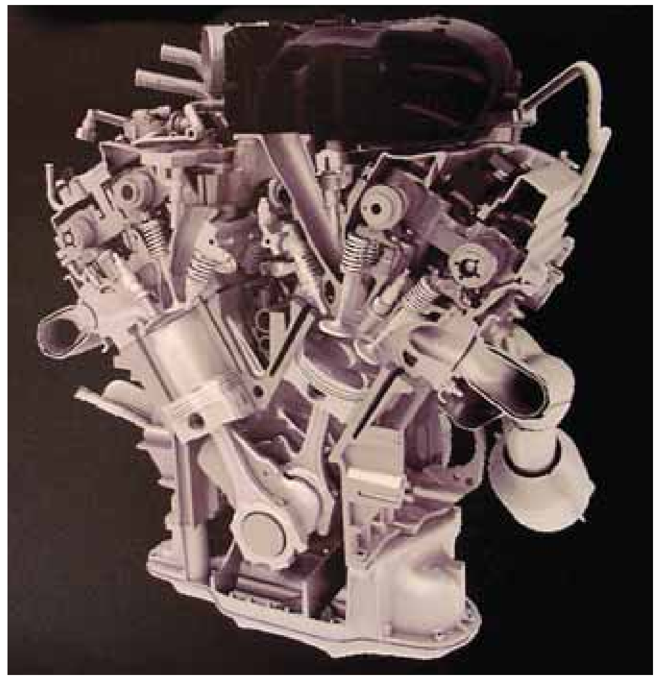
Lexus gives V6 dual injection

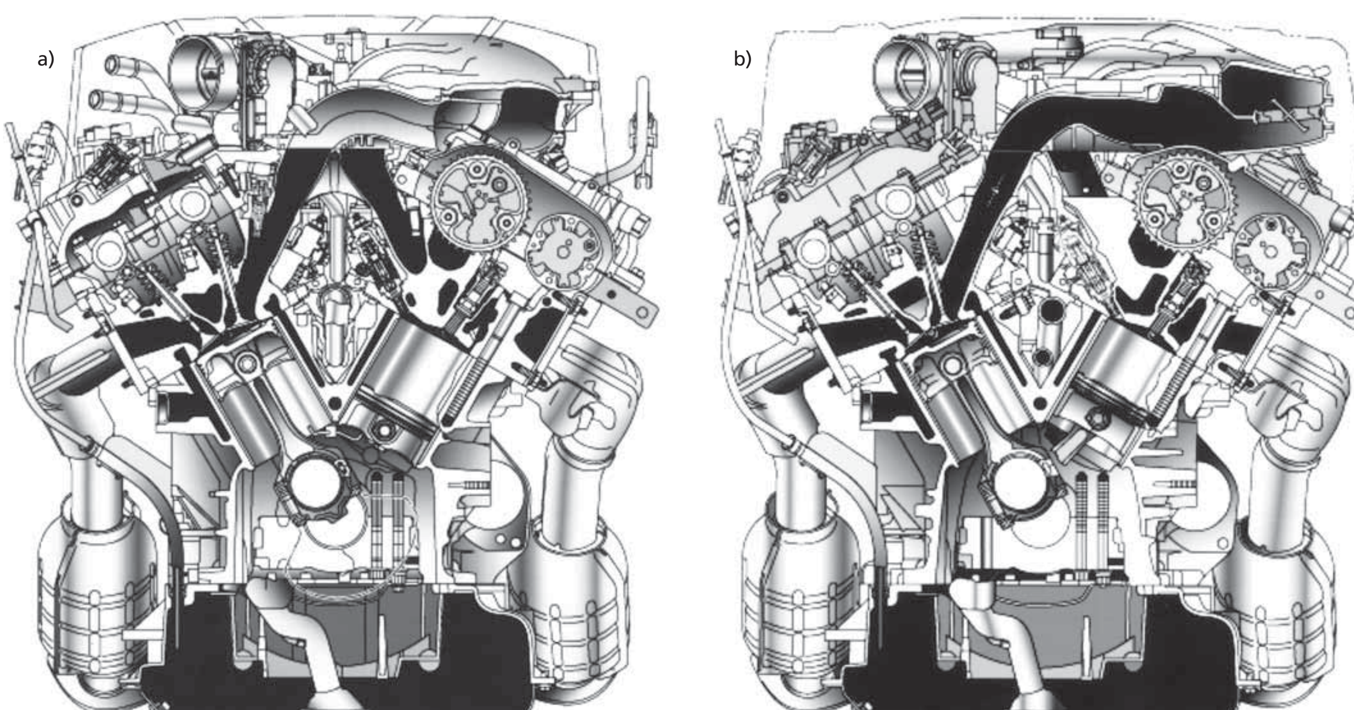
The 2GR-FSE is the latest and most powerful member of **Toyota**'s GR-series light-alloy, quad-camshaft, four-valves-per-cylinder, 60-degree bank angle V6 family, and encompasses the company's leading-edge direct-injection gasoline engine technology.

The 2GR-FSE is uniquely significant for Toyota and its newly formed (for Japan) **Lexus** Division, says Project General Manager Shizuo Abe of Engine Design Dept. 1, Engine Engineering Division 1. It propels the new Lexus GS and IS sedans, two of the three launch vehicles of the premier brand in Japan, as well the IS350 for the world market and the soon-to-be-launched GS450h gasoline-electric hybrid.

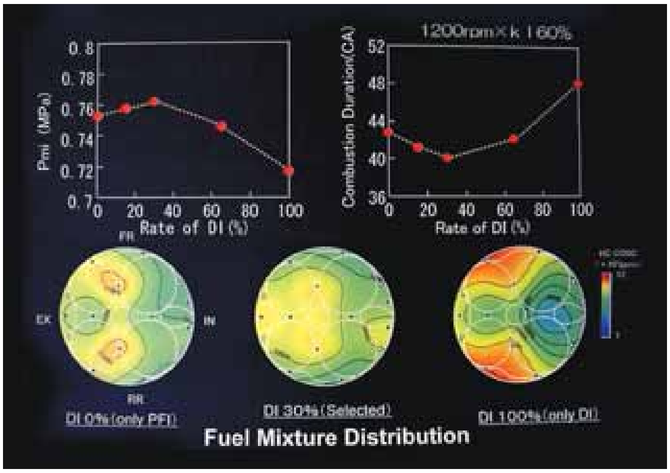
The 2GR-FSE was conceived, designed, developed, and seen to its product fruition in Toyota's project-focused system called Project "Suishin" Department. As the Japanese words means "propel with urgency," the environment allows the team to fiercely dedicate its efforts on the project on hand that is THE ONE, not one



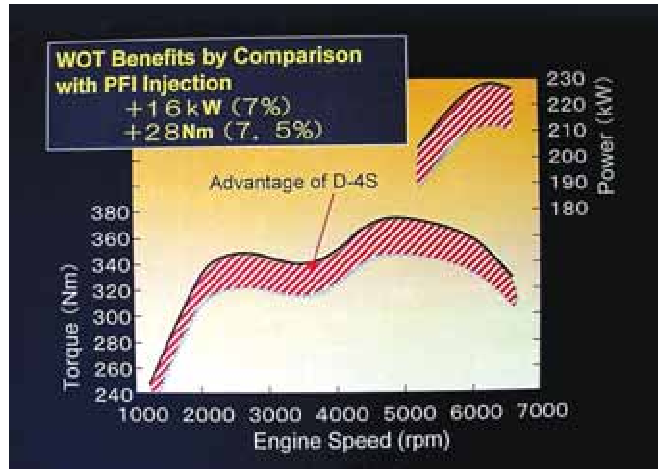
The 2GR-FSE engine for Lexus applications initially gets port and direct injectors.



