

## GM moves closer to market with HCCI



(a)



(b)



(c)



(d)

The HCCI stroke cycle begins as (a) air flows into the cylinder; (b) air and fuel mix and are compressed; (c) simultaneous combustion pushes piston down for the power stroke; and (d) piston rises to its original position as exhaust gases escape through the exhaust valves.

Designing an HCCI (homogeneous charge compression ignition) gasoline engine to work over a wide rpm and load range has been an enormous engineering challenge, but **General Motors** believes it finally knows how, and will introduce a demonstration vehicle next year. To satisfy HCCI's requirements for precise control of mixture, temperature, and pressure throughout the cylinder, GM will use direct fuel injection, cylinder pressure sensing, variable (two-step) valve lift, and variable intake and exhaust valve timing with dual electric/electronic cam phasers. This fast-acting, precise, but expensive technology is currently used only on 2007 **Lexus LS460** intake camshafts.

The HCCI principle—featuring nearly simultaneous compression ignition throughout the combustion chamber instead of a flame front—has been demonstrated satisfactorily by many companies. The fuel economy advantage—80% of the fuel economy increase typically provided by diesel for as little as 50% of the diesel cost premium—justifies the effort to commercialize, explained Uwe Grebe, GM Director of Advanced Powertrain Development. Today's HCCI engine runs on spark ignition during engine start and high load (such as hard acceleration). However, up to a 20% overall improvement in fuel economy is still possible vs. a conventional gasoline engine, depending on the vehicle powertrain combination.

Although GM will not disclose the demonstration vehicle engine configuration it will use, its illustrations have shown a dual-overhead-cam four-cylinder. Grebe said that, because HCCI is an in-cylinder process, not cylinder-to-cylinder as in cylinder deactivation, the issues that must be solved are the same for four, six, or more cylinders.

HCCI is a lean-mixture combustion process that operates without a throttle restriction. Without a flame front, it produces low peak temperatures and therefore only low levels of nitrogen oxides (NOx). This contrasts with a spark-ignition stratified-charge combustion process,

which, although lean and very close to HCCI in fuel economy, results in the high peak temperatures at which NOx is formed.

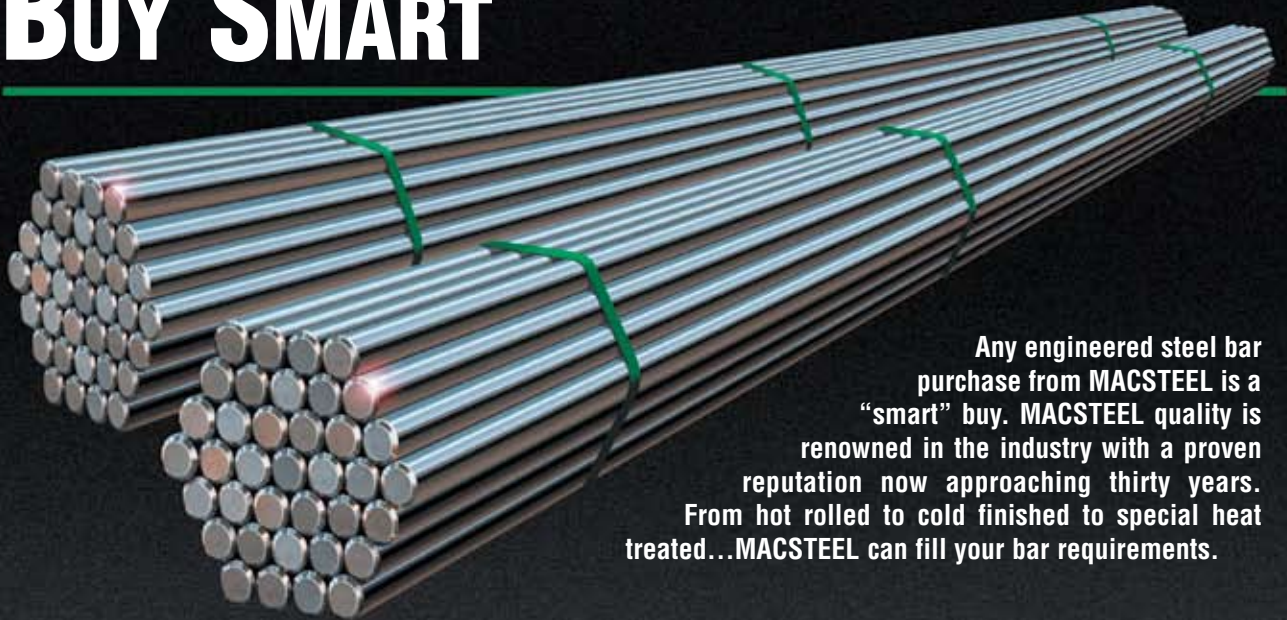
Quickly establishing and maintaining compression ignition with gasoline, using much lower compression ratios than a diesel and without a flame front, is just the surface aspect of the challenge. HCCI requires a complex combination of mixture preparation, temperature and pressure controls. Although HCCI produces high peak pressures ranging from 65-70 bar (943-1015 psi) to as high as 110 bar (1595 psi) in turbo designs, they are still less than half the 160-200 bar (2321-2901 psi) pressures that are typical of diesel. In the GM design, a sensor monitors cylinder pressure, and a complex control system uses the valvetrain's timing and lift to keep cylinder pressures and gas temperatures at the required levels.

