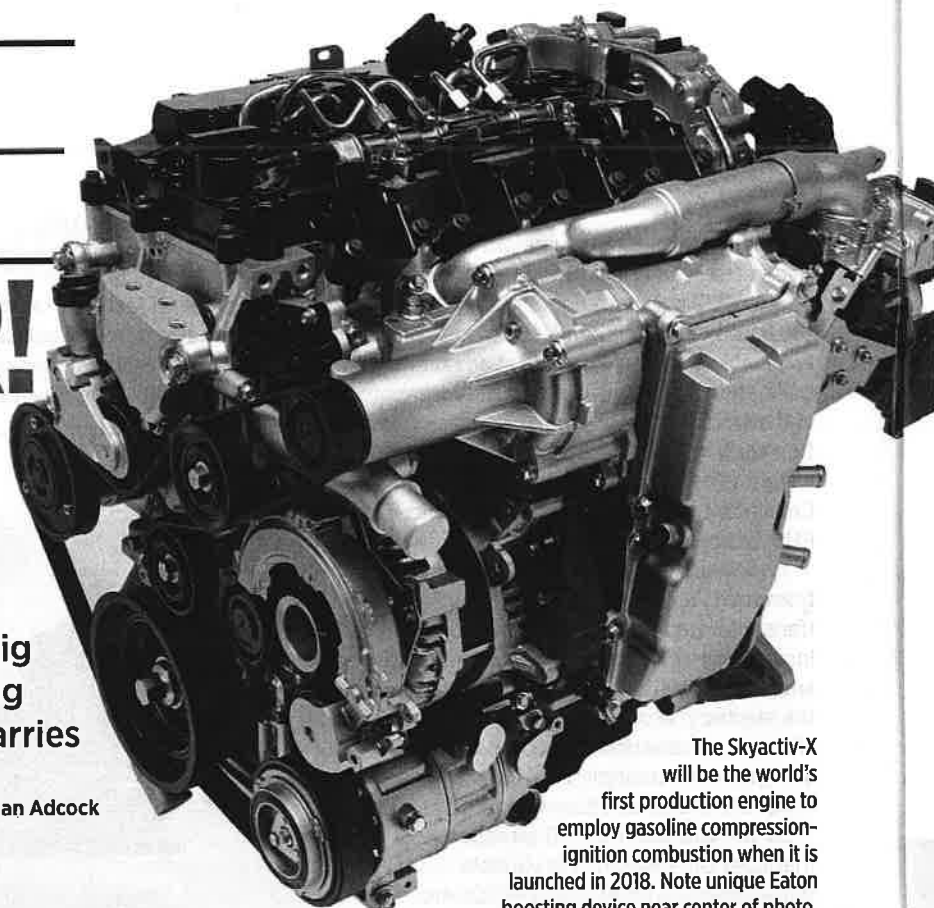


ICE BREAKER!

Mazda's Skyactiv-X beats the big guys to market with a promising new production engine that marries Otto and Diesel attributes.

by Ian Adcock



The Skyactiv-X will be the world's first production engine to employ gasoline compression-ignition combustion when it is launched in 2018. Note unique Eaton boosting device near center of photo.

One of the most significant developments in internal combustion engine (ICE) technology for decades, Mazda's innovative Skyactiv-X Spark Controlled Compression Ignition (SpCCI) combustion system is slated for production in 2018. It has the potential to extend the practical life of gasoline engines, which are increasingly under threat from both global emissions legislation and the accelerating development of electric vehicles (EVs).

According to Kiyoshi Fujiwara, a company director and Senior Managing Executive Officer, SpCCI will form the foundation of Mazda's gasoline-engine strategy until mid-century. Fujiwara told *Automotive Engineering* that SpCCI is designed to embrace larger-displacement power units that eventually will run on micro-algae bio-fuels to deliver "zero tailpipe emissions" (see sidebar).

The SpCCI system is the culmination of more than eight years of intensive development by Mazda to design a gasoline engine that embraces the frugality and torque of a diesel with the high-revving capacity of a twin-cam gasoline unit, while delivering sub-60 g CO₂/km emissions. Adding to the attraction, SpCCI requires relatively minimal investment in the engine bill of materials—electronic controls and a revised cylinder head comprise the major changes.