The cross sections show: a) the D-4S engine with direct and port injectors, and b) the 3GR-FSE direct-injection D-4 version.



Combustion is improved by combining direct and port injection.



Shaded area shows improved torque by D4-S dual injection.

of many. Abe is now back "home" with Engine Design Dept. 1.

The 2GR-FSE team set three development objectives: 1) enhanced power output, emissions performance, and fuel economy, 2) higher revolutions, and 3) "Lexus sounds." As the number in its designation indicates, the 2GR-FSE displaces 3.5 L by enlarging the bore and gaining 500 cm^3 over the preceding 3GR-FSE that had preceded powering the new Lexus GS300 for the U.S. and Europe and the Japanese Toyota Crown.

The team was not content with the mundane method of increasing displacement, however, and decided to further improve the D-4 direct injection system, progressing it to D-4S, the suffix meaning Superior.

The D-4 label, first put on the original stratified-charge, lean-burn inline four-cylinder 2.0-L engine in a Japanese-market mid-size sedan in 1996, meant four distinctive benefits with each adjective beginning with the letter D. The system evolved to the second and third generations with numerous refinements in both inline four and six cylinder series. As emissions regulations became more stringent, Toyota shifted from the stratified-charge, lean-burn strategy to a stoichiometric one, first in the 2.0-L four in a mid-size European sedan launched in 2000 that satisfied Europe's tough Step 4 standards in 2003, together with its sister 2.4-L version and the new 3/4GR-FSE 3.0- and 2.5-L V6s. During the progression, the D-4 designation has become a simple descriptive "Direct-injection, 4-stroke engine."

The 2GR-FSE employs two injectors per cylinder, versus the 3GR/4GR-FSE's single direct injector. The direct-injector position is unchanged from the smaller engines', at the outer side of the intake valves on the cylinder periphery. The injector is the new "double vertical fan-shaped spray" type, versus the 3GR-FSE's single fan spray variety. The injector tip has two inverted V-shaped slits, each measuring 0.13 x 0.52 mm (0.005 x 0.02 in), injecting twin fan-shaped (viewed from the side) sprays into the combustion chamber, achieving optimally homogeneous and dense fuel mists. The vertical spray injector was conceived specifically for the stoichiometric direct-injection engine, versus the previous single-slit, "lateral spray" type that had been designed for the original stratified D-4, however, adapted to the latter stoichiometric types, according to Abe.

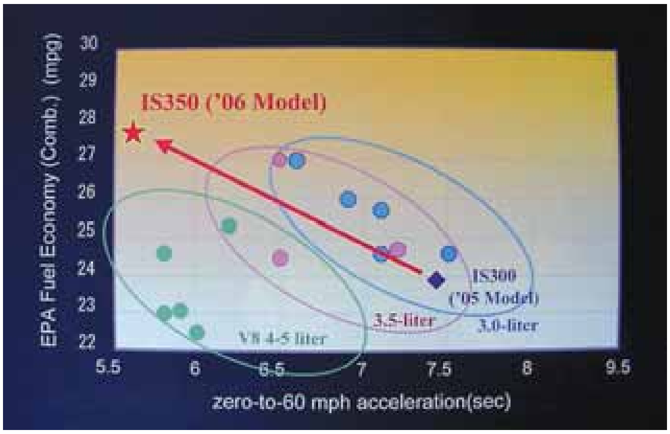
Abe praises two partners, **Yamaha** and **Denso**, for their contributions to the design and development of the D-4S system. The vertical slit injector is a fruit of Toyota-Yamaha collaborative efforts, the latter playing an important role in the design and development of the engine's injection system, and putting it in series production as well. Of Denso, Abe said, "Had it been not Denso, or been a non-Japanese supplier, it wouldn't have undertaken the development and production of this precision injector. It was two years ago we approached Denso with the conceptual design of this novel injector, after only a few years since we had adopted the first single-slit injector in our GR-series engine!"

The port injector, a 12-hole type—each hole 0.19 mm (0.0075 in) in diameter and also of Denso supply—is positioned upstream in the intake port.

The stoichiometric direct-injection's benefits are lower mixture temperature by charge vaporizing effects, improving volumetric efficiency and precluding early knocking, thus allowing a higher compression ratio at 11.8-to-one in the 2GR-FSE. The engine has gained about seven percent in WOT performance versus the port-injection type, the 2GR-FE that powers the U.S. Avalon sedan—more specifically, 16 kW (21 hp) and 28 N·m (21 lb·ft) higher in the peak outputs than the FE version.

The 2GR-FSE employs what may be described as "hybrid direct-injection, port-injection strategy," the only known such system among volume production engines in the "emission control zone," according to Abe. He cites a sample operating condition at 1200 rpm with a 60% load ratio: with direct-injection alone, fuel tends to form in lumps due to heavier fuel volume and slow piston speed, lengthening combustion duration, and thus limiting torque output. On the other hand, port-injection alone would not necessarily be better. Adding 30 to 40% direct-injection to port-injection accelerates gas flow, significantly improves torque output.

Injection ratio between the two injectors is continuously varied—for example 30 to 40% in a specific parameter, and increased to 50 to 60% in another zone—optimizing the mix and distribution. Ultimately in high-rpm zone, 100-perecent direct-injection is used to obtain higher torque. "Simply stated, the ratio is dependant on rpm and load, but its control is extremely intricate and complex—for example, not impairing the system's learning ability," Abe said. "It is stepless; nevertheless, each process is carefully preserved, all based on our accumulation of dual-injector knowledge and experiences



Performance and efficiency are improved in the new Lexus IS350 powered by the 2GR-FSE.

Project General Manager Shizuo Abe has seen the 2GR-FSE D-4S to fruition.

since the early 1990s, obtaining more than 300 patents."

In the 3GR-FSE 3.0-L unit of the Lexus GS300, in-cylinder mixing is promoted by two flow control measures: one the high-tumble intake port shape, and for lower speed mixing a swirl-control valve in one of the two intake ports for each cylinder. The 2GR-FSE employs neither, and does away with the smaller engine's ACIS (acoustic variable induction system).

Reduction of cold-start hydrocarbon emission is critical in the vehicle's emissions control performance. The 2GR-FSE adopts an elaborate strategy, operating in "weak stratified-charge combustion." First the port injector injects fuel during the expansion and intake strokes before the intake valves open. Homogeneous charge is introduced into the combustion chamber when the intake valves open. During the latter part of the compression stroke, the direct-injector spurts fuel into the cavity in the piston crown, forming "weak lean stratified charge"; in the combustion chamber, the air/fuel ratio is in the 15-to-one range. The centrally positioned spark plug ignites the richer mixture during the expansion stroke. This combustion process retards ignition timing without adverse effects in the engine's running, enabling higher exhaust temperature to quickly light off the catalyst.

The piston cavity's sole purpose is for this weak stratified-charge operation, and it need not be a deep one—only 5.0-mm in depth. The oval cavity is a Toyota/Abe patent, its shape and position in relation to the spark plug optimized so that all the mixtures in the cavity reflect and travel to the spark in equal distance. The D-4S-equipped 2GR-FSE qualifies for the PA ULEV II emission category, versus the D-4 3GR-FSE's ULEV I classification.

The engine is equipped with dual VVT-i variable valve timing system. The rotating and reciprocating components are strengthened and lighter in mass.