With gasoline, auto-ignition occurs at about 1100°C (2012°F). Temperatures in the HCCI combustion chamber are adjusted and controlled primarily by the combination of exhaust gas recirculation (going as high as 75%) and variable valve timing to change residual gas concentrations and the effective compression ratio. Pre-heating the intake air is possible, but the response is too slow to be broadly useful, Grebe said.

A multi-pulse fuel-injection system is part of GM's HCCI calibration strategy, but because there is no conventional flame front, the objective is different. The first squirt of fuel is not intended to immediately burn and produce energy. Rather, Grebe said, the chamber's heat changes the fuel's chemistry, part of the complex air-fuel mixture preparation necessary for cylinder-wide combustion.

Much work is under way to stretch the range of HCCI operation past moderate load, during which only about 4-5 kW (5-7 hp) is required to move a vehicle down the road. During hot idle and up to moderate load, the fuel-economy improvements over a conventional gasoline engine can be as high as 50%, Grebe

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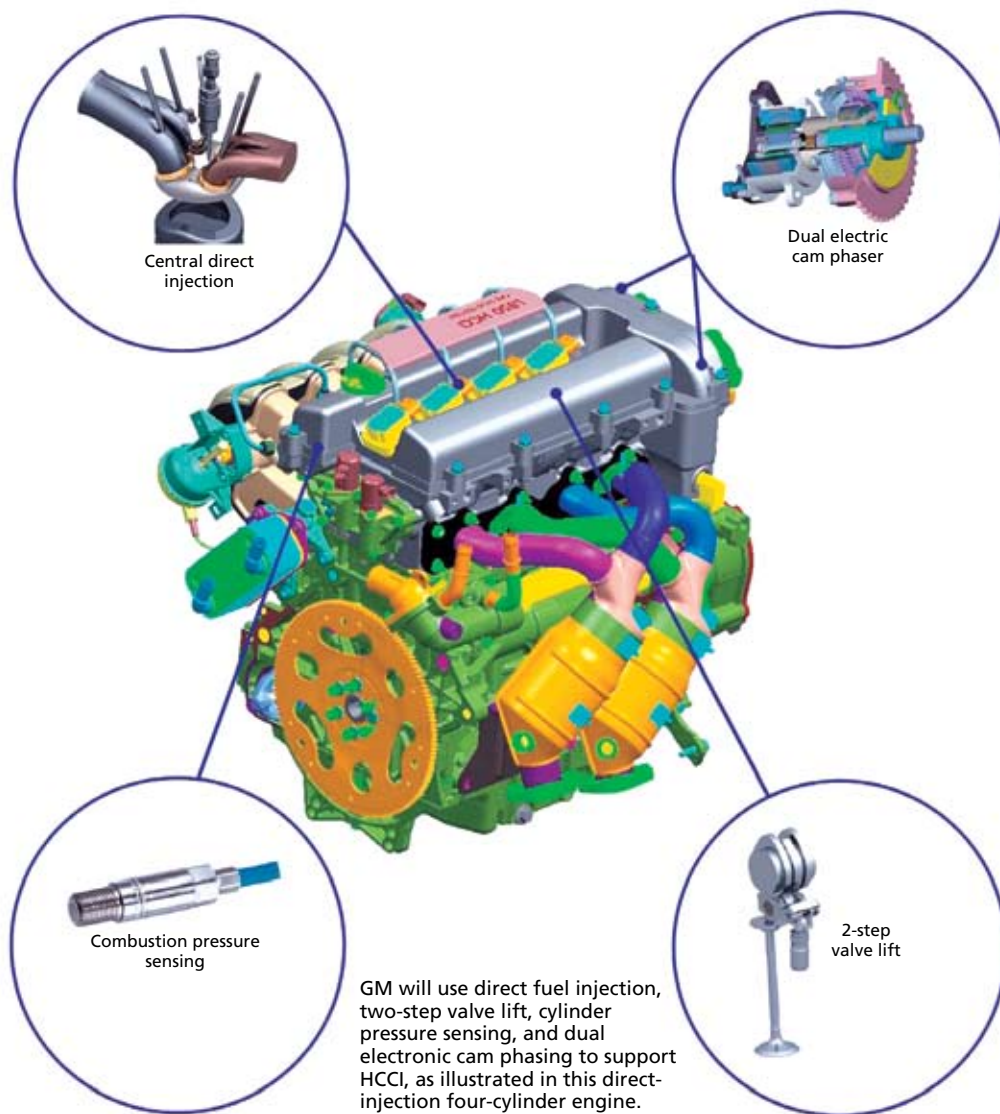
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GM will use direct fuel injection, two-step valve lift, cylinder pressure sensing, and dual electronic cam phasing to support HCCI, as illustrated in this direct-injection four-cylinder engine.

