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ABSTRACT

Detroit Diesel Corporation (DDC) is developing the DELTA 4.0L V6 engine, specifically for the North American light truck market. This market poses unique requirements for a diesel engine, necessitating a clean sheet engine design. DELTA was developed from a clean sheet of paper, with the first engine firing just 228 days later. The process began with a Quality Function Deployment (QFD) analysis, which prioritized the development criteria. The development process integrated a co-located, fully cross-functional team. Suppliers were fully integrated and maintained on-site representation. The first demonstration vehicle moved under its own power 12 weeks after the first engine fired. It was demonstrated to the automotive press 18 days later. DELTA has repeatedly demonstrated its ability to disprove historical North American diesel perceptions and compete directly with gasoline engines. This paper outlines the Generation 0.0 development process and briefly defines the engine. A brief indication of the Generation 0.5 development status is given.

INTRODUCTION

DELTA is an acronym for Diesel Engine Light Truck Application. DDC's internal development program was code-named DELTA and the name was later attributed to the 4.0L V6 engine, which the program produced. Refer to **Figure 1**. This program was partially funded by the Department Of Energy (DOE), under the Light Truck Clean Diesel Program.

The DOE Light Truck Clean Diesel Program targets are summarized below:

- North American Market
- Light Truck / SUV Applications
- For 5,751 to 8,500 lb GVW Vehicle
- Program Target Particulate Mass = 0.05 g/mile*
- Program Target No_x = 0.50 g/mile*
- 50% Fuel Economy Improvement (MPG) versus Competitive Gasoline Engines

* Emissions targets are being revised to comply with new EPA standards.

Before discussing the North American vehicle market and its implications for diesel engines, it is important to first consider European markets. Diesel engines are extremely popular powertrain options within Europe, reaching over 40% penetration in some European countries. High fuel prices (over $4.00 per gallon), provide the most significant reason for diesel popularity. Tax incentives have encouraged smaller displacement, higher power density engines. Thus engine makers increased rated engine speeds (4,000 to 4,500 RPM), maximizing power density and improving driveability. The resultant powertrain behaves more like a gasoline-powered vehicle.

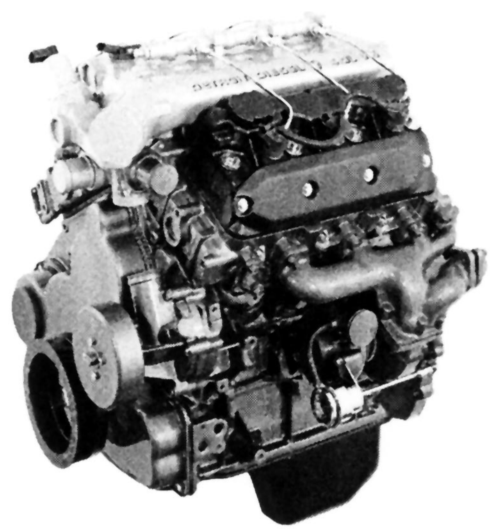

Figure 1. DELTA 4.0L 60 Degree V6 Diesel

Vehicle size is an important consideration when evaluating unique differences between European and North American markets. Many European vehicles tend to be smaller than their North American counterparts. The largest European Sport Utility Vehicles (SUV's) tend to equal their smallest North American counterparts in size. One example is the Jeep Grand Cherokee, which is one of the larger European SUV's, while being smaller than many North American competitors: Ford Explorer, Ford Expedition, Ford Excursion, Dodge Durango, and GMC Suburban. The duty cycles are also different. European vehicles are most often used as passenger vehicles and predominately experience high speed and short distance driving. North American light trucks are used for more diverse purposes, including passenger commuting, long distance travel, and towing applications.

Light trucks, which include pick-ups, SUV's, and vans, are gaining popularity in North America. Vehicles from these classifications comprise over 50% of the family vehicles used in the United States. Vehicle makers have repeatedly increased light truck vehicle size, in response to consumer demand. These marketing characteristics, coupled with relatively low fuel prices within the United States, have drastically changed the product mix away from smaller, more fuel efficient cars and toward larger, more profitable light trucks. This trend has also resulted in poorer fleet fuel economy averages, making it difficult for vehicle makers to reach their CAFE fuel economy targets.

Additionally, international concern for global warming is placing increased emphasis on carbon dioxide (CO_2) reduction. For internal combustion engines, this necessitates improved fuel economy. Since diesel engines are 30 to 50% more fuel efficient, they provide a logical near term solution to meet the global warming challenge.

North America presents another unique constraint upon the diesel engine designer. During the 1970 oil crisis, a number of poorly optimized diesel engine were launched into the United States vehicle market. These engines were used in large passenger car and light truck applications. Unfortunately, most of these engines were modified gasoline engines, which severely compromised noise, vibration, durability, emissions, and performance characteristics of the diesel version. Many were naturally aspirated, causing poor acceleration and objectionable black smoke. Fuel system technologies were not as refined as the modern common rail and electronic unit pump systems, which are available today. These events and associated technological limitations conspired to create negative impressions of diesel engines for many North American consumers. Additionally, many younger U.S. consumers have no diesel exposure, other than through heavy equipment. They often associate diesel engines with the compression ignition combustion "bark" and black smoke during acceleration. Therefore, the modern diesel engine faces a number of sociability concerns, resulting from preconceptions of the North American public.

Fuel and infrastructure are additional considerations for the North American market. Most European countries have an extensive diesel supply infrastructure, at the same locations where motorists typically refuel their vehicles. European diesel fuel usually has higher cetane, contains lower sulfur concentrations and has a lower aromatic content than is available in the United States. These characteristics have a significant benefit for reducing emissions and insuring aftertreatment device durability.

The final consideration for the North American market is legislative emissions constraints. The California Air Resource Board (CARB), recently pronounced very stringent emissions legislation, affecting light trucks sold in California (LEV2). The United States Environmental Protection Agency (EPA) announced its TIER 2 emissions standards. Without improved fuel quality (lower sulfur, lower aromatics, and higher cetane), these standards pose a significant challenge for the diesel engine. Additional compression ignition engine technology developments must be coupled with efficient and durable aftertreatment devices before these standards can be satisfied in production applications. Therefore, the diesel engine makers are focusing development activities in these areas.

DISCUSSION

DELTA is an ongoing development project. The first level prototype was the Generation 0.0 engine, which served as a proof of concept test mule. DDC is currently testing Generation 0.5 prototypes, with a Generation 1.0 design in process. Generation 1.0 will be the production intent design. A subsequent Generation 2.0 design is scheduled, representing the pre-production prototype. This paper focuses on the Generation 0.0 design and development effort, but provides some insight into the Generation 0.5 development activities. Vehicle tests are ongoing with both engine configurations.