Creating an ICE with Otto and Diesel attributes is an engineering target discussed in scores of SAE Technical papers and vigorously pursued by Mercedes-Benz with its DiesOtto (see <http://papers.sae.org/2009-01-2701/>), General Motors with its Homogenous Charge

Compression Ignition (HCCI; <http://articles.sae.org/6635/>), Honda with its similar investigations (<http://books.sae.org/b-hon-016/>) and Hyundai, among others. But while these larger, better-financed OEMs have focused significant R&D on HCCI, they have thus far stopped short of committing the combustion regime to production.

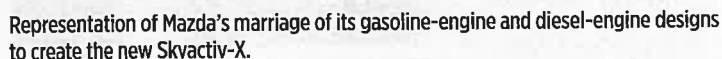
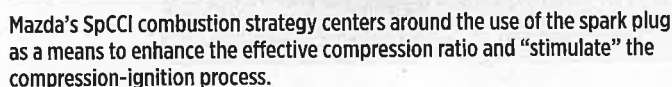
Mazda's new technology partner Toyota also is said to be interested in SpCCI, including potential applications for hybrid-electric vehicles (HEVs), long a Toyota specialty.

Diesel-like torque

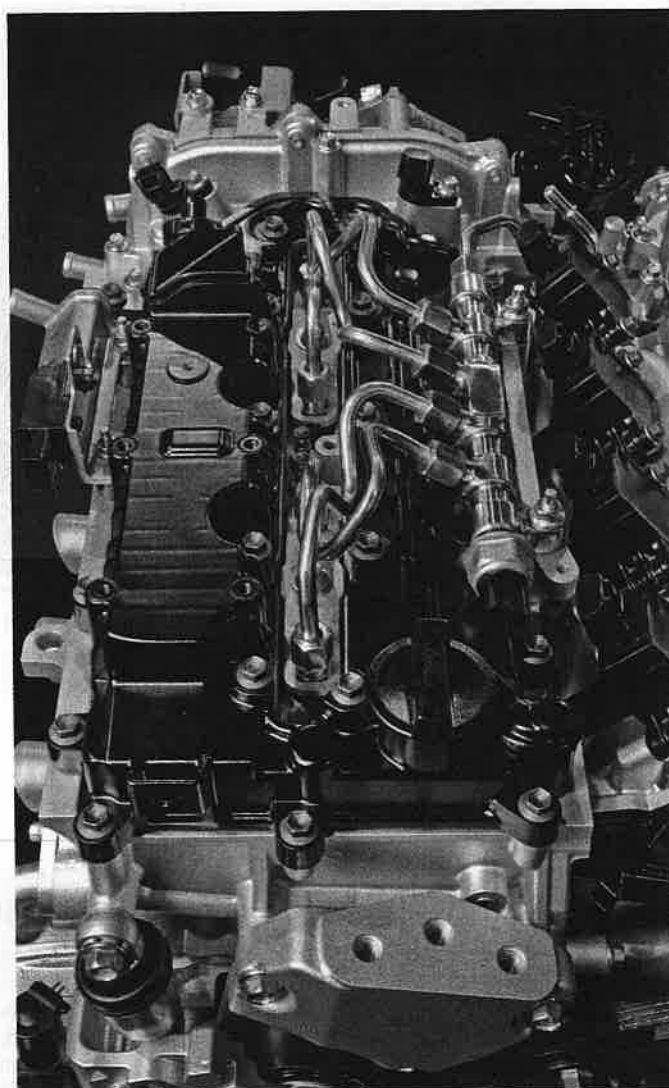
At a recent media technical background event at Mazda's European technical center in Oberursel, Germany, the author test-drove two prototype Mazda 3s powered by a 2.0-L SpCCI engine—one fitted with a manual transmission, the other automatic—over a 30-mile (48-km) test loop. The experience seemed to confirm that the longstanding challenge of smooth transition from spark-ignition mode to compression-ignition had been overcome. The prototype SpCCI engines did display some low-rpm harshness, but final calibrations and engine production still are about a year away, engineers said.

What can be confirmed: in everyday driving, the transitions from SI to CI are barely noticeable. On a route that included high-speed autobahn and country and urban roads, the all-new SpCCI unit pulled strongly to its approximately 6000-rpm redline, accompanied by a healthy—if not outright sporty—exhaust note. The engine's diesel-like torque curve was amply demonstrated by its willingness to pull without fuss from as low as 1200 rpm in sixth gear.

