

## From Conventional Combustion to a Cleaner Future

By Paul Bickford for

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When looking to future trends in vehicle engine development, take a deep breath and look up. The atmosphere around us arguably drives engine design more than either gas prices or horsepower races.

The ten warmest years of the last century have occurred in the last 15 years. Sea levels have risen ten to twenty centimeters over the last hundred years. In the next century the average yearly temperature is expected to rise 1.4 to 5.8 °C, and the sea level is projected to rise 60 centimeters. The major cause of this warming trend is greenhouse gases spewed into the atmosphere. Global concentrations of carbon dioxide, CO<sub>2</sub>, have risen 35% since the industrial age, primarily due to the combustion of fossil fuels. In 2002, over  $25 \times 10^{12}$  metric tons of CO<sub>2</sub> were added to the atmosphere with approximately 33% from the transportation sector. This overall amount has been increasing by about 1.3% a year for the last 14 years.

Concurrent with the increase of CO<sub>2</sub>, unhealthy concentrations of smog, soot, and acid rain producing chemicals have become increasingly common. About forty years ago, the wealthy nations of the world started to tackle smog by regulating emissions from power plants, vehicles, and other pollution sources. These programs have met great success in lowering pollution levels even while the amount of fuel burnt has increased. Unfortunately, however impressive the gains in air quality have been, they still need to go further (just look at the increasing rates of asthma in urban areas). And this must be done while the number of cars and other combustion sources continues to grow as the global population expands and gets richer.

In response to these issues, in 2003 the European Community funded the ECO-Engines (for Energy CONversion in Engines) Network of Excellence to aid the development of high efficiency, low noise, and low emissions engines for ground transport. Its mandate includes organizing research and disseminating information among 24 European universities, institutes and industry in 9 countries, creating a virtual research center for advanced combustion technologies, as well as alternative and renewable fuels. It is coordinated by the Institut Français du Pétrole.

In order to effectively spread the results of their work, ECO-Engines sponsored a two week Advanced Engine Combustion Summer School this July. Twenty instructors from nine institutions taught four modules attended by 81 industry participants and graduate students from 14 countries. While longer than most seminars at two weeks, the time was well spent covering four modules: an overview of advanced combustion processes, associated control techniques, modeling, and experimental techniques.

Before delving into the technology covered by the Summer School, consider what we are injecting into our lungs every time we start our engines. The emissions that exit your tailpipe consist of, among other things, carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter and nitrogen oxides. Take a brief look at each:

Carbon Dioxide (CO<sub>2</sub>) - An inevitable emission from burning hydrocarbons, it is not poisonous in itself. However, it is a greenhouse gas that is a major contributor to global warming. The only way to reduce it is to raise efficiency, i.e. burning less fuel means less CO<sub>2</sub> produced.

Carbon Monoxide (CO) – Primarily formed by incomplete combustion, CO is toxic.

Unburned hydrocarbons (HC) - Mainly associated with spark-ignition gasoline engines, these are toxic and also lead to smog and ground-level ozone. HC is a result of fuel that has not undergone complete combustion.

Nitrogen oxides (NO<sub>x</sub>) – A major cause of ground-level ozone and acid rain. It is formed by excessive temperatures during combustion.

Particulates (PM) – Also called soot, they constitute a range of health hazards. They are caused by local cooling of incomplete combustion and are primarily produced by diesels.

Clean combustion is a balancing act. Current technologies trade off one noxious side effect for another. Take, for instance, a diesel. It runs lean and hot and thus generates NO<sub>x</sub>. At the same time, a portion of the combustion gets cooled by unburned fuel in the injection spray, producing soot. On the other hand is a spark-ignition engine, in which fuel is injected early, producing a relatively homogeneous mixture of fuel and air at the time of ignition. However, temperatures are lower than diesels due to a lower compression ratio so this mixture needs a spark to initiate the flame. Once ignited, pressure, temperature, and chemical composition differences appear due to the quickly traveling flame front and quenching of the chemical reactions as they hit the cooler cylinder walls. These inhomogeneities cause local volumes of incomplete combustion, i.e. unburned hydrocarbons, CO, and formaldehyde.