said, but they drop off to zero when the engine switches to conventional spark-ignition operation. He noted that **Saab** is working with turbocharging to try to extend the HCCI mode, but he said that approach poses even greater calibration difficulties than an earlier switch to spark ignition.

In either case, the transition to spark ignition is a challenge, and may be greater with a turbo even though the frequency of the switchover could be reduced, Grebe added. In either case, the customer would expect the change to be seamless.

In HCCI operation, it is necessary to control the rate of energy release despite the multiple combustion locations in the chamber. Although it might be easier with a customized fuel, Grebe made it clear that GM has decided it must manage the rate with engine control alone. The engine would have to run on any market fuel—regular gasoline, E-10, and E-85, he added.

Low peak temperatures that virtually eliminate NOx production are a benefit of HCCI, but related aspects of the combustion process increase the production of unburned hydrocarbons and carbon monoxide. However, controlling these pollutants with a three-way catalyst is a well-established technology.

The major task remaining is to make HCCI a transparent addition to vehicle operation, something the motorist only will notice in the form of improved fuel economy.

*Paul Weissler*

## Mazda expands DISI Turbo to additional models

For some time **Mazda** has quietly—for Japan, anyway—been running a direct-injection spark-ignition turbocharged (DISI Turbo) version of the MZR DOHC 16-valve 2.3-L inline four-cylinder in the Mazda6 (called Atenza in Japan) MPS sedan. The Hiroshima company is now expanding the engine's application to other models, including the American-market CX-7 crossover, the Japanese MPV minivan, and more recently the Mazda3/Axela compact car.

The unit in the minivan and crossover is a slightly detuned version of the engine that powers the high-performance sedans, the latter equipped with manual transmissions only. Appealing to wider customer

segments both in Japan and the U.S., an automatic transmission is a prerequisite—in this case, a new six-speed unit.

The minivan version of the DISI Turbo is rated at 180 kW (241 hp SAE) at 5000 rpm and 350 N·m (258 lb·ft) at 2500 rpm, versus the Mazda6 MPS' 200 kW (268 hp SAE) and 380 N·m (280 lb·ft), respectively. The engine also employs a smaller turbocharger than the performance sedan's unit. The engine's single injector per cylinder is positioned at an angle under the intake valves, and it sprays into the combustion chamber formed by a "flat-crown" piston, which has a very shallow, plate-like recess.

Mazda's engine designers are proud



Engineers Motoi Aoki and Ryotaro Nishiida are responsible for the development of the DISI Turbo.