IDENTIFYING CUSTOMER WANTS – DDC initiated the DELTA design process by conducting a Quality Function Deployment (QFD) analysis. This technique captures primary customer wants and through an unbiased process, it evaluates tradeoffs and dependencies. In the QFD first phase, these parameters are reduced to technical system expectations. These form the basis for the second QFD phase and ultimately the engine design process.

The key to this development process is defining customer wants and prioritizing their importance to the engine design characteristics. Once established, discipline must be used to maintain these guidelines throughout the development process. This avoids "creeping elegance" throughout development and protects the voice of the customer.

The primary customer wants are outlined in **Figure 2**. Their impact on Cost was the most highly ranked development criteria, followed by Durability and Driveability. Performance, Fuel Economy, Noise, and Vibration are also highly ranked. The design team avoided adding "technology for the sake of technology alone", as it would not provide value to the customer and would add significantly to the engine cost.

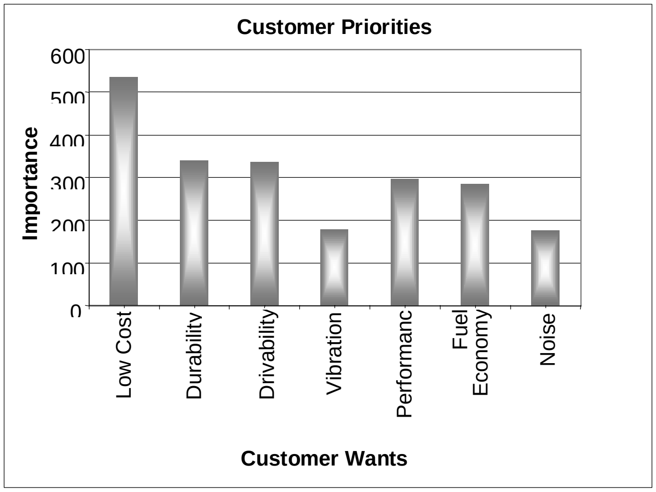

Figure 2. Key Development Criteria

Cost – The most highly weighted customer want is low cost. This includes all life cycle costs, such as: development, component, assembly, service, operating, and recycling. Cost impacts nearly every design decision. Additionally, DELTA is competing with low cost, high volume gasoline engines. With the exception of fuel consumption, most consumers are satisfied with their gasoline light truck engines. Diesel engines include several technologies, which inherently add cost to the engine:

- Fuel System
- Charge Air System (turbocharger, intercooler)

Therefore, the diesel engine design must focus upon reducing Bill Of Material (BOM) costs, while satisfying all customer expectations. The durability target (250,000 mile B-10 Life) was set to exceed that of competing gasoline engines and is consistent with customer wants. Service requirements were established to minimize regular maintenance requirements over the engine's operating life, while simplifying service procedures, in the event that a repair is necessary. Material selections, such as a parent bore cast iron block and cast iron cylinder heads reduce engine-recycling costs at the end of its life cycle.

Durability – Extended durability is not only a life cycle cost consideration, but also a strong customer want for the North American market. North American light trucks operate on more aggressive duty cycles than many European passenger vehicles. They are subject to more strenuous towing operations and the vehicles are expected to outlast most passenger cars. Additionally, many consumers associate diesel engines with durability and long life. This increases the importance of setting aggressive durability goals. Based upon an evaluation of the customer's expectations, a 250,000 mile B-10 life target was set for the DELTA engine. Long life diesel engines can also increase the vehicle's resale value, allowing the original buyer to recover their financial investment. In the case of leasing, higher residual values reduce the operator's lease payments.

Noise & Vibration Harshness (NVH) – European automobile manufacturers often optimize their vehicle for use with diesel engines. Rigid mounting structures, engine & transmission mount tuning, vibration isolation, driveline matching & damping, and engine encapsulation are common methods to address unique diesel NVH issues. Such comprehensive system level approaches are most likely to yield successful results. However, most North American vehicles are not intended for diesel applications. Therefore, great care must be taken when designing a diesel for vehicles, which are primarily intended for gasoline powertrains.

Combustion Noise – Compression ignition cycles have an inherently louder combustion sound than comparable spark ignition engines, particularly during low speed operation. At higher speeds, the two combustion cycles can produce nearly indistinguishable noise differences. Under maximum power operation, diesel engines often produce less noise than their gasoline counterparts, in part due to their lower rated speed requirements.

Although the diesel engine produces a slightly louder sound, up to approximately 1,000 RPM, significant improvements can be made in sound quality. New high-pressure common rail fuel systems and modern electronic control strategies provide flexibility to precisely control pilot injections. These strategies drastically reduce total combustion noise and more dramatically improve the sound quality. Pilot injection strategies are most effective at lower engine speeds.

Noise and Vibration Transmission through Structures – Computer aided analysis systems have dramatically improved the structural design process, allowing the designer to optimize rigid block, cylinder head, and bedplate structures. Brackets were eliminated, where possible, in favor of direct mounting to major castings. When necessary, brackets were designed to avoid natural frequencies, which can be excited by the engine. Mounting points are selected to mount at vibration nodes.

Noise and Vibration Isolation & Damping – Noise and vibration must be considered throughout the engine design process. Systems like the valvetrain are designed to minimize the frontal area of the geartrain, which is required to drive the camshaft, oil pump, fuel pump, and vacuum pump. The OHV design is ideal for minimizing the area enclosed by the front gearcase cover. The gearcase cover and oil pan are

Various options are available to minimize noise and vibration transmission to the external environment, including use of: sound damping covers, engine encapsulation, tuned and/or active engine mounts. For maximum effectiveness, the engine and vehicle must be considered as a complete system. Noise generating components must be located, such to minimize noise transmission to the passenger compartment and the vehicle's surroundings. Noise transmission and attenuation must be considered, when designing the engine. For example, while designing the charge air handling system, the engineer must consider turbocharger location and its influence on noise transmission through air system ductwork and in the vicinity of the turbocharger itself. Devices, such as intake system resonators, can be integrated with existing air system components, to tune turbocharger noise with minimal negative cost impact.

Performance & Driveability – Most light truck owners are extremely satisfied with the performance of large displacement gasoline engines. Therefore, a diesel engine must match this level of performance. The diesel engine's torque characteristics are ideal for improving vehicle launch characteristic and increasing vehicle towing capability. In many cases, a moderately sized diesel (4.0 liter V-6) can compete with much larger displacement gasoline engines (over 5.0 liter V-8). Refer to the compilation of North American light truck engines, shown in **Figure 3**. However, charge air-handling systems must be designed to minimize turbocharger lag during acceleration. This is necessary, because the diesel engine behaves essentially like a naturally aspirated engine, until the turbocharger overcomes the initial lag. Variable geometry turbines are one popular method to minimize the sensation of turbo lag. Other more expensive approaches, such as supercharging and electrically assisted turbochargers are directed toward the same objective.