The 2GR-FSE obtains a total cubic displacement of 3456 cm^3 with 94.0-mm (3.70-in) bore and 83-mm (3.28-in) stroke. In the U.S.-market Lexus IS350, it is rated at 306 hp (228 kW) at 6400 rpm and 277 lb·ft (376 N·m) at 4800 rpm. The Japanese-specification engine in the same vehicle produces 234 kW (314 hp) and 380 N·m (280 lb·ft) at the same rpm.

Abe confides that the 2GR-FSE engine in the Lexus GS450h gasoline-electric hybrid application is little changed from the straightforward gasoline GS350 (the Japanese model is powered by the 3.5-L unit). The engine combines high performance and ULEV II-level emissions reduction capability. It is literally synergy effects that the THS-II hybrid system derives in combination with the 2GR-FSE, attaining on-road performance matching that of a comparable conventional 4.5-L V8-powered car. The released performance data quotes engine output of "over 200 kW/286 DIN ps, motor output over 140 kW/190 DIN ps, and combined system performance over 250 kW/340 DIN ps (as of the 2005 Frankfurt Show)." The car is to qualify for EPA SULEV and European Step 4 emissions standards, the latter including CO_2 emissions of under 195 g/100 km.

On Toyota's claim of the GS450h's fuel consumption to be comparable to "a 4-cylinder 2.0-L-engined vehicle, Abe explains that it is attributable to three technological features: 1) idle stop, 2) the THS-II's CVT effects, and 3) regenerative braking. The Hybrid Synergy System's forte is indeed largely in city and urban operation. At higher highway cruising the engine is already near its optimum efficiency, therefore the hybrid system's contribution is small.

Jack K. Yamaguchi

Ford joins the 3.5-L V6 club

Ford's new 3.5-L V6 engine will enter production next fall, and it's already putting smiles on the faces of the automaker's North American vehicle development teams and retail dealers.

As competitors have launched increasingly refined, better-performing D- and E-class front-wheel-drive (FWD) sedans and crossover utility vehicles (CUVs), Ford has found itself falling behind in the power arena in these critical segments. Currently it has only the 3.0-L Duratec V6 available to battle 3.5-3.6-L V6 engines with significantly more power and torque from **Toyota**, **Nissan**, **Honda**, and **General Motors**.

The new 3.5-L V6, known to suppliers as the Cyclone program since approval in early 2003, rectifies the 3.0-L's power deficit. It also brings major strides in NVH attenuation and emissions control, and its base design offers ample development headroom. Slated to power 20% of Ford's North American vehicles by 2010, the 3.5-L is key to the automaker's future product strategy.

The engine will see widespread duty across Ford's highest-volume midsize vehicle architecture. The so-called CD1-3 platform underpins the **Mazda**6, Ford

Together, the new Ford 3.5-L V6 engine and 6F 6-speed automatic transmission deliver improved powertrain stiffness

Ford's new V6 engine features chain-driven camshafts, pencil-type ignition coils, and a conventional (non-active) intake manifold.

Fusion, **Mercury** Milan, and numerous future FWD and all-wheel-drive passenger vehicle programs. It will be paired with Ford's new 6F FWD transmission, the planetary six-speed co-developed with General Motors.

Launched in naturally aspirated form with sequential-port fuel injection, the 3.5-L is protected for turbocharging and direct injection. These technologies, according to Ford's new Vice President of Powertrain Operations, Barb Samardzich, are being investigated for future iterations to improve overall performance. The engine also is compatible with hybrid-electric-vehicle drivetrains; Ford is developing its so-called third-generation hybrids for the 2008 time frame.

First applications for the new V6 will be the 2007 Ford Edge and **Lincoln** Aviator CUVs unveiled at the North American International Auto Show. Total annual production volumes are expected to reach 750,000 units from the Lima and Cleveland, OH, engine plants, according to Casey Selecman, powertrain analyst at forecaster **CSM Worldwide**. He added that it is likely Ford also will employ the new V6 in some markets outside the United States.

With claimed output ratings of 250 hp (186 kW) at 6250 rpm and 240 lb·ft (325 N·m) of torque at 4500 rpm, the 3.5-L easily out-muscles the 3.0-L's 203 hp (151 kW) and 207 lb·ft (280 N·m) and puts Ford back in the power game against its V6 rivals. Although the larger V6's maximum power is produced 500 rpm farther up the rev range than the 3.0-L's, its maximum torque arrives at the same 4500 rpm.

Increased thrust was but one priority among the program's design targets, explained Program Manager Tom McCarthy. "Our goal was to deliver to the customer on many fronts with a simple, straightforward, basic design," he said.

While both engines feature aluminum construction, twin overhead camshafts, and four valves per cylinder, the new V6 is considered a completely new architecture by Ford. The 3.5-L's 106-mm (4.17-in) bore centers are spaced 4 mm (0.16 in) farther apart than on the 3.0-L, which "is pretty much maxed out at its current displacement," said Dan Kapp, Director of Powertrain Engineering.

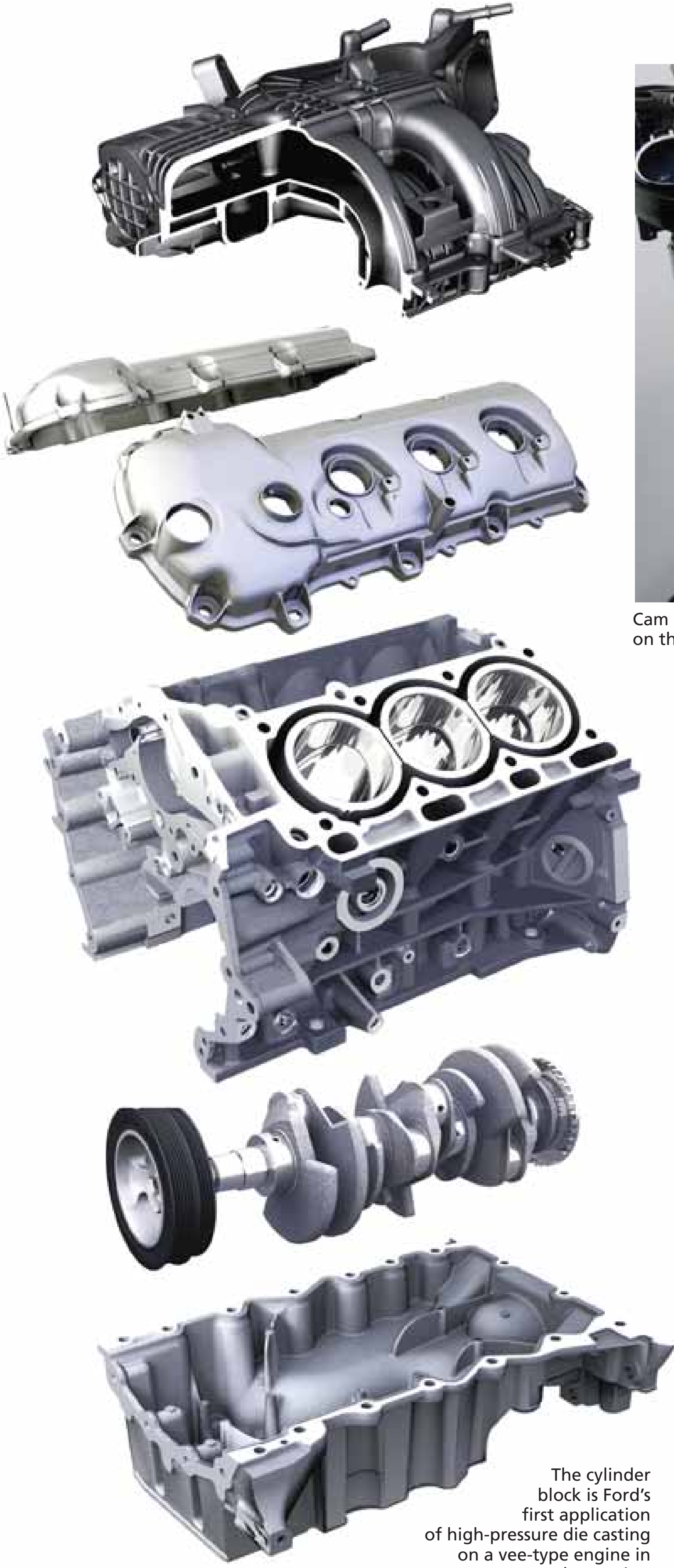
Bore and stroke measure 92.5 x 86.7 mm (3.64 x 3.41 in)—a 1.06 bore/stroke ratio—making the new V6 a bit less oversquare than the old Duratec's 88.9 x 78.7 mm (3.5 x 3.1 in) and 1.13 bore/stroke ratio.