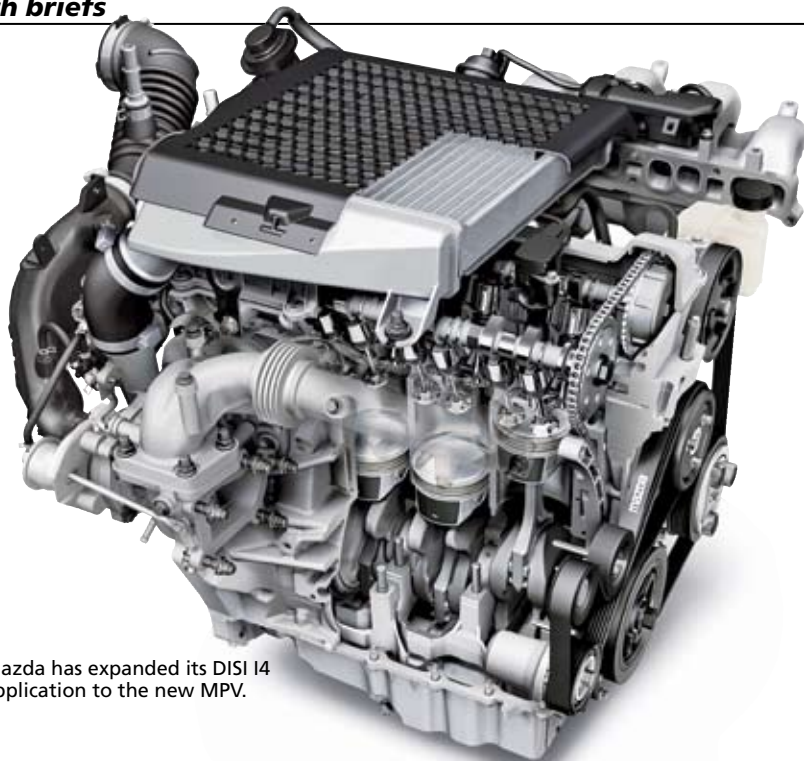
Pop quiz: It never needs replacing and has a longer lifespan than a diesel vehicle, which DPF are we talking about?

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Mazda has expanded its DISI I4 application to the new MPV.

that they were able to attain a relatively high compression ratio of 9.5:1 in a large-bore—87.5 mm (3.4 in)—turbocharged engine. Cylinder cooling by directly injected fuel helps combustion stability, they explained.

A pressure-fed engine must withstand higher combustion and mechanical stress, and Mazda has increased density of the upper block cast using **Ford's** unique **Cosworth** method.

Previously, the MPV had a Ford-sourced V6 option. The new Japanese-market-only model is offered with the DISI Turbo in addition to a naturally aspirated, port-injection version. The DISI Turbo attains an improved fuel economy level, while meeting the country's low-emission classification.

*Jack Yamaguchi*

## Making one motor from two

Over the last 10 years, more than 200 engineers have contributed scientific formulas, engineering schematics, and sentence upon sentence of excruciatingly detailed information about how their company can engineer a more efficient motor for hybrid-electric vehicles.

One future vision is the memory motor. It combines the best aspects of a permanent-magnet interior motor and an induction motor. According to proponents such as those at **Siemens VDO**, the memory motor would enable a substantially longer driving range, improve vehicle performance by providing a high torque-to-volume ratio, and simplify pow-

ertrain design and assembly by virtue of being an axially shorter machine.

Many engineers working for other companies and academic entities are also devoting time and talent toward the development of a memory motor. "There's always a race to be first to market, but if you come out before the technology is perfected, that's not good. So it is really just a race within Siemens vs. being a race against anyone else," said engineer Tom Dohrner, Business Development Manager for Hybrid Electric Vehicles at Siemens VDO.

Dohrner believes Siemens is probably two years shy of being production-ready with a memory motor. The primary hurdle that needs to be resolved relates to torque output. "Right now, there is insufficient torque being generated by the motor at high speed," said Dohrner.

Today's in-production hybrid-electric vehicles use a motor that provides sufficient torque for low-speed acceleration and lower-speed range boost. "With a memory motor, we want to have the motor give boost at both low-speed acceleration and high-speed highway driving," Dohrner said.

A comparison of the memory motor, an induction motor, and an interior permanent-magnet motor reveals several memory motor advantages, such as negligible field weakening losses, low perma-

nent-magnet corrosion, and a high operating temperature. For instance, because the memory motor uses aluminum-nickel-cobalt (AlNiCo) magnets, field weakening and the stator current needed to compensate for magnetic flux is not an issue.

"Instead of having to use the battery to put out more power for higher speed, AlNiCo magnets are used to create field weakening, and that prohibits magnetic drag from happening in principle," said Dohrner. The use of AlNiCo does not require coating, which means the memory motor's magnets are not susceptible to corrosion. In addition, the memory motor's maximum operating temperature is between 500 and 550°C (932 and 1022°F).

An electric motor should possess high reliability, high efficiency, wide speed range capability, high thermal stability, and acceptable cost, according to Dohrner. In principle, the memory motor is an ideal candidate to meet the desired operating criteria necessary for high-mileage applications.

"The highest system efficiency possible is up to a 65% longer driving range with a vehicle equipped with a memory motor, and/or you can use a smaller battery," said Dohrner, noting that the 65% longer driving range is in comparison to today's hybrid vehicles.