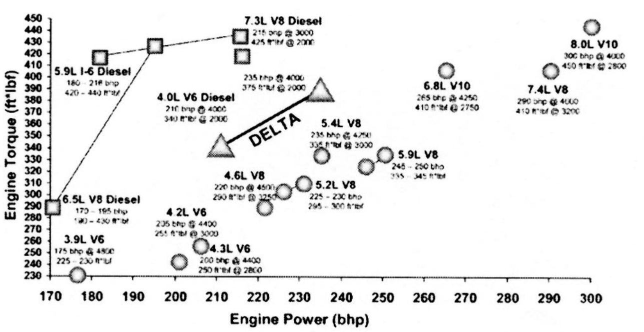

Figure 3. Typical North American Light Truck Ratings

Several medium duty engines are shown in **Figure 3** for reference. These engines are used for medium duty vehicle applications, having a Gross Vehicle Weight (GVW), over 8,500. The DELTA 4.0L V6 engine is positioned with its power and torque well above most gasoline counterparts.

A 4,000 RPM rated speed requirement was targeted to provide gasoline-like shifting characteristics. The engine has a 5,200 RPM overspeed target.

Fuel Economy – Fuel economy is one of the largest negatives for gasoline light truck engines. United States gasoline prices peaked over $2.00 per gallon in early 2000 CY. Although fuel prices are now relatively low in the United States ($1.30 to $1.60 at the time of this publishing), many North American light trucks continue to consume relatively large quantities of fuel. This not only increases operating costs, but limits the vehicle's range. Both are negatives for the consumer. Market studies indicate fuel costs are often not a primary consideration at the point of a new vehicle purchase, but poor fuel economy is often the leading cause for customer dissatisfaction during the vehicle ownership period.

CORE COMPETENCIES – Evaluation of the primary customer wants, clearly indicated that the North American light truck market demands a clean sheet development approach. DDC assessed its core competencies, and recognized the DELTA engine must be a hybrid of several design philosophies. Refer to **Figure 4**.

High durability requirements and passenger car refinement necessitated a blend of European style High Speed Direct Injection (HSDI) diesel technology, with North American heavy-duty diesel experience. Recently developed technologies were necessary to address NVH and driveability expectations. Emissions reduction and after-treatment technologies are still under development to comply with future emissions legislation. New technologies from DDC's advanced research and development programs were necessary to satisfy these targets.

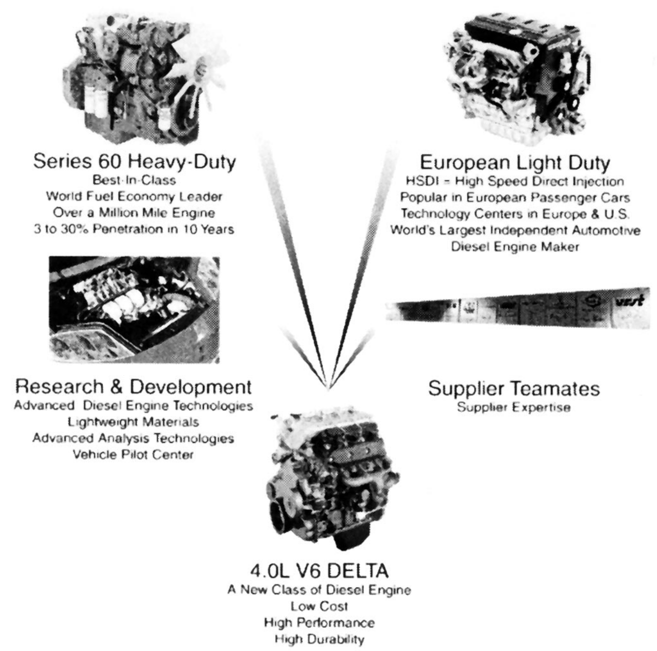

Figure 4. DDC Core Competencies

DDC also recognized that the success of this program depended upon the expertise of its supplier partners. Key suppliers co-located onsite in Redford, with the rest of the DELTA team.

ENGINE ARCHITECTURE & DESIGN

Bank Angle – DELTA was designed to satisfy the key customer wants, while complying with required emissions and vehicle application constraints. NVH targets drove the design toward the 4.0L 60 degree V6 architecture, rather than alternatives with larger displacements and 90 degree bank angle architectures. **Figure 5** clearly depicts the packaging benefits of the narrow 60 degree bank angle. The black outline depicts an undressed 90-degree engine against a fully dressed 60-degree silhouette.

The 60-degree configuration permits accessory packaging to the sides of the engine block. This approach reduces the overall engine length by 3.4 inches (86 mm).

A 60-degree V6 configuration also provides a significantly improved balance configuration, with minimal cost. A single second order balance shaft provides complete balance, through the second order. A 90-degree V6 would require one first order balance shaft and two second order balance shafts to achieve the same level of refinement as DELTA's 60-degree even firing design.

DELTA's common fuel rail is mounted centrally, along the intake manifold. The 60-degree bank angle minimizes fuel line length, without requiring two fuel rails, expensive connecting lines, fittings, and junction blocks. The reduced complexity of DELTA's fuel system also minimizes assembly costs and the risk of fuel leaks.

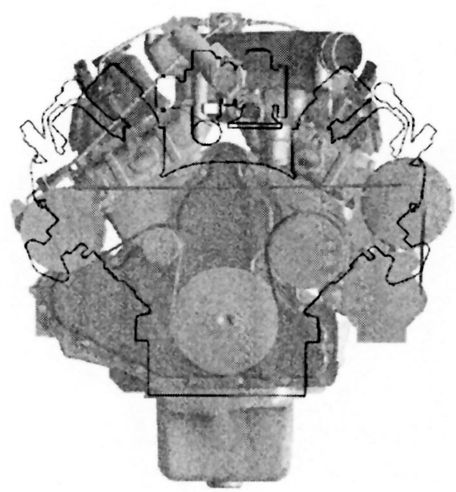

Figure 5. Bank Angle

Valvetrain – Fuel economy and emissions requirements demand a 4-valve per cylinder approach. Although this adds cost, the design is necessary to achieve a central vertical fuel injector orientation. This arrangement improves combustion chamber symmetry, which is a prerequisite for meeting future emissions legislation.

Unlike their gasoline counterparts, most HSDI diesel engines achieve comparable power at much lower rated speeds. Rated speeds between 4,000 and 4,500 RPM can be achieved more efficiently with an Overhead Valve (OHV) configuration, rather than Single Overhead Camshaft (SOHC) or Dual Overhead Camshaft (DOHC) arrangements. **Figure 6** depicts the DELTA valvetrain arrangement. This approach improves engine packaging, reduces friction and cost.