Increasing displacement by half a liter created concerns about greater NVH—an issue that also challenged Nissan when it bumped its VQ V6 out to 3.5-L. "We focused heavily on the overall powerplant stiffness—engine and 6F transmission combined—bending performance compared with our previous powertrains and believe we're absolutely competitive in this area," McCarthy said.

He noted that the V6 and 6F transmission were Ford's first application of the Six Sigma design process on an overall program. "We tried to deliver all the key customer attributes up front within the base design," he said, "so there was a lot of concurrent analytical design work—far more than any architecture in the past."

The V6 is Ford's first application of a high-pressure die-cast cylinder block, said Kapp. Much attention was paid to creating an extremely stout rear face of the cylinder block casting, which is double-walled and extensively webbed around the rear main bearing circumference. The

Cam phasers on intake cams deliver high-value emissions performance on the newest V6 engine from Ford.



The cylinder block is Ford's first application of high-pressure die casting on a vee-type engine in North America.

block itself is in 383 alloy and features a deep skirt and cast-in iron liners. The overall design is sufficiently optimized for stiffness and thus does not require a bedplate, unlike the 3.0-L.

Other key weapons in the NVH war include cross-bolted, six-bolt main bearings; a forged-steel, fully counterweighted crankshaft; high-pressure, die-cast structural oilpan; cast-aluminum cam covers with fully isolated mountings; and three-layer metallic/rubber damping material on the front cover.

For the cam covers, McCarthy's team chose aluminum rather than an engineering composite, believing that it more effectively damps noise and gives superior isolation without the "creep" of plastic materials. Also, the aluminum better resists the higher temperatures created by the 3.5's close-coupled exhaust catalysts, he said.

Validation testing proved that the new engine's NVH numbers virtually match those of the 3.0-L V6—a triumph, said McCarthy, because the smaller engine has a slightly more compact structure and less inherent reciprocating mass.

The 3.5-L continues Ford's move to powder-metal connecting rods with "cracked" big ends. Cast-aluminum pistons are moly-coated for reduced friction. According to McCarthy, the pistons carry a "fairly standard" ring pack. Crevice volumes are similar to those on the 3.0's pistons.

To reduce crankcase pressure, the cylinder block incorporates windows within the cylinder bulkheads that help augment bay-to-bay breathing. The windows control the buildup of pressure during the downstroke of the pistons, which helps dissipate the crankcase pressure.

The V6's compact water pump is located inside the block. Cam-driven, it is fed through the block's valley into an axial coolant inlet. The pump has a radial outlet that McCarthy believes is best for pump efficiency. The 3.5-L was designed for very low complexity in terms of the number of variants (intake and exhaust manifolds, for example) and variant codes.

Another major program target was good airflow and com-

Ford's New V6 vs. the Competition

Vehicle	Displacement, L	Valve gear—all have 4 valves/cylinder	Cylinder deactivation	Bore x stroke, in (mm)	Compression ratio, :1	Power, hp (kW)@ rpm	Power density, hp/L (kW/L)	Torque, lb·ft (N·m) @ rpm	Fuel grade required
Ford Edge	3.5	DOHC with VCT	No	3.64 x 3.41 (92.5 x 86.7)	10.03	250 (186) @ 6250	71.4 (53.2)	240 (325) @ 4500	Regular
Buick LaCrosse	3.6	DOHC with VVT	No	3.70 x 3.37 (94 x 85.6)	10.2	240 (179) @ 6000	66.4 (49.5)	225 (305) @ 2000	Regular
Honda Pilot	3.5	SOHC with i-VTEC	Yes	3.50 x 3.66 (89 x 93)	10.1	244 (182) @ 5750	69.7 (52.0)	240 (325) @ 4500	Regular
Nissan Maxima	3.5	DOHC with VVT	No	3.76 x 3.20 (95.5 x 81.4)	10.3	265 (198) @ 5800	75.7 (56.4)	255 (346) @ 4400	Premium
Toyota Avalon	3.5	DOHC with i-VVT	No	3.70 x 3.27 (94 x 83)	10.8	268 (200) @ 6200	76.5 (57.0)	248 (336) @ 4700	Regular

Program Manager Tom McCarthy (left) and Director of Powertrain Engineering Dan Kapp (right) .

Rapid-prototyping the V6

Durability testing late in the 3.5-L V6 program revealed the need for some significant changes that **Ford** engineers said could potentially affect the durability of the engine and threatened to delay launch if not quickly rectified. To resolve the issues, Ford called on its rapid prototyping facility (officially called the Beech Daly Technical Center) near Dearborn, MI.

"There were some design changes required," said Todd Kloeb, Manager of Rapid Manufacturing Technologies. Although he declined to pinpoint the issues, Kloeb explained there was one particular component that would have been prohibitively costly and time-consuming to completely retool.

"Using our stereolithography process, we produced five iterations of a redesigned item and had them cast, machined, and on the dyno within five days," said Kloeb. "We did five different designs at different design levels simultaneously, rather than waiting for one at a time. You make the modification on the CAD, then the next part can be as different as you want it to be."

Ford intends to increasingly use rapid-prototyping tools further up front in future powertrain projects, said Kloeb.

"The bottom line is, we want to get to dyno quicker and, more importantly, with fewer prototypes to achieve the same test bed." Traditionally Ford commits to 50-60 prototypes for each development phase, and nearly ten times that many in the late stages of some programs. With the Beech Daly facility, it can make as many different parts as required to get through a test sequence.

"Less time is important," said Kloeb, "but more importantly, it reduces our commitment to any type of quantity."

bustion for improved fuel efficiency and emissions. Variable camshaft timing is incorporated on the intake side, and extensive CAE analysis of the combustion chambers and ports negated the need for a more costly variable-geometry intake system. The 3.5-L will launch with a ULEV-II emissions rating, but McCarthy noted it is capable of achieving California's more stringent P-ZEV (partial zero emissions vehicle) levels with slight calibration changes.

The V6's air-fuel system features an electronically controlled throttle and two-section inlet manifold—a nylon 6/6 upper half with cast-aluminum lower section.

"This engine's chambers and porting are not carryover," said McCarthy. "It's all new. We spent an enormous amount of time using CAE to optimize the squish characteristics of the central-plug chambers. The 3.5-L's air-fuel mixing is much improved; we achieved excellent idle stability, fuel consumption, and performance in terms of flow."

The 3.5 uses cam phasers on the intake side. The decision to use variable cam timing, which varies valve timing but not lift, vs other types of variable-valve timing was driven by cost and valvetrain architecture, McCarthy explained.