*Kami Buchholz*



Applying a memory motor architecture to a belt-driven starter generator (shown) could help muscle more mileage out of each gallon of gasoline put into a hybrid vehicle.

## Zytek, Xtrac, and the diesel hybrid

Motorsport experience and technology solutions are being applied to a new diesel-hybrid demonstrator designed and developed by automotive engineering consultancy **Zytek**. Although diesel-hybrid drivetrains offer far greater fuel efficiency and subsequently lower emissions (notably CO<sub>2</sub>) than gasoline hybrids, cost is a serious downside. Major companies including **PSA Peugeot Citroën** and the **Volkswagen Group** are researching and developing diesel hybrids as potential production models, with PSA even saying that its model(s) will be on the market by 2010. Any diesel hybrids must, however, drive down unit costs to at least the same level as the gasoline hybrid.

Zytek decided it could help meet this tough challenge by developing a dual-mode hybrid that uses sophisticated control strategies to replace clutches and complex epicyclic gearsets. The project has received UK government support.

Claimed by Zytek to be the world's first "affordable" diesel-hybrid drivetrain and ready for production, the new system is designed to be quickly implemented within the packaging constraints of compact European passenger cars. The company reports that it has exceeded all targets set for the program, delivering 85g/km (137 g/mi) of CO<sub>2</sub>, installed—purely for demonstration purposes—in a **Smart ForFour**.

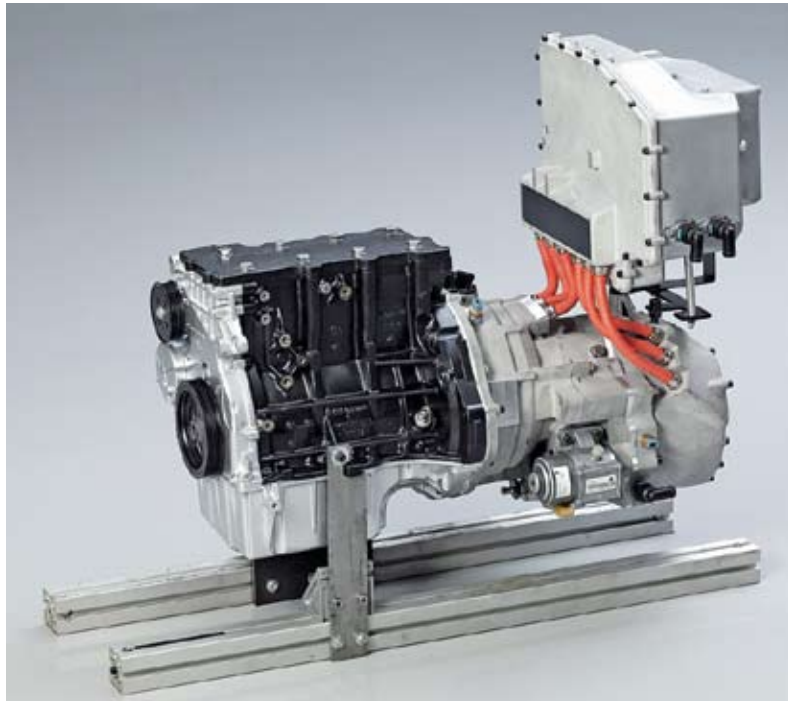
Outlining the thinking behind its system, Zytek explained in a statement that although pure series hybrids offer high efficiency at low speeds, this effect is greatly reduced with increasing speed, so current passenger car production hybrids are either parallel or dual-mode systems. Parallel hybrids, in which the internal-combustion engine is permanently coupled to the wheels, are more efficient at high speeds, but offer less flexibility to optimize the drive for low-speed duty cycles. Dual-mode transmissions offer the ability to operate in series or parallel mode, so the drive can be optimized for each operating condition. Dual-mode transmissions are substantially more complex and are therefore larger and more expensive.