Responding to all these compounds attacking our air quality, regulators from the European Union and the USA, California in particular, have set increasingly strict emissions standards over the years. For example, HC and NO<sub>x</sub> emissions have been reduced 99% over the last 40 years. These regulations have become the engineers' primary obstacle in developing new engine technology. The previous and current standards for passenger cars and light trucks are given in table 1.

**Table 1 EU and California emission standards in g/km.**

	Year	HC	CO	NO <sub>x</sub>	PM	HCHO
EURO III	1999	--	--	0.15 (0.5)*	-- (0.05)*	--
California	1997	0.16	0.21	0.25	0.05	--
EURO IV	2006	--	--	0.08	0.025	--
California LEV	2006	0.047	2.1	0.03	0.006	0.009
California ULEV	2006	0.025	1.1	0.03	0.006	0.005

Source: [www.dieselnet.com/standards](http://www.dieselnet.com/standards)

\* Gasoline (Diesel) . Note: while the EU has one set of standards, California's system allows each manufacturer to certify each model to one of ten emissions categories (Low Emission Vehicle—LEV—and Ultra Low Emission Vehicle—ULEV—are the least stringent). Manufacturers are required to sell a mix of vehicles from among several of the categories.

Engine technologies have made great progress in reducing these pollutants, in large part through exhaust after-treatment. Rather than costly after-treatment, what manufacturers really want is to clean up the combustion stage of the system, reducing their reliance on fragile, precious metal catalysts. However, pushing the frontiers of such a highly developed technology as the internal combustion engine is an increasingly difficult project. This is what ECO-Engines was created for.

ECO-Engines decided to focus the Advanced Engine Combustion Summer School on two promising technologies, both of which could lead to a clean combustion process. Named Homogenous Charge Compression Ignition (HCCI) and Controlled Auto-Ignition (CAI), these are two closely related technologies that both chase after the same combustion conditions in which fuel is burned quickly, but at a relatively low temperature. Exhaust emissions from this type of combustion are extremely low, e.g. NO<sub>x</sub>, a particularly difficult emission to get rid of through after-treatment can be reduced by a factor of more than 100.

What is now called the HCCI/CAI combustion process was first investigated by Mr. Onishi, at the Nippon Clean Engine Research Institute, who called it Active Thermo-Atmosphere Combustion, ATAC. It was essentially a form of run-on in a two-stroke gasoline engine. After the spark was turned off, the high exhaust gas recirculation, EGR, of the two-stroke caused the engine to continue to fire. By manipulating the EGR to initiate auto-ignition, Mr. Onishi was able to run continuously at low load, without spark. However, more interestingly, the engine ran much smoother, with much improved cycle-to-cycle repeatability, a significant factor in efficiency and performance. Further research indicated that this combustion showed neither a flame front nor an initial flame kernel, instead it displayed a homogeneous fine gradual combustion reaction across the cylinder.

Around the same time, research by Noguchi at Toyota & Nippon Soken, studying the same combustion process which they called T-S, showed remarkable emissions and efficiency. Subsequent research has looked into the role of EGR in the process of burning fuel homogeneously at relatively low temperatures, as well as the role of EGR's high residual temperatures and chemical radicals in promoting the low temperature heat release.

The HCCI/CAI combustion process is for the most part only achievable at low loads. This means that in order to create a practical engine with a flexible load range, you must start with an existing engine and modify it to switch between combustion modes as load varies. HCCI technology starts with a diesel engine, running diesel fuel, and modifies it in order to achieve clean combustion at appropriate conditions. CAI starts with a gasoline, spark-ignition motor. At idle, it runs in spark mode, at low loads it switches into CAI mode, and then back to spark mode at higher loads. While the desired clean combustion process is the same in the two technologies, the differences in the base engine necessitate quite different techniques.