"This design gives best value to the customer," he said. "Intake phasers deliver a very good augmentation of the torque curve by controlling the intake breathing. They also give some fuel efficiency because they allow us to optimize cam timing at part-throttle. This system also gives us good control of overlap, which helps improve idle quality, stability, and lower emissions."

The V6's 37-mm (1.46-in) intake and 31-mm (1.22-in) exhaust valves are actuated via Ford's first North American use of shimless, direct-acting mechanical bucket tappets. According to McCarthy, this design reduces valvetrain vibration during high-rpm operation, another NVH bonus.

The 3.5-L's cylinder heads were developed for CNC flexible machining, a strategy Ford originally developed for its V8 heads. CNC production will help augment a switch to direct fuel injection, a route McCarthy indicated that Ford is seriously considering for this V6 in the future.

Not in the cards for this engine, at least with its current cylinder heads, is cylinder deactivation. McCarthy said Ford has not yet developed this technology for its V6, but it is currently employed by Honda on its 3.5-L and will soon be used by GM and other competitive engines.

Combined with close-coupled catalysts (for quicker light off) and retargeted fuel injectors (for better cold-start performance), the 3.5-L's admittedly simple intake system allows the new engine to meet all of Ford's internal targets running on 87-octane gasoline, and without what McCarthy calls "a lot of add-ons" such as EGR and other valves. It provides P-ZEV capability with minimal calibration tweaks if required. And in terms of package efficiency, the dressed engine is "fairly close" to the 3.0-L, with nearly identical width and height and only slightly longer length (due to the broader bore spacing).

No wonder the vehicle teams are excited.

Lindsay Brooke

VW combines turbo, supercharging

Thanks to the rapid development of engine combustion systems and electronics technology, downsizing to achieve improved fuel consumption and lower emissions without losing driveability and tractability qualities has become a reality. Part of the equation for successful downsizing—particularly of diesel engines—almost invariably involves the use of turbocharging.

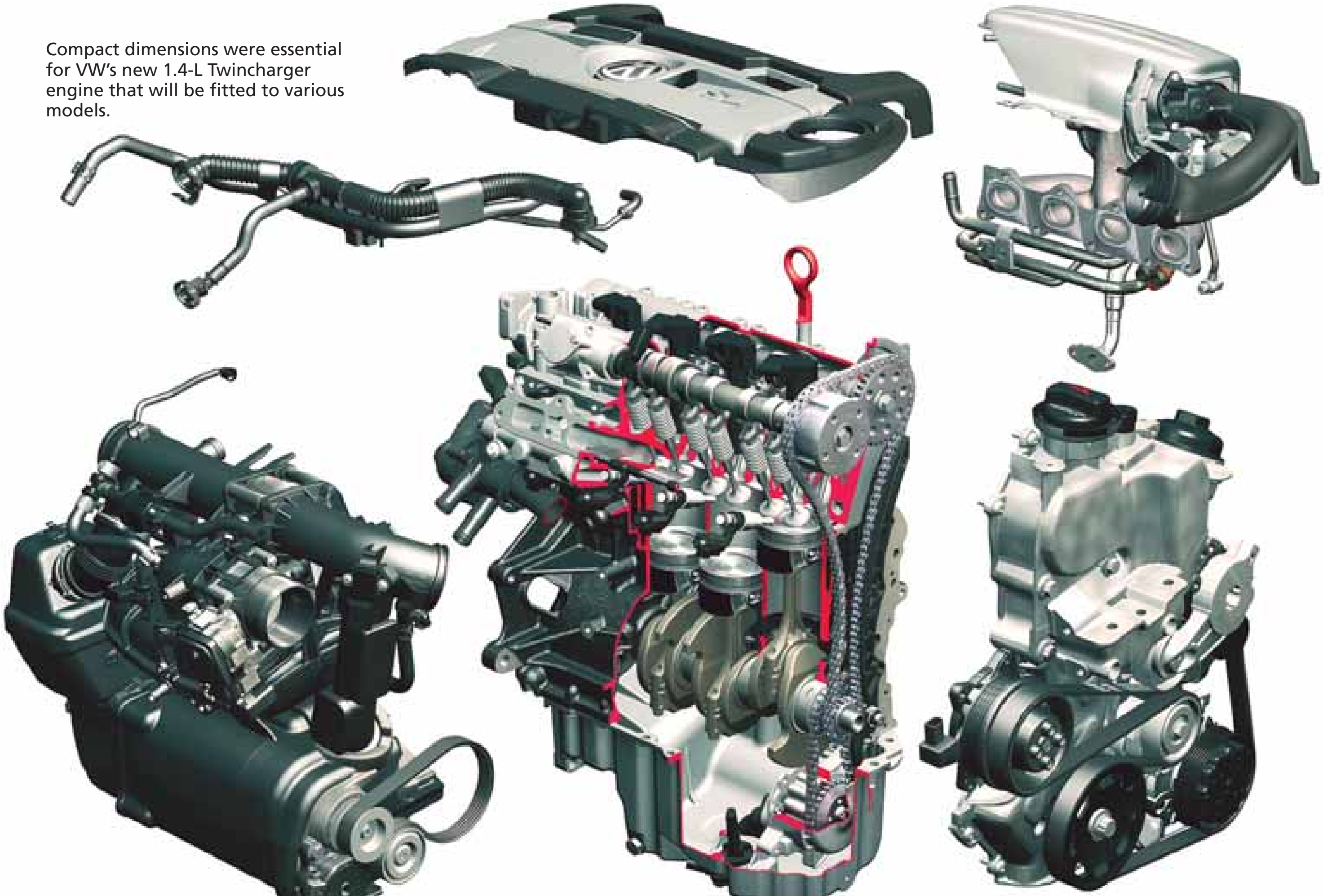
Although turbochargers have become highly sophisticated, their use still brings elements of compromise in terms of driveability and torque delivery, particularly at low revs. A mechanically driven supercharger will overcome this, but it is a compromise solution. So **Volkswagen** has set out to minimize those compromises by applying a new system called Twincharger—not to a diesel but to a direct-injection gasoline (FSI) 1.4-L engine, combining both turbocharger and Roots-type supercharger functions, each designed to complement the other and provide a high degree of linear power and torque delivery from very low engine speeds.

VW has chosen the Golf GT as its first model to use the engine. The company's figures comparing the performance of the 1.4-L Twincharger version of the car with that of the regular 2.0-L FSI make very interesting reading. The 1.4 Twincharger (TSI) produces 125 kW (168 hp) at 6000 rpm, or 90 kW/L (120 hp/L), the 2.0-L unit 110 kW (147 hp) at the same engine speed. Maximum torque of the smaller engine is 240 N·m (177 lb·ft) from 1750 rpm to 4500 rpm, that of the 2.0-L, 200 N·m (147 lb·ft) at 3500 rpm. At 7.9 s, the 1.4-L is 0.9 s quicker to 100 km/h (62 mph), and its maximum speed is 220 vs. 209 km/h (137 vs. 130 mph). Overall fuel consumption of the 1.4 is 7.2 L/100 km with CO_2 emissions of 173 g/km; the 2.0 L returns 7.6 L/100 km