This wider spread of torque has allowed Mazda to revise the development cars' gearing to further improve fuel economy and reduce emissions.



It was a similar tale for the automatic-transmission car: a 14.75% improvement (29.9 U.S. mpg vs. 35.1; 29.9 L/100 km vs. 35.1 L/100 km), while the automatic-backed SpCCI engine spent even more time operating in SpCCI mode.

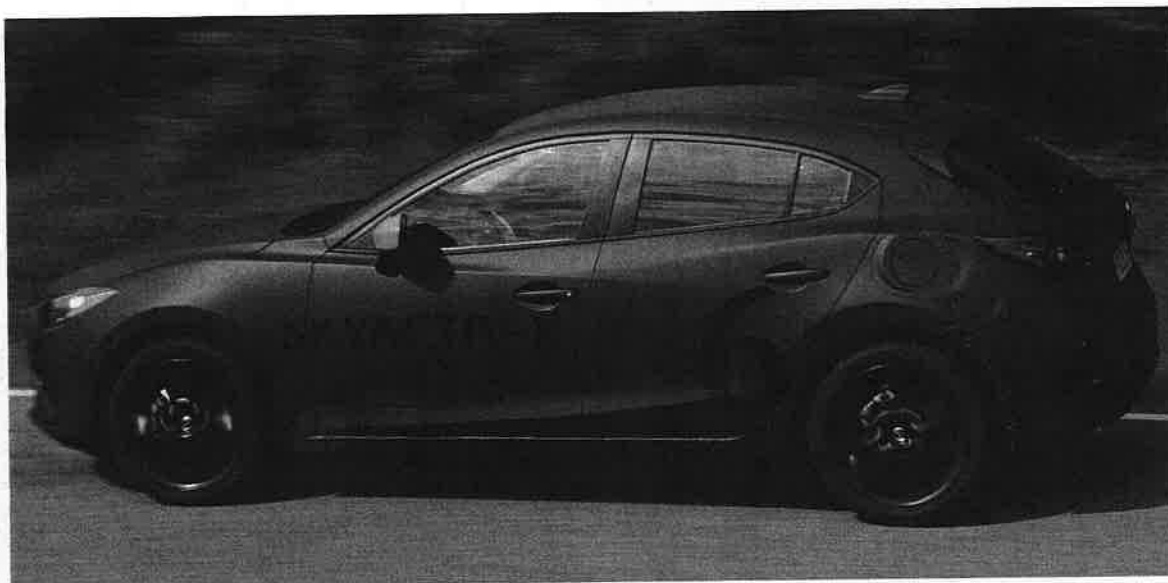


The primary alternations to existing engine architecture needed for the SpCCI are the cylinder head, more-sophisticated electronic controls and the air-pump supercharger.

However, this can be attributed to the exaggerated testing regime, aimed more at assessing the engine's attributes such as low-speed and in-gear acceleration in high(er) ratios and trying to detect the SI-to-CI switch-over points than would typically occur in "normal" driving.

SpCCI is a progression of Mazda's comprehensive Skyactiv efficiency-improvement initiative unveiled in 2011, which debuted gasoline and diesel engines with a common 14:1 compression ratio (CR). The new Skyactiv-X engine operates at a 15.0:1 CR, according to company engineers.

ICE BREAKER!



Mazda demonstrated the SpCCI system's production-readiness with on-road demonstration in summer 2017.

MAZDA

"We selected 15:1 compression ratio as it is close to compression-ignition conditions in normal ambient temperatures," explained Powertrain Executive Officer Ichiro Hirose. "The spark creates an expanding fireball that acts like a secondary 'air spring' to create additional compression. Because the spark plug creates this fireball, it effectively controls the switch between spark ignition and compression ignition," he noted.

Hirose added that achieving a "super-high compression ratio was a key breakthrough in realizing combustion with a lean fuel-air mix. Secondly, the leaner you make the air-fuel ratio, the more the specific heat ratio increases. To make the big step forward we needed to double stoichiometric levels from 14.7:1 to 30.0:1, at the very minimum."

As AE reported previously, during Skyactiv-X's development through G1, G2, and G3 program stages, engineers targeted an 18:1 compression ratio at lambda 2.5—a 40% improvement in thermal

Algae lipids key to Mazda's emissions-free ICE plan

New bio-fuel technology is key to Mazda's strategic plan to have a CO₂-emissions-free internal combustion engine in production by 2050, noted managing executive officer, Mitsuo Hitomi.

