions, Diesel Engine for Light Trucks and Sports Utility Vehicles", ref. 1.

The primary program goals are as follows:

(1) EMISSIONS GOALS

For vehicle class of 5751-8500 GVW:

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

These goals were eventually modified by the publication of Federal Tier 2 emission standards early in 2000:

NOx = 0.07 g/mi
PM = 0.01 g/mi

(2) FUEL ECONOMY GOAL

A 50 percent MPG improvement (combined city/highway) over the current (1997) gasoline powered light truck or sport utility vehicle in this class for which the diesel engine is being designed to replace.

(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 started the development of an engine system with the intent to meet the above goals. The engine development project is in progress. Results are reported and should be considered a Progress Report. Further development will improve the engine system allowing it to achieve all of the project goals. The Phase 1 V6 engine was shown in 2000, ref. 2. This report covers the Phase 2 design which includes a V8.

MARKET BACKGROUND

The entire North American automotive market can be divided into two segments, light truck and car. Figure 1 shows the market penetration of these two segments since 1984 from auto industry sales data, ref. 3.

Two observations should be made from Figure 1. First, the trend from Car to Light Truck is gradual. There do not appear to be accelerations in the data. Second, the trend to Light Truck is not a recent phenomenon, and has been occurring for at least 15 years, and is expected to continue. There does appear to be a softening of the Light Truck market share in 2000, possibly due to higher fuel prices which began to occur early in the year. This trend continues into early 2001 where Light Truck share declines to 47 percent for the first two months; fuel economy is important.

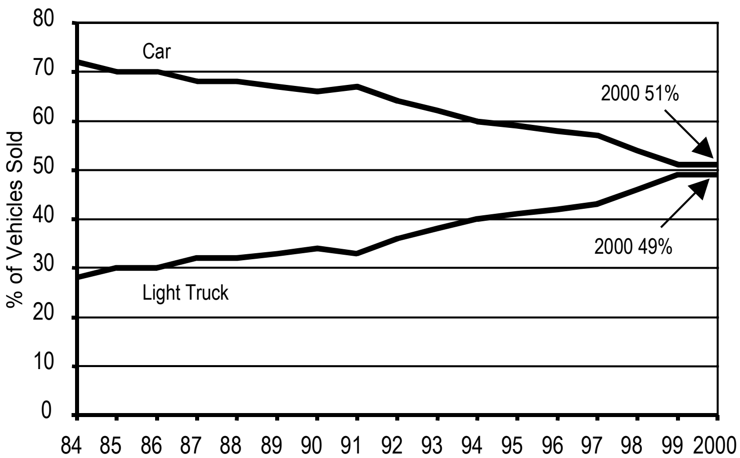

Figure 1. Car/Light Truck Market Share

Light Truck Market segments are shown in Figure 2. Pickup Trucks comprise about 39 percent of the sales in this market during 2000. Sport Utility Vehicles (SUV's) also comprise 39 percent, with Vans of all types coming in third place at 22 percent.

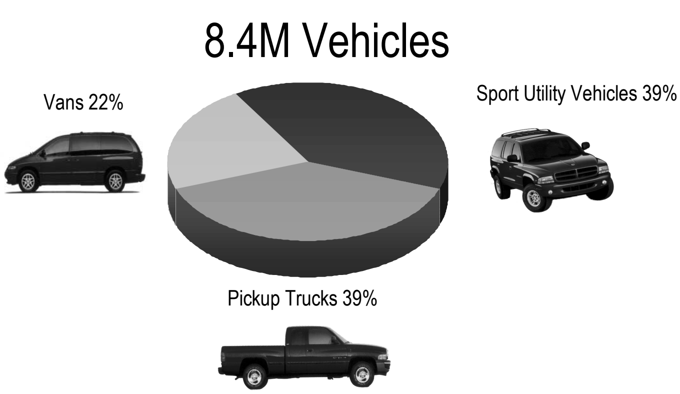

Figure 2. Light Truck Major Segments

Further analysis of the sales data for the past several years, ref. 4, shows that there are distinct buying trends. These are shown in Figure 3. The movement toward purchase of SUV's is the strongest and the most recent phenomena, as is shown by the relative width of the arrow in Figure 3. Most new SUV customers have replaced their car buying patterns with SUV purchases. The second trend, although not as strong, is the migration of car buyers to vans and pickup trucks. The third trend is a small migration of van and pickup customers to SUV's. And finally, there is also a small trend toward upgrade in the purchase of SUV's by some customers.