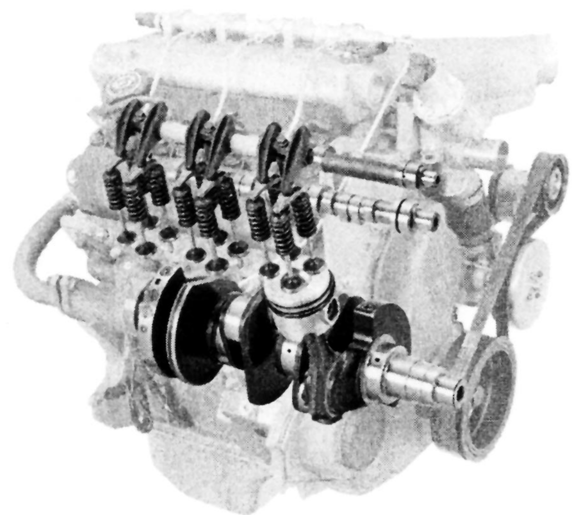

Figure 6. DELTA's OHV Valvetrain

DELTA's OHV design reduced valvetrain costs by 82%, compared to a comparable DOHC design. Rather than four camshafts, DELTA uses only one, with identical push rods for intake and exhaust valves. One push rod activates each valve pair, through a free-floating valve bridge. The OHV configuration reduces the number of valvetrain components and minimizes cost, while lowering valvetrain friction, minimizing engine weight, and reducing engine package size.

Hydraulic lash adjusters eliminate the need for valve lash adjustment requirements, while minimizing valvetrain noise and avoiding performance degradation. The lash adjusters are shipped and housed in a plastic carrier, which pre-aligns the oil holes and simplifies assembly. The cylinder block contains machined grooves, which receive and orient the two lash adjuster assemblies. Refer to **Figure 7**.

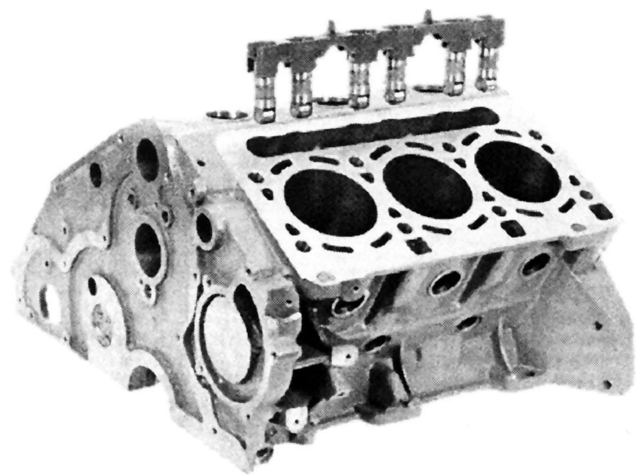

Figure 7. Valve Lash Adjuster Assemblies

DELTA uses a spur gear driven camshaft. Although this design approach added cost to the engine, it was necessary to insure a 250,000 mile B-10 life. Conventional chain and belt drive alternatives can reach 180,000 and 150,000 miles respectively.

The compact geartrain is designed to minimize gear noise, using high contact ratio gears. Refer to **Figure 8**. The optional balance shaft and vacuum pump gears have 1.9 contact ratios. This compromise is not problematic, because the gears are located at extreme ends of the valvetrain and do not experience reversed loading. All other gears have contact ratios over 2.0. The gear tooth profile contains crowned and undercut teeth, for smooth engagement during operation.

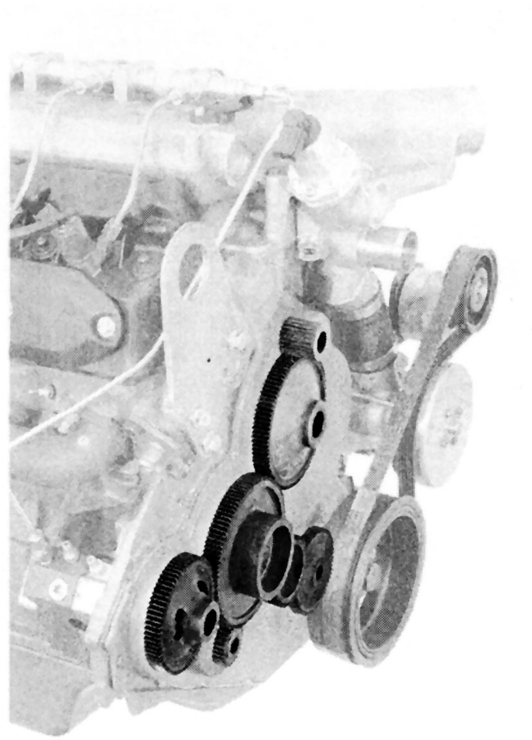

Figure 8. DELTA Geartrain

The geartrain is easily contained within a small stamped damped steel cover. The laminated steel composite minimizes sound transmission to the environment. A similar material is used for the oil pan.

Block, Bedplate, and Cylinder Head Structures – The block, bedplate, and cylinder heads are cast from gray iron. Aluminum could not satisfy the durability target by the intended production launch date. Cast iron provides DELTA exceptional strength, rigidity, vibration damping, and durability characteristics.

The cast iron block is a parent bore configuration. Feature incorporation provides significant BOM cost reductions, while benefiting NVH and reducing assembly costs. Oil drain-back passages are cast into the outboard sides of the block, improving block stiffness and minimizing engine cost. The water pump volute is cast into the front of the block for a cost reduction.

DELTA's crankshaft is mounted between the block and a lower bedplate structure. This approach provides a rigid structure for improved NVH and main bearing support.

The cylinder heads are reversible from bank to bank, reducing machining investment costs and assembly line complexity. Although the Generation 0.0 design uses valve guides and valve seats, the Generation 1.0 design eliminate these components, in favor of a lower cost induction hardened design.

Air System – DELTA is turbocharged and intercooled for emissions compliance, fuel economy, and performance. A compact cooled Exhaust Gas Recirculation (EGR) system is integrated into the intake manifold (patent pending). Refer to **Figure 9**. The intake manifold forms the EGR cooler housing, avoiding a separate cooler housing, coolant plumbing, clamps, external brackets, mounting hardware, seals, and potential leak paths. The cooler is formed by a bundle of stainless steel tubes, which are brazed together.