Speaking at the presentation of the Spark Controlled Compression Ignition (SpCCI) engine, he said: "Together with **Hiroshima University** and the **Tokyo Institute of Technology** we are developing algae lipid, genome editing and plant physiology to produce high-quality bio-fuels that do not impact on food stocks.

"If this fuel can be artificially manufactured to replace fossil fuel it will make a big contribution towards, not only, CO₂-free vehicles but, also aeroplanes and ships as well as energy security," Hitomi said.

He expects that the new biofuel technology development "might take time" but asserted that Mazda believes new renewable fuels are the most efficient way of drastically reducing CO₂ compared with the widespread adoption of electric vehicles (EVs).

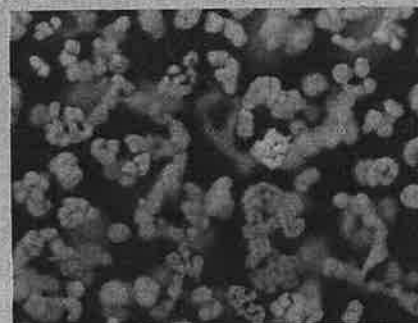
The innovative SpCCI engine, says Hitomi, is the foundation for that development pro-

gram. With Hiroshima University leading the research into genome editing and Tokyo Institute of Technology developing plant physiology, Mazda is confident that issues surrounding improved fuel productivity and cost reduction can be solved.

Mazda is on a similar path pursued by Audi, which launched a research facility in Hobbs, New Mexico, in 2013 for the production of e-ethanol and e-diesel in partnership with **Joule Unlimited**. Using a combination of sunlight, CO₂ and waste water to feed cyanobacteria to generate continuous streams of ethanol or long-chain alkanes, which are important constituents of diesel, the biofuel component can then be added to gasoline or as a basis for E10 or E85.

Automotive OEMs and suppliers are increasing their investigations into bio- and synthetic fuels for advanced combustion engines, as an alternative to electric drivetrains.

In his keynote address at the 2017 **Bosch** Mobility Experience event, Dr. Rolf Bulander, chairman of the company's Mobility Solutions sector, said, "...the combustion engine itself



Algae is showing increasing promise as feedstock for future fuels.

may become an alternative powertrain if it runs on synthetic fuel produced using renewable energy. This would make it resource-conserving and CO₂-neutral. Many paths lead to emissions-free mobility, and Bosch is exploring them all."

Hitomi's thoughts are parallel to those of Dr. Bulander: "I believe that if renewable fuel can be efficiently produced that will be the best way [to power vehicles]," he told *Automotive Engineering*.

Ian Adcock

NOAA GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY, VIA WIKI COMMONS

GM lost the HCCI race but continues R&D

Eight years ago, if I had to place a bet on which OEM would be first to productionize an HCCI combustion system, my clear choice would have been **General Motors**. As *AE* reported in July 2009, GM's HCCI program was making steady progress in extending the speed/load map of the 2.2-L Ecotec development engine while operating in compression-ignition mode. At 3000 rpm excessive combustion noise was a limitation—but one that program engineers were confident of overcoming.

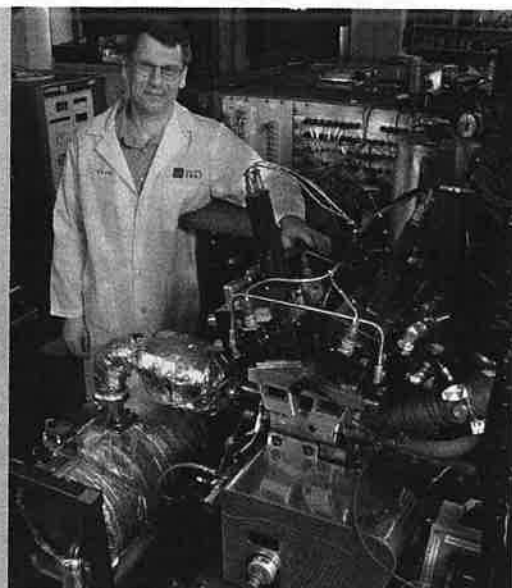
The **Chevrolet Malibu** mule I drove with engineers back then operated in fuel-saving HCCI mode for slightly more than 75% of the test drive. During this time the engine's leanest air/fuel operation was 28:1. In GM's vehicle testing, measured at 60 mph in sixth gear, steady-state engine-out NOx emissions were 0.186 g/km while operating in HCCI mode, compared with 1.938 g/km NOx in spark-ignition mode. The improvements in overall drivability, NVH and performance were big leaps beyond those of the mule I

had driven six months before.