In a diesel, fuel is injected into hot, compressed air, igniting almost immediately. In a spark ignition engine, a homogeneous charge of air and fuel is compressed but does not ignite until the spark is produced. In HCCI/CAI mode, a relatively homogeneous charge of fuel, air, and EGR is compressed without a spark. There is no direct control of ignition. Auto-ignition with clean combustion will occur when temperature, pressure, and chemical composition are at favorable levels. Of the variables that affect ignition, e.g. air-fuel ratio, temperature, intake pressure, and fuel composition, the primary factor in controlling the ignition point is the amount and temperature of the high levels (>40%) of EGR. It is obvious that without a spark or fuel injection to initiate combustion, HCCI and CAI will require very sophisticated means of operating control.

The Advanced Engine Combustion Summer School presented several possible technologies to control ignition of HCCI/CAI engines. Of those discussed, the most important would have to be Variable Valve Actuation, VVA, due to its direct control of EGR. VVA's ability to change the valve timing of both intake and exhaust valves independently allows a relatively simple and effective way to vary the percentage EGR. Closing the exhaust valve early traps residual gas in the cylinder. The earlier it is closed, the more EGR and vice versa. Keeping in

mind that controlling EGR percentage and temperature are vital to achieving HCCI/CAI, one can see why advances in VVA are being closely watched.

Another technology called Variable Compression Ratio, VCR, could be a very effective means of controlling ignition. VCR gives direct control over pressure and temperature which are of primary importance in the ignition of the mixture. Unfortunately, VCR is not as developed as VVA, requiring larger investments to achieve production-ready systems.

Other control methods seek to vary EGR and boost with variable rate turbocharging, intercoolers, and sophisticated EGR plumbing systems. These configurations try to address the differing requirements at different speeds and loads. Not only does the percentage EGR need to change for every operating point but the temperature as well. At low loads, the EGR might need to be very hot, while at high loads, the EGR might need to be cooled to avoid excessive temperatures.

The development of such indirect control of ignition is hampered by the incomplete analysis tools for the HCCI/CAI combustion process, especially in the chemically complex, turbulent environment inside the cylinder. In order to address this issue, the Summer School discussed various modeling techniques. The actual thermodynamics and chemical kinetics involved in combustion are mind-bogglingly complex and must be approximated with simpler models in order to reduce computation time to practical levels. For example, a multi-zone model reduces computation by assuming the majority of the cylinder volume is at one condition while a much smaller volume in contact with the cooler walls is at another. Using only two states greatly simplifies the thermodynamic conditions, allowing more time to be spent on detailed chemical reactions. While there is a full toolbox of increasingly detailed methods to predict in-cylinder conditions and chemistry, it cannot be expected to give accurate results until the approximations are validated in the regime of HCCI/CAI.

Experiments validating these models are sorely needed before these models can be practical in designing and testing technologies. The Summer School presented a series of experimental techniques available to researchers to measure and visualize cylinder conditions, including optical, probe and a particularly interesting set of sophisticated laser-based techniques. In general, each laser-based technique shines coherent light into the cylinder while the frequency and amount of light returned is measured. Each type of molecule in the cylinder can only absorb and emit light energy in specific amounts governed by quantum theory. By examining the frequency of light absorbed, emitted, or scattered, desired parameters, such as flame propagation, chemical species, and temperature can be calculated. While many of these methods are capable of rendering impressive 3-D maps of actual combustion parameters, they require complex set ups, expert operators, and, most importantly, changes to the combustion chamber, thereby altering the process that is being studied. Windows need to be installed in the combustion chamber, such as a sapphire ring sandwiched between the cylinder liner and the head. This affects the thermodynamic behavior and limits the engine to running at reduced load.

Such complex techniques may seem out of reach but it is all part of an effort to push the understanding of HCCI/CAI. In order to reach production, engineers need experimental techniques, advanced control technologies, models, and, most of all, knowledge. The ECO-Engines Advanced Engine Combustion Summer School provided a much needed, in-depth look at these important new technologies aimed at reducing engine emissions. Participants got not just an overview but a chance to get comfortable with new technologies that will likely become essential in meeting new air quality standards. As light-duty vehicle sales are forecast to almost double in the next ten years, more seminars like this are going to be needed to keep our children's air breathable.