Designed to eliminate the limitations of a dual-mode transmission, the Zytek solution is claimed to reduce component

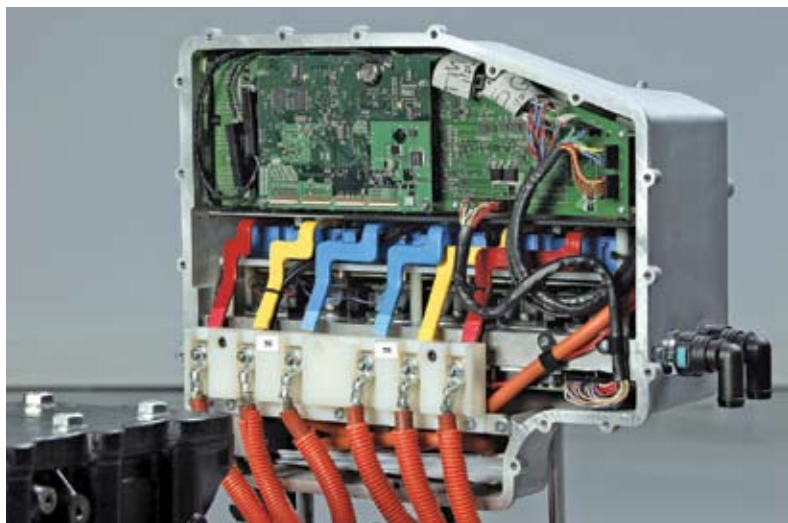
count, eliminate wearing friction surfaces, reduce packaging volume, and substantially lower manufacturing costs. The technology also avoids licensing issues that may be associated with the use of hybrid-vehicle epicyclic gearboxes.

Dual-mode architectures depend on

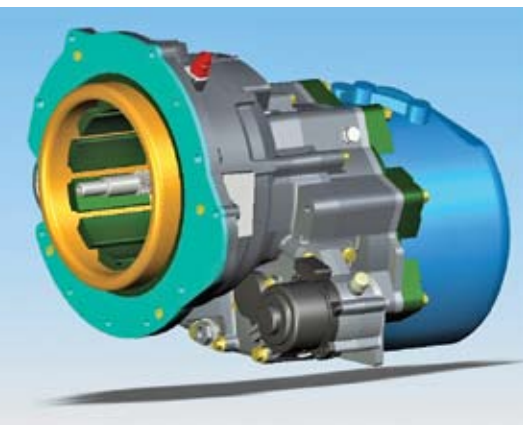
two motors: a starter/generator permanently engaged with the engine, and a traction motor. In the Zytek system, both motors are specifically designed for their function, a philosophy that provides increased efficiency. When required, the motors are engaged with the drivetrain



Zytek's hybrid diesel powertrain is tightly packaged.



The Zytek diesel hybrid's inverter uses the same software-managed current-control system for both dc and ac motors to provide vehicle manufacturers with substantial design flexibility and the possibility of component sharing across different architectures.



Xtrac used small, lightweight gear and internal components made from high-performance steels to create the 35-kg (77-lb) torque split gearbox.

unit that is capable of operating at speeds up to 3600 rpm. It provides torque assist to automatically boost acceleration in higher-demand situations. Supplementing the drive torque allows a single, very high gear to be engaged at low revs (1600 rpm) to keep the engine operating in its most efficient range and to reduce frictional losses. The traction motor is a 50-kW ac brushless permanent-magnet type mounted on the end of the gearbox and capable of operating at speeds up to 11,500 rpm.

Although it shares the same fundamental architecture as the starter/generator, Zytec has chosen a different internal construction to optimize it for low-speed, high-torque operation, a benefit that de-

(5.43-in) gearbox is small enough that the complete hybrid transmission, including both electric motors, can fit into a space similar to that required for the six-speed **Getrag** automated manual transmission in the standard Smart ForFour.

For **Xtrac** to meet the project's gearbox packaging requirements, small, lightweight gears and internal components were necessary, a requirement met via the use of high-performance steels specifically developed for motorsport applications. Adrian Moore, Xtrac's Technical Director, said: "Zytec's achievement with the new hybrid illustrates how the motorsport industry can apply its technology and technical skills to help vehicle manufacturers build more environmentally friendly road cars by delivering energy-efficient solutions."

Zytec's new diesel control system, the DEMS (Diesel Engine Management System), was developed and calibrated in less than 14 months. Integrated into the DEMS control unit is a separate hybrid systems control board, which calculates the optimum blend of diesel and electric torque by comparing the throttle position with factors such as battery state of charge, vehicle speed, and safety inputs (required to validate torque demand).

The lithium-ion battery is mounted on the trunk floor, flush with the loading lip. An onboard charger allows the vehicle to be recharged (from 0 to 100% state of charge) in less than three hours from a standard domestic electrical outlet. To minimize electrical losses, the inverter is mounted under the hood, close to the electric motors. Its software-managed current-control system can be used for both dc and ac motors, thus providing vehicle manufacturers with substantial design flexibility and the possibility of component sharing across different architectures.