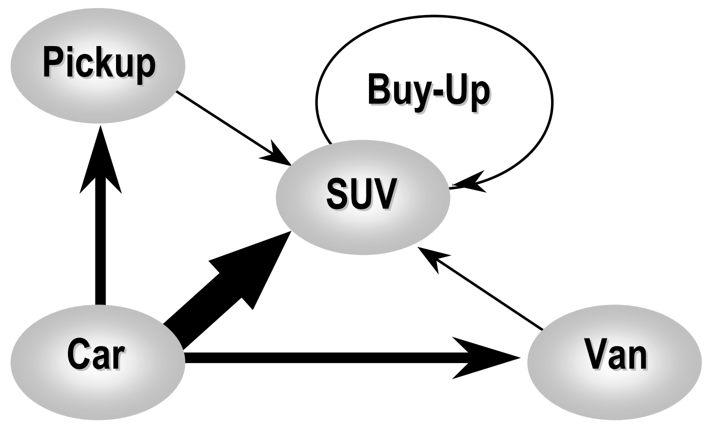

Figure 3. Migration to SUV's

ENGINE DESIGN PROPOSAL

Continued design of a new engine family that would carefully consider the above customer needs and trends was undertaken. An outline of this engine family is shown in Figure 4.

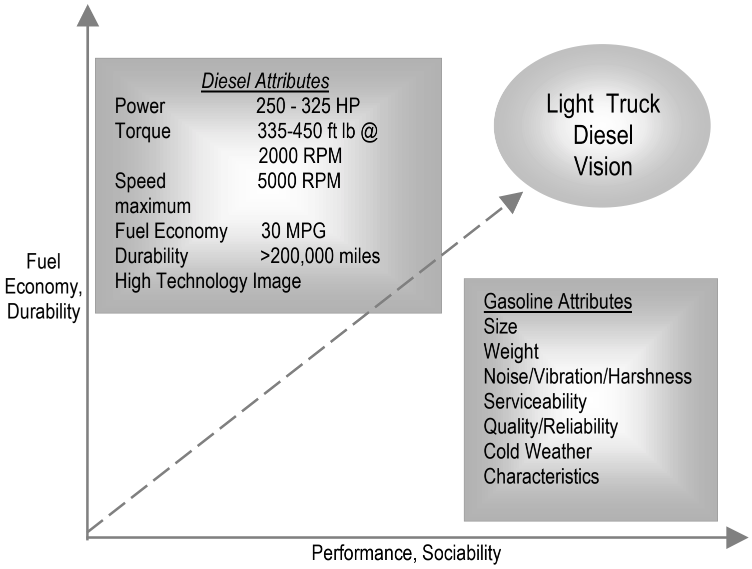

Figure 4. Light Truck Diesel Proposal

The engine family proposal combines the traditional best features of gasoline and diesel engines. The sociability strength of gasoline engines is combined with the fuel economy and durability of diesel. The Light Truck engine proposal is shown in Table 1.

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

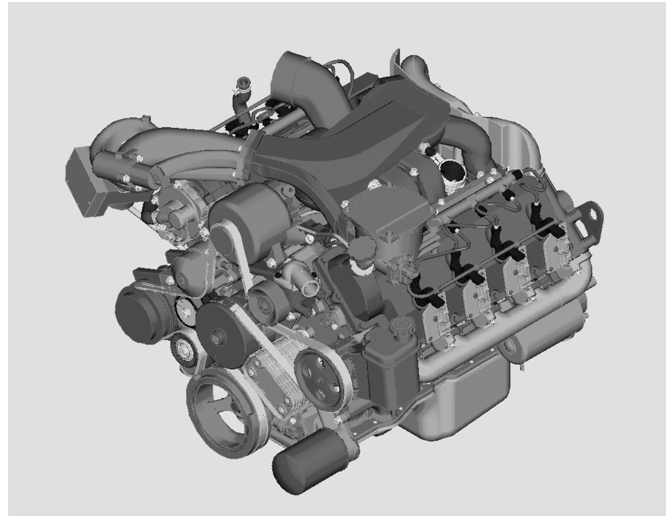

Figure 5. Light Truck Diesel Engine CAD Model

An overall description (architecture) of the major subsystems of the engine is described in Table 2 below.