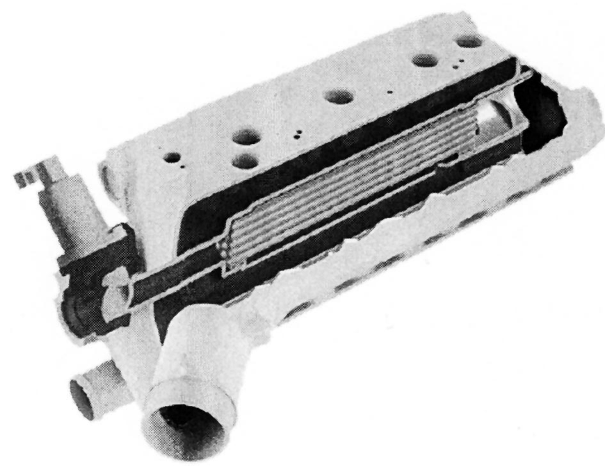

Figure 9. Intake Manifold with Integrated EGR

This system approach minimizes weight, cost, assembly time, components, and leak paths. It also shortens exhaust gas passages, minimizing restrictions, and increasing EGR rates. The exhaust manifolds include an extra connection to direct exhaust gases into the cylinder heads. EGR passages, which are cast into the cylinder heads, conduct EGR to the intake manifolds. Refer to **Figure 10**. The intake manifold provides a housing for the EGR valve and EGR cooler bundle.

The electronically controlled turbocharger provides efficient boost under transient operating conditions. Base development is being conducted with a single wastegated turbine configuration. However, twin wastegate and Variable Geometry Turbine (VGT) versions are also under development. A potential upgrade include a turbine wheel composed of ultra-low inertia Titanium-Aluminide (Ti-Al) material.

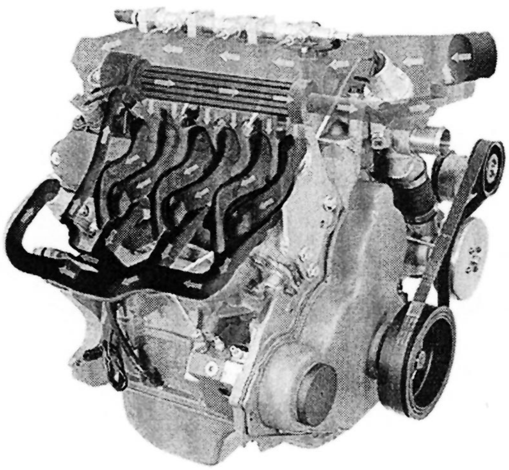

Figure 10. Intake Air & EGR System

Cranktrain – DELTA's V6 crankshaft is designed with an even firing split pin arrangement. This configuration insures smooth engine operation, which is further enhanced by the torsional vibration damper. The damper contains an integrated pulley, to reduce costs.

The crankshaft is constructed from a robust forged steel, with intermediate flying webs. Refer to **Figure 11**.

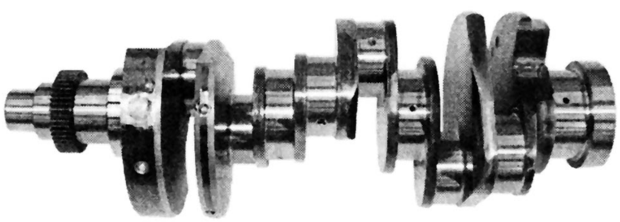

Figure 11. Even Firing Forged Crankshaft

The connecting rods are constructed from robust forgings, using an angle split design. The rods are "cracked" at the split line, to maintain tight tolerances during assembly. DDC originally used this approach on its heavy duty Series-2000 engine, to maximize bearing area and insure high tolerances between the upper and lower connecting rod halves.

The connecting rod mounts to a trunk cast aluminum alloy piston, using a free-floating piston pin. The piston is designed to withstand heavy loads and cylinder pressures up to 150 bar. The piston is cooled from below using oil jets, which are mounted to the cylinder block.

Fuel System – DELTA's quiet operation is achieved, in part, through new fuel system and the flexibility offered by modern electronic control technology. The engine incorporates a variable displacement high-pressure common rail fuel system. The rail is centrally mounted to the intake manifold. Individual lines supply high-pressure fuel to each injector.

The variable displacement high-pressure pump minimizes fuel heating and helps avoid a fuel cooler requirement. This is an important consideration on vehicles, which use plastic fuel tanks. Certain tank materials are susceptible to incompatibility with high temperature diesel fuel, which can cause fuel system plugging. The high-pressure common rail pump includes a low-pressure transfer pump. This eliminates the fuel tank lift pump and reduces vehicle costs.

Engine tests are currently injecting fuel at 1,350 bar maximum rail pressures. Future versions enable fuel injection at higher pressures (in excess of 1,600 bar) and optimize pilot injection tolerances. The next generation common rail fuel system upgrade permits multiple pilot injection, with reliable fuel quantity metering.

The common rail fuel system provides post injection capability. Post injection is a method, which injects a small fuel quantity after the main combustion nears completion. The fuel partially oxidizes, causing higher hydrocarbon concentrations. These exhaust constituents provide a reductant for certain lean-NO_x aftertreatment devices.

Long-term development activities target piezo-controlled systems, which provide variable valve lift. This flexibility separates the injection timing parameter from the fuel quantity metering function. This added degree of freedom allows further combustion and emissions optimization.

VEHICLE DEVELOPMENT

Engine Installation – A development vehicle was tested for the first time on 04AUG98, 12-1/2 weeks after the first prototype fired in the test cell. DDC repowered a 1998 Dodge Durango with the second prototype DELTA engine. Refer to **Figure 12**.

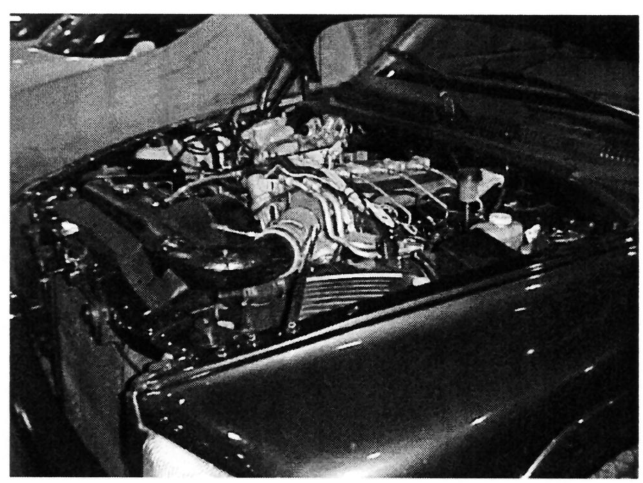

Figure 12. Vehicle Repower

The vehicle weight was 4,300 lb, with a 6,400 lb Gross Vehicle Weight (GVW). The emissions test weight was 5,252 lb. The engine was coupled to a 5-speed manual transmission, having the following gear ratios:

- Rear Axle Ratio = 3.92
- First Gear Ratio = 3.49
- Second Gear Ratio = 2.16
- Third Gear Ratio = 1.40
- Fourth Gear Ratio = 1.00
- Fifth Gear Ratio = 0.73

A 5.9L gasoline V8 engine was removed from the vehicle. Vehicle modifications were minimized. However, minor modifications were necessary to accommodate the diesel air intake system. These included installing an inter-cooler, which required that the air cleaner and battery positions be reversed. A diesel fuel filter system was added, with an integral fuel heater and water separator.