Further fuel-consumption savings have been achieved by replacing parasitic systems with more efficient and controllable electrically driven solutions.

Performance figures include a 0 to 100 km/h (0 to 62 mph) time of 12 s.

A technical paper on the Zytec dual-mode diesel hybrid is scheduled to be presented at the 2007 **SAE** Congress in Detroit this April.

*Stuart Birch*



The Zytec diesel-hybrid drive was engineered to fit into the Smart ForFour engine bay.

via a dog-synchromesh system, an application that is unique to Zytec in this context. The system uses electronic control to take the place of the synchro cone by automatically matching the speed of the input shaft and the layshaft to allow "seamless" shifts with zero torque interruption, according to Zytec.

The technology uses experience from Zytec's successful A1 Grand Prix engine and gearbox, which last season completed more than one million clutchless gear changes at race speed, without a failure.

For the starter/generator, Zytec uses a 43-kW dc brushless permanent-magnet

rives from the unique dual-mode architecture.

When the vehicle pulls away, torque is delivered only from the electric traction motor. As speed increases, electric and diesel drive meld until torque from the electric drive is reduced to zero. The broad power range of the dual-mode system, combined with the phasing of electric and diesel drive at the extremes of the vehicle speed range, allows the purpose-built gearbox to operate with only two ratios (one for diesel drive, one for electric drive) without compromising NVH or economy, stated Zytec Director Steve Tremble. The compact, 138-mm

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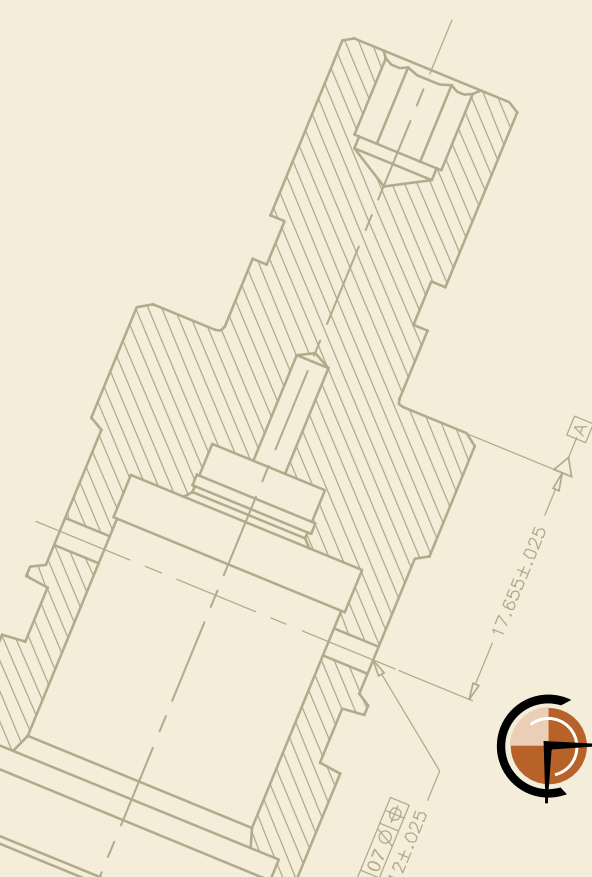
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## Turbocharger technology: far from exhausted

Experiencing the full potential of a front-wheel-drive car powered by a high-output turbocharged gasoline engine a couple of decades ago was something to be remembered—particularly so in the wet. If a driver did not understand the meaning of the terms “turbo lag” and “torque steer” before a pedal-to-the-metal standing start, it would become dramatically clear within a couple of seconds.

the effects of turbo lag, and the increasing capability of chassis electronics to counter the relatively milder but still significant effects of torque steer, turbocharger technology became efficient, effective, and firmly established.

Until very recently, VTG turbochargers were not suitable for use with gasoline engines because of the very high exhaust-gas temperatures involved, so turbo-