Table 2. Light Truck Diesel Subsystem Description

Subsystem	**Description**
Configuration	90° V
Displacement	4.2 L V6 5.6 L 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 (HPCR)
Control system	Full electronic
Emissions control	Modulated-cooled EGR plus deNOx catalyst
Aspiration	Wastegated turbocharged
Intercooling	Vehicle mounted air-to-air
Block	Cast iron, thin-walled
Head	High temperature alloy aluminum
NVH control	Deep skirted block, with bedplate
Accessories	Common automotive V-8 gasoline
Accessory drive	Single serpentine belt, self-adjusted

EMISSIONS RESULTS

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 US and tested on the light duty EPA FTP cycle.

Testing of the engine as produced 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 Tier 1 LDT 2 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 Cummins fuel and air handling system including a Holset wastegated turbocharger and cooled, modulated EGR system were then installed. The results were very encouraging with Tier 1 requirements achieved: 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 6.

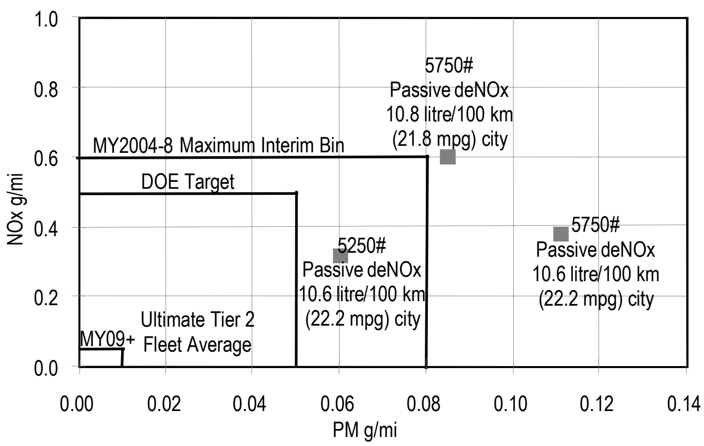

Figure 6. Interim Tier 2 Emissions Results

The first series of result are shown at test weights 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 6. 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 treated with the use of a NOx adsorber and particulate emissions were removed with a downstream soot filter.

Diesel fuel was used as the reducing agent in the NOx adsorber. The reductant was introduced after the turbine, external to the base engine. The flow of the reductant was controlled via the engine control module.

This 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, vehicle mounted 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 Phillips, ultra low sulfur diesel, with measured sulfur content of less than 4 ppm. This is a petroleum based fuel with 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) warm-up cycle, followed by three sets of back-to-back Highway Fuel Economy Test then UDDS cycles were used to demonstrate the effectiveness of the aftertreatment system. The multiple cycles were used to ensure that regeneration of both devices, not just accumulation, was actually occurring. The results are shown in figure 7, with values as low as NOx = 0.05 g/mi and PM = 0.005 g/mi measured.

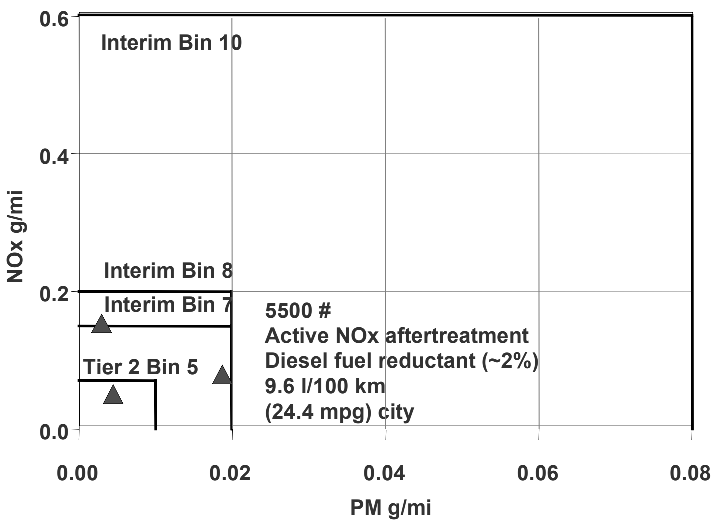

Figure 7 – Tier 2 Emissions Results

The NOx adsorber did not appear to show an 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.