The vehicle exhaust system was used as received, except for eliminating the muffler. The muffler was replaced with an aftertreatment device, which includes a Johnson Matthey Continuously Regenerating Trap (CRT).

Existing engine mount locations were used, but the mounts were tuned for the diesel engine. A minor sheet metal modification was necessary in the dash wall, due to the configuration of the prototype fuel rail and manifold. The Generation 1.0 hardware eliminates the need for this alternation and the engine will easily fit into the existing production vehicle without modification.

Stock DaimlerChrysler accessories were used, as removed from the original 5.9L V8 gasoline engine. These included: power steering pump, alternator, and the air conditioning compressor. The water pump, fuel transfer pump, and vacuum pump are components of the core DELTA diesel engine. The DELTA 4.0L V6 was equipped with the optional second order balance shaft for the first vehicle repower.

An engine top cover was developed to provide additional sound attenuation, but it was not required for this vehicle. Extremely quiet operation was achieved without encapsulation.

Vehicle Demonstrations – The completed vehicle, shown in **Figure 13**, was demonstrated to the public after 2-1/2 weeks of calibration development. The engine was rated at 210 hp @ 4,000 RPM and develops 340 ft*lbf of torque at 2,000 RPM.

ACCELERATION PERFORMANCE – With the initial 8.0 cm^2 turbine match, the 4,950 lb vehicle developed a 10.7 second 0 to 60 MPH (0-100 km/hr) acceleration time. This compares favorably with the 9.8 second time, measured with a stock 5.2L V8 powered Durango. Refer to **Figure 14**. Subsequent turbocharger and calibration optimization provided substantial improvements for the DELTA diesel powered vehicle. Further improvements achieved much more impressive results on a Generation 0.5 vehicle.

Figure 13. 4.0L Diesel Development Vehicle

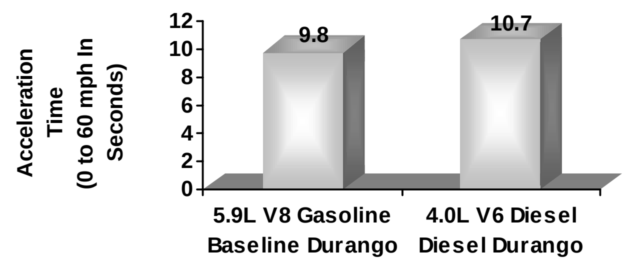

Figure 14. Launch Characteristics, 4.0L V6 DELTA w/5-Speed Manual Transmission

Fuel Economy – The stock 5.2L V8 gasoline Durango produced 14 MPG on the highway cycle. The 4.0L V6 diesel powered development Durango established 30 MPG on the highway and 22 MPG in city use. The most significant fuel economy improvements were achieved under heavy load conditions (vehicle tested at maximum GVW), where the gasoline engine operates least efficiently.

Noise & Vibration Harshness – Combustion sound quality was improved substantially through use of the common rail fuel system. Pilot injection strategies were employed over much of the engine speed range. **Figure 15** compares baseline 5.9L V8 gasoline and DELTA 4.0L V6 diesel interior noise levels. Sound pressure measurements were made at the driver's ear position. The diesel was within 2 dBA of the stock gasoline engine. This margin was further reduced during subsequent calibration development.

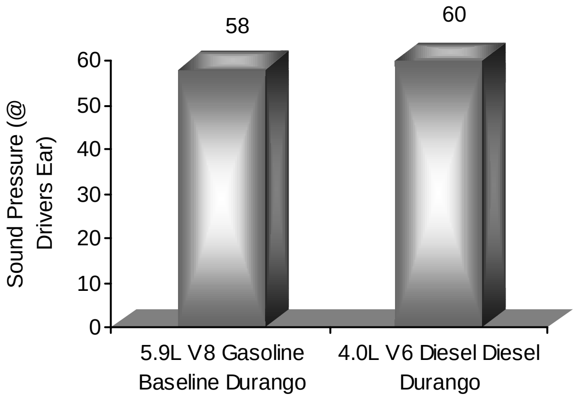

Figure 15. Interior Noise

Figure 16 depicts noise measured outside the vehicle, during an engine speed sweep. Two sets of competitive European HSDI diesel vehicle noise traces are provided for comparison.

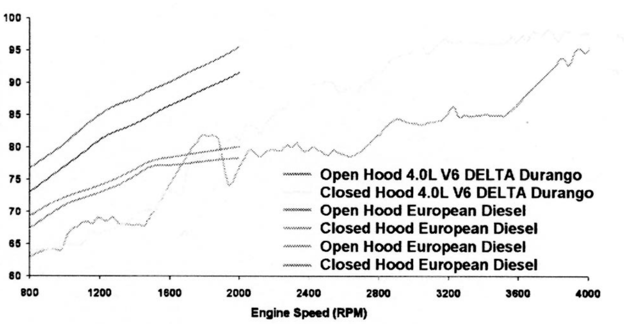

Figure 16. Exterior Noise (4.0L V6 DELTA versus European HSDI Diesels)

DELTA's noise characteristics have been competitive with gasoline engines, despite the early development stage of the prototypes. **Figure 17** compares open field DELTA engine noise to two North American gasoline V8 engines.

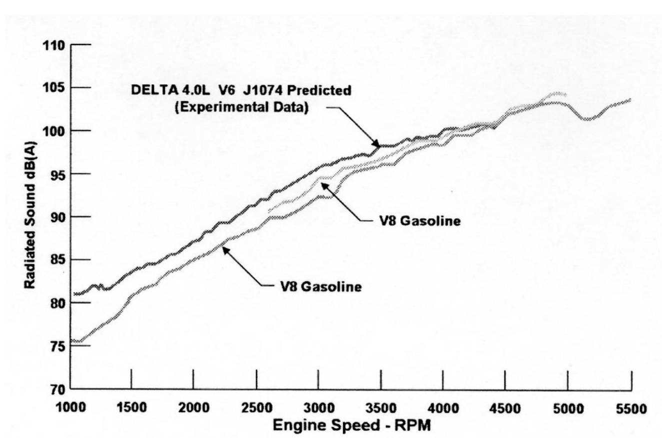

Figure 17. 4.0L V6 DELTA Engine Noise versus North American V8 Gasoline Engines

<u>Emissions</u> – DDC is developing the DELTA engine toward a goal of satisfying future emissions regulations, starting with the 2004 Federal TIER 2 emissions. However, the 2007 timeframe requires different hardware and software packages than earlier 2004 models. Development activities focus on technologies to reduce engine-out emissions and complementary aftertreatment approaches.