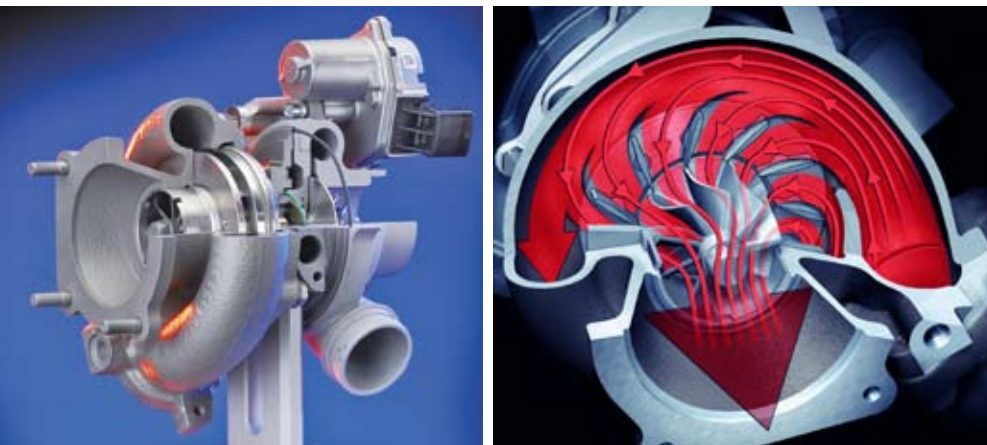
charging, it achieves almost the same output and a similarly dynamic engine response as in normally aspirated engines with a larger displacement. At the same time, these improvements are achieved with much lower fuel consumption. This shows that modern spark-ignition engine turbocharging is not focused exclusively on increasing engine output, but also on combining exceptional engine performance with good fuel economy. Fuel savings of between 15 and 20% are achievable in normal driving.”

A significant development in the extension of VTG to turbocharged gasoline engines came in early 2006 with the cooperation between BorgWarner and Porsche for development of a VTG system for the latest 911 Turbo. The key feature of the turbocharger—which incorporates nickel-based alloy materials used by the aerospace industry and which is capable of coping with temperatures of some 1000°C (1832°F)—was its adjustable guide vanes, said Schmalzl. At low engine speeds and subsequently low exhaust gas flow rates, the vanes in closed mode develop high boost pressure. This falls as the vanes open, thus eliminating the need for the conventional turbocharger’s bypass system with wastegate valve.

With the 911’s VTG system, the total exhaust gas flow passes through the turbine wheel and is immediately converted to output, providing a much-improved engine response at low engine rpm and minimizing turbo lag compared to a conventional turbocharger with wastegate. The 911 has two BV50G turbochargers with electric VTG regulators. The car’s 3.6-L engine produces 353 kW (473 hp) with maximum torque of 620 N·m (457 lb·ft). The rev range over which high power and torque are available has been broadened, with peak torque spread from 1950 to 5000 rpm.

BorgWarner has estimated that over the next five years, one in three spark-ignition engines produced in Europe will be fitted with a turbocharger. The present figure is 13%. From 2011, the company expects to see increasing use of VTG turbos in spark-ignition engines and plans to focus on further developments of the technology.

Stuart Birch



Porsche’s latest 911 Turbo is fitted with two BorgWarner Turbo & Emissions Systems variable turbine geometry BV50G turbochargers. At right it is shown with vanes open.

**Saab** was a pioneer of production turbocharged gasoline engines in the late 1970s, and others quickly (in every sense) joined the action. But the sharp power-on effect that was manifested on those early, turbo-lagged engines called for skill and concentration if things were not to get out of control. Even rear-wheel-drive turbocharged cars such as the early **Porsche 911 Turbo** were not to be toyed with. But it was tempting for manufacturers to pursue the turbocharging route because, in theory, it came close to offering a “something-for-(almost)-nothing” solution to performance enhancement. With turbocharging, a relatively small engine could provide big-engine power. But in practical terms it was not appropriate for the general gasoline-engine mass market, even in light or mild form.

However, turbocharging was very well suited to diesel engine applications, as it could transform the tardy response and performance of oil burners to more closely simulate those of a gasoline unit. With the advent of the variable turbine geometry (VTG) turbocharger to help negate

charged gasoline engines remained very much in the minority. But all that is starting to change.

“The spark-ignition engine with exhaust gas turbocharging and gasoline direct injection will have an equally successful career as that of the diesel engine,” said Hans-Peter Schmalzl, Vice President Technology, **BorgWarner Turbo & Emissions Systems**, which has headquarters at Kirchheimbolanden, Germany. He is convinced that next-generation gasoline direct-injection technology combined with turbocharging has the potential to deliver enhancements for specific output, fuel consumption, and driving dynamics. Knock resistance would also be increased, and optimizing the valve timing in the lower-engine-speed range would lead to improved residual gas scavenging, so increasing the cylinder charge with fresh mixture and delivering higher engine output.

“Compared to other turbocharging concepts, VTG offers the best cost-benefit ratio after the wastegate charger,” said Schmalzl. “Without additional turbo-



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