FUEL ECONOMY RESULTS

Fuel economy was measured during the interim Tier 2 emissions testing described above. Results as measured are shown in Figure 8 for a series of test weights. The range used was 4500 lb approximating a small pickup truck, to 5250 lb approximating a medium SUV, to 5750 lb approximating a full-size pickup truck.

Highway fuel economy ranged from 34 mpg for the small pickup to 32 mpg for the full-size pickup. City fuel economy varied from 25 mpg to 22 mpg for the same vehicles.

The measured results are then corrected to reflect in-use consumer fuel economy, and industry procedures for vehicle labeling are used. The resulting combined mpg improvement versus gasoline for the SUV test weight is 59 percent.

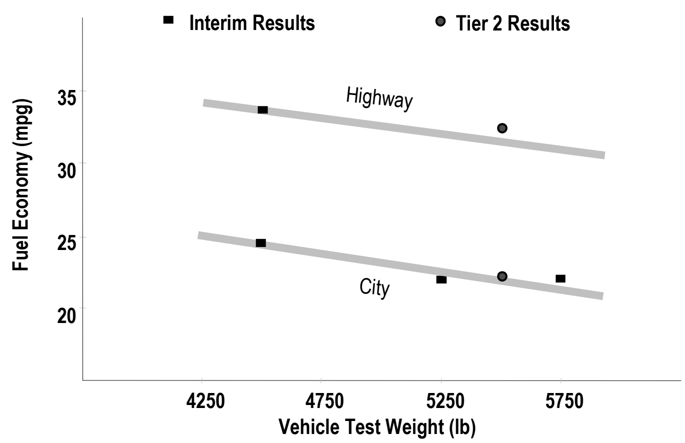

Figure 8 – Measured Fuel Economy Results

Measured fuel economy for the Tier 2 demonstration was also included in Figure 8. The value shown is the average of the three UDDS (city) and the HFET (highway) cycles from the sequence described above.

There is a slight, but notable improvement in fuel economy in the Tier 2 data over that of the Interim results. It is theorized that due to continuous testing (back-to-back cycles), the engine and vehicle systems are fully warmed and therefore have less parasitic load, resulting in improved mileage.

ENGINE PERFORMANCE

Performance curves for the Light Truck Diesel V8 are shown in Figure 9. The data shows the engine achieving its torque goal at 2000 rpm and power goal at 4000 rpm.

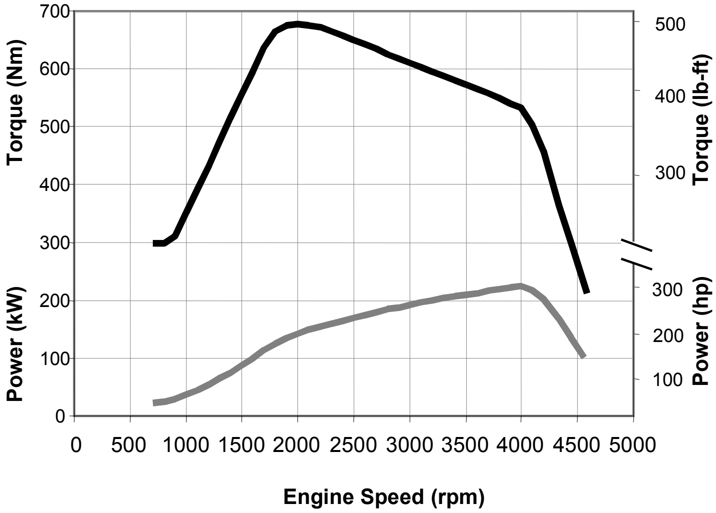

Figure 9. V8 Performance

NOISE TEST RESULTS

Noise results, comparing the Light Truck Diesel with a current production gasoline V-8 engine are shown in Figure 10. Testing was conducted on an engineering prototype MY 2000 Dodge Ram pickup truck. This vehicle equipped with a 5.9 L V-8 gasoline engine was used as the base case. The production vehicle did not have any special noise abatement equipment added for diesel noise attenuation. The results reflect early engine calibrations without EGR. Three test conditions are reported: interior noise at idle, 60 mph cruise, and exterior at 3 ft with the hood open.