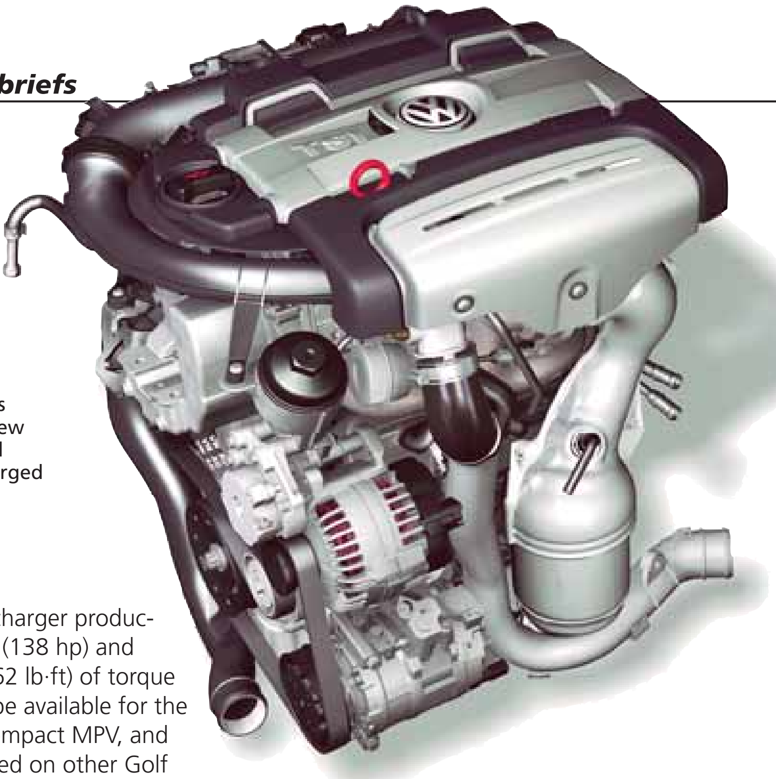
Beneath the hood of the VW Golf GT is a 1.4-L Twincharger engine producing 125 kW (168 hp) and 240N·m (177 lb·ft).

and pumps out 182 g/km of CO_2. The Twincharger Golf GT can also be specified with a double-clutch Direct Shift Gearbox (DSG).

Design criteria for the Twincharger engine included high specific output, low fuel consumption, and compact dimensions to enable it to be integrated into various models. A lower-powered version



Compact dimensions were essential for VW's new 1.4-L Twincharger engine that will be fitted to various models.



The sum of its parts: VW's new turbocharged and supercharged four-cylinder engine.

of the Twincharger producing 103 kW (138 hp) and 220 N·m (162 lb·ft) of torque will shortly be available for the Touran, a compact MPV, and will be offered on other Golf models.

VW also needed to ensure that cost-effective high-volume manufacture of the engine could be achieved without introducing production line complexity. The company elected to use its four-cylinder EA 111 FSI power unit as the basis for the Twincharger. In its regular applications, the engine is a 1.4-L producing a relatively modest 66 kW (88 hp) or as a 1.6-L with 85 kW (114 hp). Immediate priority was to develop a new gray-cast-iron crankcase to withstand pressures of up to 21.7 bar (314 psi) for extended high-speed running. Supercharging technology was a parallel technology challenge, as was a water pump with integrated magnetic clutch.

The base engine's injection technology was modified, and multiple-hole high-pressure injectors with six fuel outlets introduced. As with naturally aspirated FSI engines, the injector is positioned on the intake side between the intake port and cylinder head seal. Injection pressure was set at a maximum 150 bar (2180 psi). FSI technology facilitated a high (for a turbo/supercharged engine) 10:1 compression ratio.

VW decided that a single-stage turbocharger could not deliver its required power density of at least 90 kW/L from the 1.4-L engine. But the addition of an upstream supercharger would enable the boost pressure of the exhaust-driven turbocharger to be markedly increased and would also fill the torque gap at low engine revs that is always to some degree a downside with turbocharger technology. So the Twincharger concept emerged.

The Roots T24 supercharger is belt-driven, with an internal step-up ratio on the input end of its two synchronization gears. Together, the belt and gear drives cause the supercharger to turn at five times crankshaft speed. A magnetic clutch, housed within the hub of the supercharger drive pulley and operating in a similar way to that of an air conditioner compressor, enables the unit to be engaged automatically when required. The supercharger is connected in series with the **Garrett** turbocharger. A control flap facilitates the ingress of air to both the turbocharger and supercharger. As with a regular turbo setup, the air flows from a charge-air cooler and the throttle valve into the induction manifold.

Maximum boost pressure of the Twincharger is about 2.5 bar (36 psi) absolute at 1500 rpm, the turbocharger and supercharger being operated at about the same pressure ratio of some 1.53:1. VW stated that using just a turbocharger would only achieve about 1.3 bar (19 psi). The faster response of the turbocharger enables the supercharger to be de-pressurized earlier by continuous opening of the bypass valve, so compressor operation is restricted to what VW describes as a narrow map area with predominantly low pressure ratios, which make for low power consumption, so limiting the disadvantages of the mechanical supercharger's power consumption. The supercharger effectively provides boost from just over idling speed to 2400 rpm and then "hands over" to the turbocharger. By 3500 rpm, all boost comes from the turbocharger.

The engine is particularly economical in the cruise, giving an inter-urban consumption of 5.9 L/100 km. Urban consumption is 9.6 L/100 km.

A major challenge for VW's engineers was to ensure that the supercharger and turbocharger complemented each other. The company stated that the system it uses achieves this, with "absolutely no turbo lag." The supercharger provides a boost pressure of 1.8 bar (26 psi) from an engine speed "just above" idle, said VW in a statement. Torque of 200 N·m (148 lb·ft) is available from 1250 rpm. VW's statement continued: "In dynamic compressor mode, the automatic boost pressure control decides whether the compressor will be switched on in accordance with the tractive power required or if the turbocharger alone can generate the necessary boost pressure. The compressor is switched on again if the speed drops to the lower range and then power is demanded again. The turbocharger alone delivers adequate boost pressure from 3500 rpm."

VW describes the 1.4-L Twincharger as driving like a naturally aspirated 2.3-L unit and adds in its enthusiastic statement on the system: "The boost pressure gauge installed in the cockpit of the Golf GT 1.4 Twincharger is the only signal of the furious activity being undertaken by the superchargers and the complex procedure of harmonizing both systems, taking place under the hood!" In-gear acceleration times include 80 to 120 km/h (50 to 75 mph) in fifth in 8 s. The Twincharger engine can be revved to 7000 rpm.

As for fuel consumption, VW states that the overall figure of 7.2 L/100 km is some 20% better than the figure to be expected of a 2.3-L naturally aspirated engine with similar torque and power outputs. The system is at its economical best on extra-urban journeys, returning 5.9 L/100 km.

A development program for the Twincharger saw VW testing more than 250 prototype and pilot build engines, many of which underwent endurance cycles equating to 300,000 km (185,000 mi) of normal use.

Although the Twincharger technology is believed to be a large-scale production "first", a similar configuration was used by **Lancia** competition cars in the mid-1980s. Apart from VW, at least one European OEM is understood to be currently developing a similar system.

Stuart Birch

GM advances high-value OHV V6

General Motors continues to advance its strategy of developing advanced, cost-effective overhead valve engines designed to deliver customer-satisfying low-end torque along with increasingly important fuel efficiency.

"The focus was on high specific output, excellent fuel economy, and high value for the customer," said Dick Michalski, Chief Engineer, GM OHV V6 Engines.

The LZ9 3.9-L V6 carries that strategy from the LX9 3.5-L engine to its next logical step, with enlarged bores and the addition of a continuously variable cam phaser that advances or retards cam timing in response to driving conditions.

The cam phaser, which can advance timing by 15 degrees or retard it by as much as 25 degrees, permits the use of high-lift cam lobes without sacrificing idle quality or emissions.

"We advance the cam above 2400 rpm," said Michalski. "It provides a fairly measureable torque and horsepower improvement."

"We also use the cam phaser for emissions control under part load operation," Michalski said. "For NOx control we retard the cam under some driving conditions."