Compliance with future emissions standards demands a total vehicle approach to emissions. This includes the fuel quality, engine, transmission, vehicle, and exhaust aftertreatment system.

The basic engine relies upon a balanced approach to in-cylinder emissions control. Unlike their heavy-duty compression ignition engine cousins, HSDI engine combustion is influenced nearly equally by air and fuel system effects. By contrast, the heavy duty diesel in-cylinder mixing and combustion events are dominated by fuel system effects. DELTA relies upon a direct injection combustion system with analytically optimized air and high-pressure fuel systems. The air system includes a cooled Exhaust Gas Recirculation (EGR) system for NO_X control. A VGT facilitates high EGR flow rates, reduces transient particulate emissions, and offers greater flexibility to control combustion characteristics over the transient cycle. Advanced aftertreatment devices, such as particulate traps, Selective Catalytic Reduction (SCR), and NO_X traps, are being considered to fully leverage the benefits from low sulfur fuel, which is anticipated in future EPA rule making.

DDC is involved in intensive efforts to develop advanced aftertreatment technologies which satisfy 2007 emissions regulations. Some of the programs involves partnership with DOE, the National Laboratories and/or aftertreatment partners. Some of the most promising technologies require fuel quality improvements. Sulfur concentrations are one of the most problematic issues facing diesel emissions and aftertreatment development. Fuel sulfur contributes to particulate emissions and poisons many advanced aftertreatment systems.

DDC is pursuing a development strategy, which includes a combination of engine dynamometer, bench, and vehicle tests. For example, some DELTA test vehicles are configured to run the Johnson Matthey CRT™, using sub-10 ppm sulfur fuel. The device is mounted in the vehicle's existing exhaust system, replacing the production muffler. No additional exhaust noise attenuation hardware was required. **Figure 18** shows the modified exhaust system, beside a production muffler for comparison.

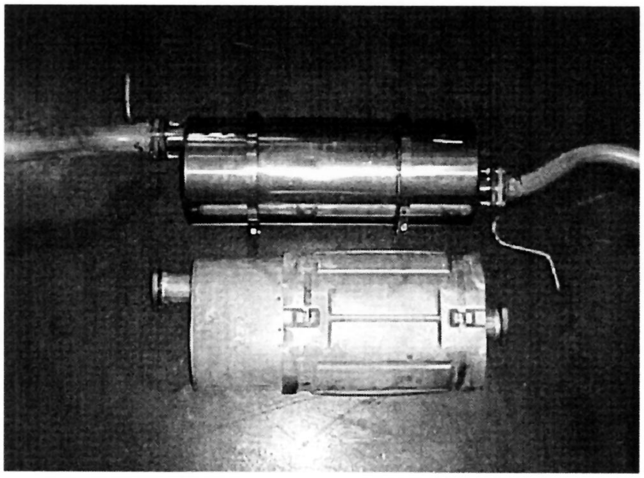

Figure 18. Demonstration Vehicle Exhaust System with Continuously Regenerating Trap System

The first vehicle-level CRT™ tests were initiated with the DELTA engine in late 1998, using non-optimized prototype systems. Despite the preliminary nature of the test hardware, these systems reduced particulate emissions by more than 90%. Refer to **Figure 19**. Early CRT™ tests were conducted with the device located almost 2 meters downstream of the engine. This resulted in considerable thermal losses, with corresponding reductions in catalyst efficiency. Hence, the system was prone to plugging under prolonged light load operation and the volatile particulate fraction was inadequately oxidized. Despite these concerns, the system fully regenerated during operation under normal highway loads.

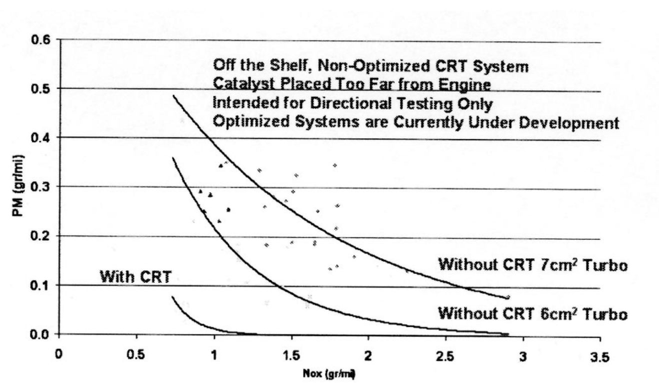

Figure 19. Early CRT™ Comparisons

Although early CRT™ results were encouraging, significant development challenges remain to fully integrate the aftertreatment device with a light duty diesel powertrain. The light duty cycle generates relatively low exhaust temperatures on a diesel engine. Current CRT™ development prototypes require exhaust temperatures over 300 degrees Celsius for a significant portion of the driving cycle to regenerate efficiently. Figure 20 depicts exhaust temperatures at the engine exhaust manifold, compared to the CRT™ inlet and exit.

Combustion system refinements are being pursued in combination with advanced control strategies, air system optimization, and calibration tuning. Engine data is being used to validate analytical modeling methodologies. These tools provide the basis for Generation 1.10 design improvements. Substantial engine-out emissions improvements are expected.

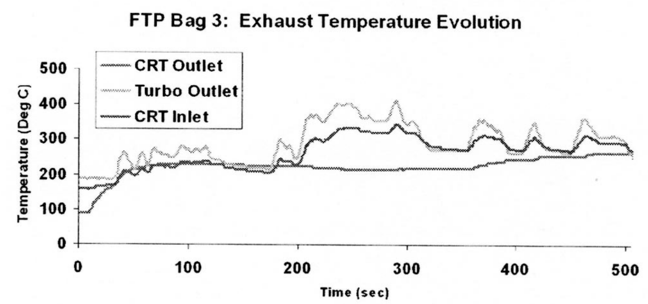

Figure 20. Exhaust Temperatures Over Light Duty Cycle

ONGOING WORK

Generation 0.5 – Following the first Generation 0.0 Durango vehicle development tests, DDC initiated a series of engine improvements. These included electronic controls upgrades and various hardware upgrades. A series of Generation 0.5 engines are now undergoing tests in vehicles and on laboratory dynamometers. Preliminary data has shown significant improvements.

Recent Generation 0.5 tests with higher rated DELTA engines produced much better acceleration characteristics. A 5,950 lb vehicle, equipped with a 230 hp / 375 ft*lbf DELTA engine and a 4-speed automatic transmission, achieved 8.5 second 0 to 60 mph acceleration times. This was within half a second of the full size V8 gasoline mature-product vehicle performance. Vehicle fuel economy improvements were measured at 32%, when compared to the gasoline V8. **Figure 21** depicts vehicle speed as a function of time. One curve represents a standard launch, which is subject to wastegated turbocharger lag. The second curve was achieved by launching the vehicle after applying load to the engine, using the torque converter and the vehicle brakes.