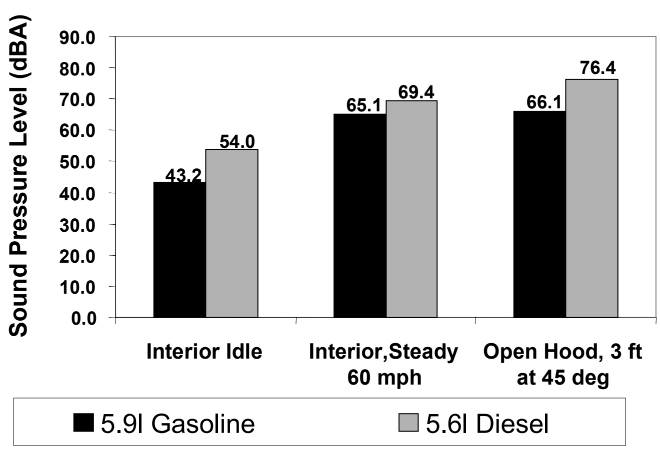

Figure 10. V8 Vehicle Noise

The diesel engine was 10.8 dB(A) noisier at idle. At highway cruise conditions the diesel was only 4.3 dB(A) noisier. With the hood open at 3 ft, the diesel was 10.3 dB(A) noisier.

PERFORMANCE TEST RESULTS

Performance test results, comparing the Light Truck Diesel with a current production gasoline V-8 engine are shown in Figure 11. Testing was conducted on the engineering prototype Ram Pickup vehicle discussed above. Again, the V-8 gasoline powered vehicle was used as the base case. Both vehicles used the same automatic transmission.

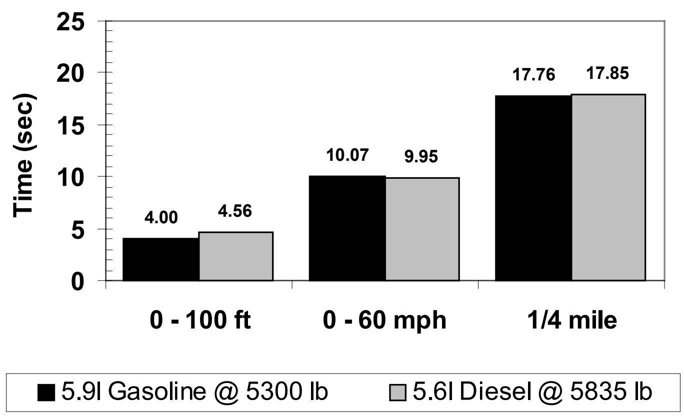

Figure 11. V8 Acceleration Test Results

Three acceleration tests were used to assess the performance of the Light Truck Diesel Engine. In the 0-100 ft elapsed time test, the Light Truck diesel completed the distance in 4.6 sec vs 4.0 sec for the gasoline engine. The elapsed time to achieve 60 mph was 9.95 sec for the diesel vs 10.07 sec for the gasoline engine. The elapsed time for the ¼ mile distance was 0.11 sec slower for the diesel at 17.85 sec. Development activity is focused on improving the launch performance of the vehicle.

SUMMARY AND CONCLUSIONS

The early development results for a new Light Truck Family of Diesel Engines shows much promise and achievement.

Fuel economy advantage over gasoline engines is clear. Depending on driving conditions, 60 percent improvement over gasoline should be regularly reported by customers.

There is also great promise and achievement in the areas of performance and sociability. The diesel leads in 0-60 mph acceleration performance, however, currently lags in launch performance. It is believed that continued development will overcome the difference. A similar situation exists in the case of noise. Again the diesel is noisier, but by only small amounts. 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.

There is a path to market for the Light Truck Diesel.

REFERENCES

1 DOE Contract No. DE-FC05-97OR22533

2 Stang, John H, "Cummins Light Truck Diesel Engine Progress Report", SAE 2000-01-2196, June, 2000.

3 "Automotive News " 1/8/2001, Page 40

4 Internal Cummins Analysis