The cam's higher-lift lobes necessitated a switch to a cam with a larger base circle diameter. That meant bigger cam bearing journals, and those just plain wouldn't fit in the narrow valley of the 60-degree engine with its huge 99-mm (3.90-in) bores—the same size as the LS1 smallblock V8's.

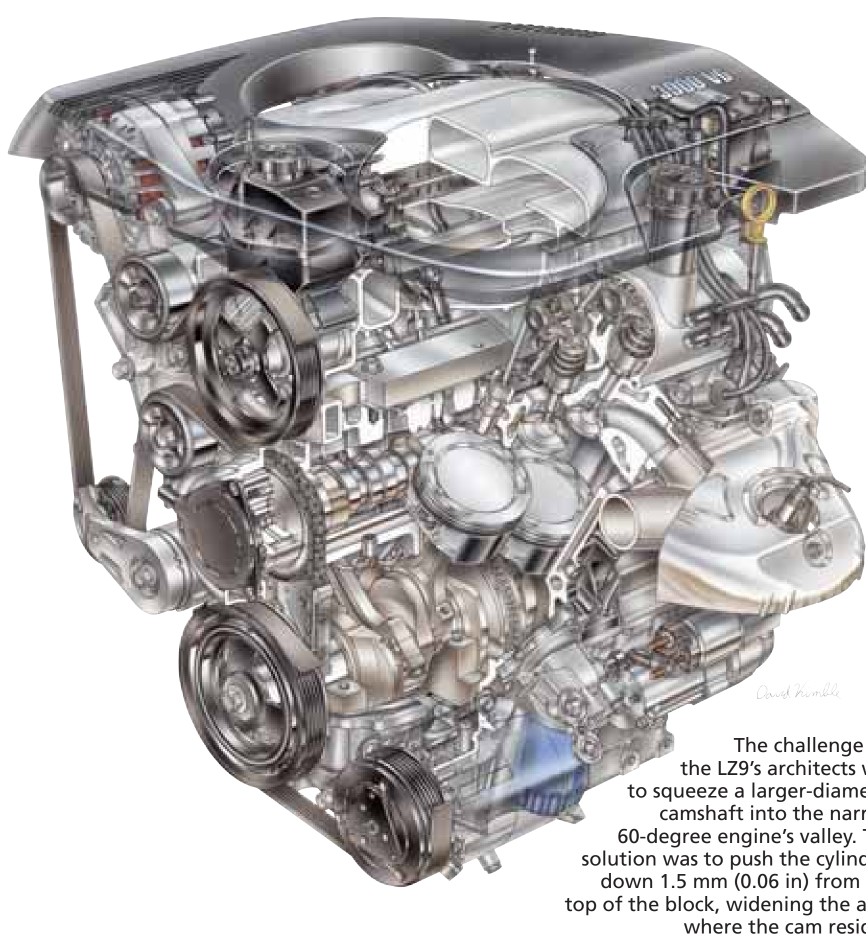
The solution was to offset the cylinder bores, pushing them down 1.5 mm (0.06 in), so that the intersection of lines through the centers of the bores no longer intersects between the two sides of the vee at the centerline of the crankshaft, but is now 3 mm (0.1 in) below the crankshaft's centerline. That increased the width of the valley where the cam resides, leaving space for the larger-diameter shaft and bearing journals.

That camshaft is unusual too, because it is fabricated, with hardened steel lobes pressed onto a lightweight hollow tube.

The high-silicon molybdenum cast-iron block eschews the deep skirts seen on many new engines, using a cast-aluminum oilpan instead to bolster rigidity and minimize noise and vibration.

"We did not feel we needed to go to a deep skirted block to acomplish what we needed to accomplish," said

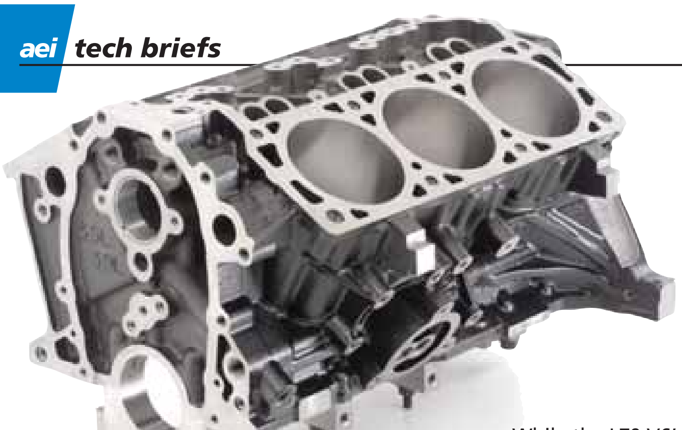
The intake manifold tuning valve separates the intake plenum into halves, with each bank of the engine breathing through its own half at lower revs for improved torque, but opening to provide access to the entire intake manifold volume at higher rpm for maximum top-end power.



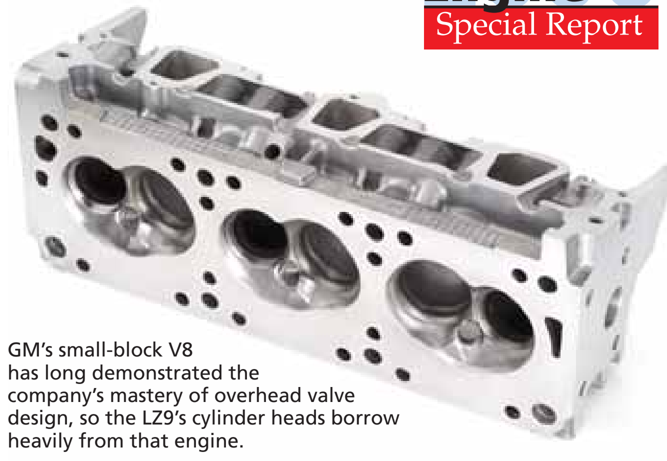
The challenge for the LZ9's architects was to squeeze a larger-diameter camshaft into the narrow 60-degree engine's valley. The solution was to push the cylinders down 1.5 mm (0.06 in) from the top of the block, widening the area where the cam resides.

The cam phaser provides the first variable valve timing on an overhead valve engine, a design that has since been replicated on the small-block V8 in the 2007 Cadillac Escalade.

Although piston oil cooling jets were pioneered on high-performance air-cooled motorcycle engines that needed to cool the piston crowns, GM uses the jets to help quiet the engine, as the pistons slide more easily in their bores.



While the LZ9 V6's block has conventional short skirts, a bolt-on cradle reinforces the block and the main bearing caps, cementing them together for maximum rigidity and minimal vibration.



GM's small-block V8 has long demonstrated the company's mastery of overhead valve design, so the LZ9's cylinder heads borrow heavily from that engine.

Michalski. "It has a structural oilpan. We put features on the oilpan for increasing natural frequency of the powertrain, so we are using the oilpan to enhance the [noise and vibration] issues."

The crankshaft is forged steel and the rods are forged from powdered steel. The pistons attach with floating wrist pins.

Also in the crankcase are oil jets, which squirt the underside of each piston with a shot of oil to keep them cool and well-lubricated. This not only provides the expected durability benefits, but it also quiets the engine by maintaining a consistent oil film for the piston to slide on. The GM Oil Life System monitors the engine's use and advises the driver when it is time for an oil change based on an algorithm that calculates expected life from the driving distance and conditions.

At the top of the engine is a two-stage variable intake manifold, which splits the manifold volume in half at lower engine speeds to exploit intake tuning of pressure waves and to increase the velocity of the intake charge. At higher speeds, the valve opens, providing a shorter path of high-volume air to the cylinders for maximum power.