Generation 0.5 engines are currently operating with VGT turbochargers, which are demonstrating considerable performance, emissions, and fuel economy advantages. **Figure 22** compares steady state fuel economy for original Generation 0.0 wastegate engine to various Generation 0.5 VGT configurations.

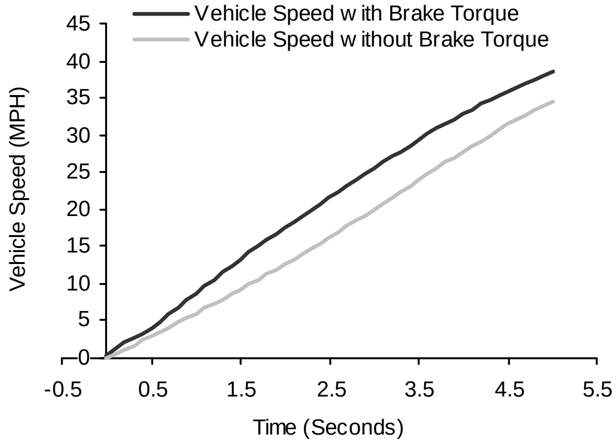

Figure 21. Gen 0.5 Launch Characteristics, 4.0L V6 DELTA w/ 4-Speed Automatic Transmission

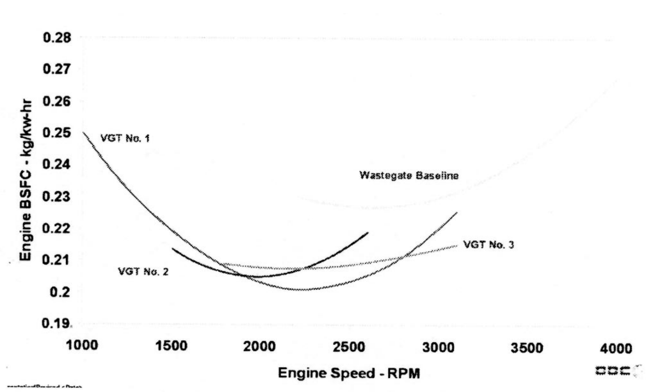

Figure 22. VGT Fuel Economy Improvements

Generation 1.0 – DDC is refining Generation 1.0 engine for testing in early 2001. This engine design includes a series of improvements, which could not be achieved using the Generation 0.0 and 0.5 tooling. An integral oil cooler will be added to the engine. Block, head, and bedplate optimization efforts will yield significant weight reductions. Manufacturing strategy improvements have been added

DDC is optimizing the air system to exploit the VGT, which significantly improves acceleration, emissions, and fuel economy characteristics. This is an enabling technology for emissions. Air system upgrades will include intake manifold modifications, which further improve EGR cooler effectiveness, EGR distribution characteristics, and total engine thermal management.

Fuel system enhancements will be added in conjunction with advanced model based control strategies. Combustion chamber refinements are targeted to reduce exhaust emissions.

CONCLUSION

DELTA technology has successfully established new benchmarks for new prototype development processes and North American light truck diesel noise, vibration, performance, and driveability. The engine provides near gasoline-like noise and vibration characteristics, while providing better driveability characteristics and improved fuel economy than its gasoline counterparts. Future development activities will focus on continued emissions development, NVH refinement, and weight reduction. Public demonstrations and drive evaluations with the automotive press have generated very favorable feedback.

DELTA technology can clearly compete with gasoline V8 engines within the North American light truck market. Through further development and vehicle integration, even more impressive NVH and driveability characteristics are possible.

CARB and EPA emissions legislation remain difficult challenges for diesel engine development in the United States. Technology development programs like the DOE Light Truck Clean Diesel Program enhance the potential to reach these standards. Fuel quality improvements, and advanced aftertreatment technologies will be necessary.

DDC remains committed to developing the DELTA engine toward this end. Generation 0.5 prototypes are undergoing performance and emissions development tests. Generation 1.0 design enhancements are underway, with a focus on incorporating consumer and vehicle OEM feedback. The first Generation 1.0 hardware is expected later this year.

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Detroit Diesel Corporation and the author wish to thank the Department Of Energy (DOE) for its support of the North American Light Truck Clean Diesel initiative and specifically the DELTA development effort. DOE's support is essential as we work to develop new technologies, which can address North America's unique SUV/Light Truck market challenges.

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Specific acknowledgements must be made to Fabien Redon and the entire DDC Pilot Center team who executed incredible team efforts to complete the first running prototype vehicles. They expedited a demonstration vehicle in under 12 weeks; ready to demonstrate to the automotive press. These incredible results speak for themselves. They are magicians.

The author would like to also thank Eric J. Merchant, who supported this program with exceptional graphics and publications. He puts the art into our technical presentations.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CAFE: Corporate Average Fuel Economy
CARB: California Air Resource Board
CRT: Continuously Regenerating Trap: A Johnson Matthey aftertreatment device, designed to remove particulate mass from the engine out exhaust emissions, with extremely high efficiency.
DDC: Detroit Diesel Corporation
DELTA: Diesel Engine Light Truck Application: This is a 4.0L V6 diesel engine, which was developed for the North American light truck market.
DOE: United States Department Of Energy
DOHC: Dual Overhead Camshaft: Valvetrain arrangement with two camshafts located above each cylinder bank. The camshafts drive the valves through a direct linkage, without push rods.
EGR: Exhaust Gas Recirculation: Exhaust, which is returned to the combustion chamber, to reduce NO_x emissions.
EPA: United States Environmental Protection Agency
GVW: Gross Vehicle Weight (in pounds)
HSDI: High Speed Direct Injection: Diesel engine classification, commonly used for passenger car applications in Europe.
lb: Pounds
MPG: Miles Per Gallon
MPH: Miles Per Hour
NVH: Noise & Vibration Harshness
OEM: Original Equipment Manufacturer
OHV: Overhead Valve: Valvetrain arrangement with the camshaft located in the cylinder block structure. The valves are actuated through a push rod linkage.
PPM: Parts per Million
QFD: Quality Function Deployment Analysis
SOHC: Single Overhead Camshaft: Valvetrain arrangement with a single camshaft located above each cylinder bank. The camshaft drives the valves through a direct linkage, without push rods.
SUV: Sport Utility Vehicle
Ti-Al: Titanium Aluminide
VGT: Variable Geometry Turbine: An electronically controlled turbine, with variable air impingement angle. The device can be calibrated to minimize efficiency compromises over most of the operating cycle. It also increases flexibility to increase EGR rates and improve engine warm-up characteristics.