So what happened with this promising program? Veteran GM Propulsion sources say pressure from the Obama administration during the company's bankruptcy forced it onto the "back burner"—the White House wanted GM to focus on hybrid and EV developments. But as of October 2017, HCCI remains an active program whose learnings are key to GM's next-gen ICE programs, including various lean-burn and aggressively downsized-boosted engines.

HCCI also is the focus of the GM/DoE High-Output Low Temperature Combustion (LTC) engine activity which leverages the learnings from the 2008-2009 demo vehicles. But while advanced combustion knowledge and IP is of high value for GM, the company currently "does not see a way to make HCCI technology cost-effective for our customers," according to a knowledgeable source. Mazda got there first!

Lindsay Brooke



GM advanced-combustion expert Paul Najt with 2.2-L HCCI engine in test cell, 2008. Najt continues to be involved with development in 2017.

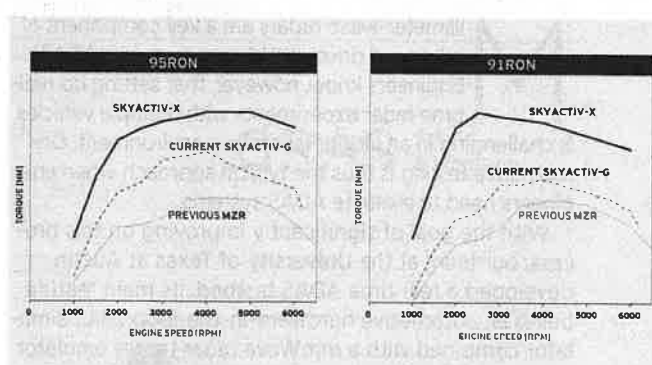
efficiency by setting the ideal pressure and temperature for homogeneous-charge compression ignition.

A key to Mazda's achievement for the production engine is precise control of the combustion process (see SAE Technical Paper <http://papers.sae.org/2015-01-1803/>). The SpCCI engine uses pressure sensors in each cylinder to enable real-time temperature and pressure monitoring, in addition to other engine parameters. The engine-management system controls the twin electrically-variable camshafts, the new split-injection strategy that operates at 500 bar (7252 psi) and the air pump. The latter is a unique Roots-type device engineered by **Eaton Corp.** for the Mazda SpCCI application, *Automotive Engineering* has learned.

Supercharging and exhaust gas recirculation are known to be effective for operating an HCCI engine in CI mode at high loads. But as of 2013, Mazda R&D was aiming to achieve successful lean-burn HCCI within a broad load range using normal aspiration, according to Takahisa Sori, then Managing Executive Officer for R&D. Sori's engineers were concerned about an air pump compromising real-world fuel economy.

Speaking with *AE* Japan Editor Jack Yamaguchi, Sori also was bullish on the potential of mating HCCI gas engines with hybrid-electric drivetrains that let the engine run in its most efficient operating range, with e-motor assist as needed. In this de-emphasized role, the electric motor and battery can be downsized, reducing their cost. Such an arrangement would seem to be ideal for collaborative work with Toyota hybrid systems engineers.

SpCCI's air-fuel mixture is created by two-phase, split injection on the intake and compression strokes. A strong swirl is created in the combustion chamber to create an intentionally uneven distribution of fuel density, with a lean mixture around the periphery for CI and a relatively rich air-fuel mixture around the spark plug in the center—



Mazda's data indicate the new Skyactiv-X engine is more powerful in addition to being markedly more fuel-efficient than the company's current 2.0-L gasoline engine.

conductive to creating the fireball.

Spark ignition is used to start the engine and under heavy-load conditions, but the switchover to CI is not at any predetermined point. When the right intake-charge boundary conditions are achieved, the expanding fireball in the combustion chamber is created, with SI providing additional compression to the geometric compression ratio of approximately 15-16:1. This reaction induces CI, Hirose explained.

He noted that manufacturing costs for the SpCCI engine fall between those of a diesel and a gasoline engine.

Automotive Engineering will report more details on Mazda's SpCCI development in future issues and online at SAE.org. ■