That air whooshes through an electronically controlled throttle managed by the powertrain control module. The fuel injectors have shrouded nozzles designed to minimize clogging and to work better with hot fuel. The iridium-tipped spark plugs are rated for 100,000 miles.

The valves and combustion chambers are similar to those pioneered by the LS1 and LS6 small-block V8s, but technology flows both directions, as the LZ9's cam phaser has recently debuted on the V8 in the **Cadillac** Escalade.

Coolant travels through a "U-flow" route through the engine, from the front to the back and returning to the front, rather than a Z-flow route, for more uniform temperatures and quicker warm-up.

The LZ9 first appeared in the **Pontiac** G6 GTP, and has since diversified into the **Chevrolet** Impala, Monte Carlo, Malibu SS, and Malibu Maxx SS, along with the company's family of minivans, the Pontiac Montana SV6, the **Saturn** Relay, the **Buick** Terraza, and the Chevrolet Uplander. Power varies depending on tuning for each application, ranging from 227 to 242 hp (169 to 180 kW) and between 235 and 242 lb·ft (319 and 328 N·m).

Dan Carney

BMW's M5 gets a V10

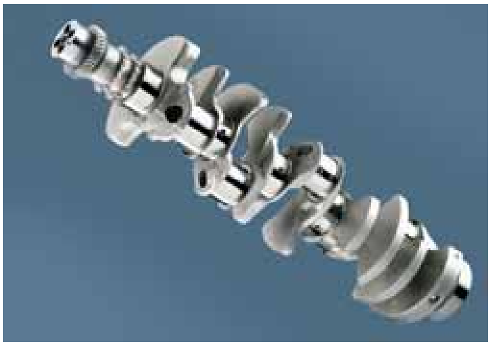
In developing the engine for its latest performance flagship, the M5, **BMW** was faced with the challenge of how to top the performance of its impressively muscular 5.0-L M5 V8 engine, which produced 400 hp (298 kW). The company's answer is an all-aluminum, double-overhead cam, variable-valve-timing 90-degree V10 that churns out 507 hp (378 kW).

Like the precedessor M5 V8, the new V10 displaces five liters of capacity and has a mass of about 240 kg (529 lb), but the new engine's extra pair of cylinders and additional 1250 rpm contribute to a 107 hp (78 kW) hike in output.

The company reached this solution after targeting a specific output of 100 hp (75 kW) per liter, which would require a 5.0-L displacement to reach the goal of 500 hp (373 kW), according to Elmar Schulte-Eorwick, Manager of the Engine Design Department. BMW also concluded that 500 cm^3 cylinders would be ideal for power and efficiency, he added. The result, therefore, is an engine comprising 10 of those 500-cm^3 cylinders.

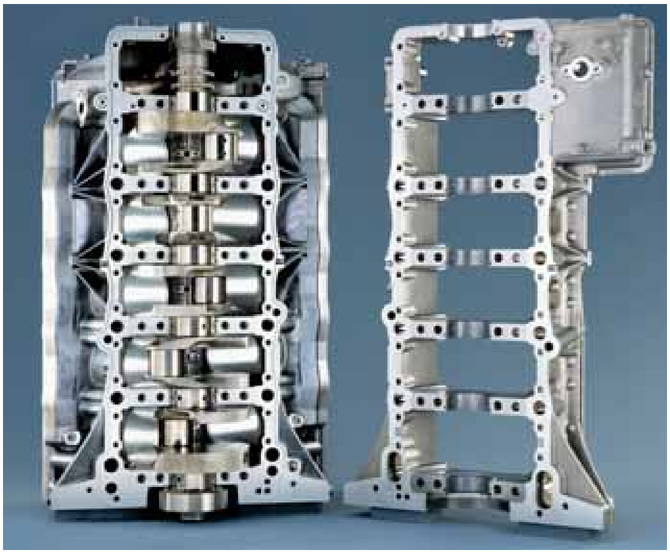
A V12 configuration was ruled out for packaging reasons. "You can imagine that a V12 would be very difficult to install in an M5 engine compartment, and it is a very heavy engine," Schulte-Eorwick said. The connection to the company's well-regarded V10 Formula One race engine is purely coincidental, he insists.

Since the M5 V10 program was launched, Formula One rules makers



The extremely stiff crankshaft is forged from high-tensile steel and has a mass of only 21.8 kg (48 lb). It spins on six 60--mm (2.36-in) diameter main bearings that are 28.2 mm (1.11 in) wide, and the crank pins are offset at 72 degrees to provide even firing intervals.

Special attention was paid to reducing mass in the M5's valvetrain, resulting in a total mass reduction of 17.5% compared with the preceding V8 engine. The hydraulic tappets, for example, acting on each cylinder's four valves, were trimmed to just 28 mm (1.10 in) across, with a mass of 31 g (1.1 oz).



The cylinder block is low-pressure gravity die-cast of hypereutectic aluminum-silicon alloy containing 17% silicon. This material permits the creation of cylinder liners by precipitating hard silicon crystals, eliminating the need for pressed-in liners.

To ensure continuous quality, each of the hand-assembled M5 engines runs for 20 min on a dynamometer to confirm its correct operation, and some engines are tested randomly for two hours.

decreed that the race series will use 2.4-L V8 engines in place of the 3.0-L V10s that have been the standard. As a result, BMW will not enjoy the halo of association between the M5's engine and the F1 engine.

But an engine as advanced and powerful as the M5's probably doesn't need the benefit of any reflected glory. The engine's rev limit is set at 8250 rpm, compared to a 7000 rpm rev limit for the old V8 engine, a level made possible by the engine's smaller, lighter pistons. The oversquare architecture features a 92-mm (3.62-in) bore with a short 75.2-mm (2.96-in) stroke. Although the V10 has more internal parts than the V8, its mass of 240 kg (529 lb) is about the same.

The V10's aluminum engine block is reinforced with a bedplate, rather than using a deep-skirt design. "I think it will be stiffer than a deep-skirt block," said Schulte-Eorwick. A special sealant is automatically applied to a groove between the two halves during assembly, with the excess that escapes sealed by ultraviolet light.

Designers incorporated cast-iron inserts for the six main bearing caps into the bedplate design. The cast iron is preferable to aluminum because it expands 50% less than aluminum when hot, maintaining the intended bearing clearance and oil supply.

Oil supply is maintained through all foreseeable conditions through the use of dedicated electric oil pumps that move oil from the valve covers to the main sump during high-*g* cornering, and another one that moves oil from a mini-sump at the front of the oilpan to the main sump in the rear under hard braking maneuvers.

The engine's 90-degree vee was chosen for it stiffness and reduced height compared to a 72-degree vee angle which would provide even firing. To achieve the even firing needed to minimize the vibration of the V10 engine, the crankshaft is offset to 72 degrees.

BMW's hydraulically controlled bi-VANOS variable cam timing system can adjust the intake cam through a range of 66 degrees and the exhaust cam through 37 degrees in relation to the crankshaft using a two-speed helical gearbox between the cam sprockets and the shafts.

In typical BMW M-car fashion, the V10 uses an individual throttle butterfly for each cylinder. On the exhaust side, the engine exhales through hydroformed stainless-steel 5-into-1 tubular headers with equal-length runners for each cylinder.

The headers incorporate close-coupled catalysts that contribute to the engine's Euro4 and LEV II emissions certification. Customers should also be pleased by the sound emitted, predicts Schulte-Eorwick, a factor that has been of concern in other ten-cylinder cars like the **Dodge** Viper. "I think we have a very good ten-cylinder sound," he said.

Dan Carney