The GASOLINE DIESEL

Research at a national lab aims to break barriers in fuel economy and emissions performance.

BY STEVE CIATTI

A common topic I often hear discussed around the coffee maker or water cooler is the seeming lack of progress in fuel economy among cars sold in the United States.

Conspiracy theories abound. So do apparent solutions, such as “If we all drove vehicles based on [fill in the technology—diesel, hybrid, electric], we wouldn’t have this problem.”

I’m not a conspiracy theorist, and I’m certain Americans will not scrap their 260 million vehicles—and the infrastructure that supports them—overnight.

Yet when it comes to fuel economy in conventional spark ignition and diesel engines, we seem to be treading water. Why?

Part of the problem is that there is not just one

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problem to solve, but multiple, simultaneous problems we must unravel.

For example, diesel engines tend to be very efficient, but they have an emissions problem. They require complex and expensive equipment to meet pollution mandates.

Spark ignition gasoline engines, on the other hand, do a much better job with emissions, but they are inherently less efficient.

Moreover, neither spark nor diesel systems have significant potential for improvement.

So our team at Argonne National Laboratory decided to look for ways to combine the best characteristics of both. This new system is more like traditional diesel combustion than spark ignition, but uses a gasoline-like fuel and a new approach to combustion to minimize emissions.

To understand how this works, let's start by evaluating engine efficiency and emissions performance and work forward from there.

DAMPERS ON SPARKS

We all know the basics:

Diesel and spark ignition are both internal combustion engines. They use a small explosion in the combustion chamber of a cylinder to power a piston up and down. The piston connects to a crankshaft, which transmits this linear motion into rotary motion to drive the vehicle's wheels.

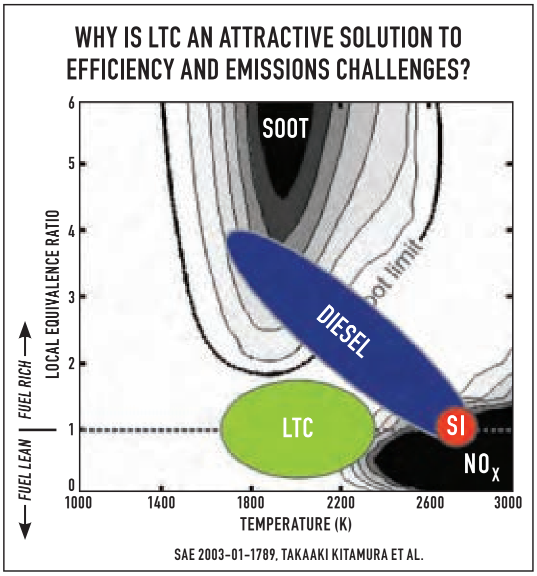
The difference between the two types of engines lies in how they initiate combustion. Diesel engines compress air, which increases its pressure and temperature. When the system injects a fine mist of fuel, it produces an explosion almost immediately, pushing the piston and turning the crankshaft.

Gasoline engines, on the other hand, start by mixing fuel with air in a fixed ratio that provides enough oxygen to completely burn all the fuel in the mixture. The engine injects this mixture into the cylinder, but it does not ignite until the spark plug fires.

Spark ignition engines have three key flaws that diesel technology addresses.

The first involves the throttle. In spark ignition engines, the throttle controls the flow of air entering the engine, while the port fuel injector controls the fuel. When the engine needs more power to accelerate or climb a hill, both the port fuel injector and throttle open wider to maintain the fuel:air ratio.

Problems crop up when the engine is cruising and uses less power. This causes pumping loss, and it is the single most important reason why spark engines are less efficient than diesels.



SAE 2003-01-1789, TAKAAKI KITAMURA ET AL.

Diesels operate in ranges that generate soot and NO_X, while spark ignition engines produce NO_X only. Low-temperature combustion seeks to avoid both realms.

The way we get a 100 hp engine to cruise at 50 hp is to restrict the flow of fuel and air into the cylinders. We can reduce fuel use by pumping less fuel through the fuel port. To limit airflow, we partly close the throttle valve. This produces a partial vacuum above the piston as it descends to suck air into the cylinder. The combination of partial vacuum above and normal pressure below the piston creates drag that can only be overcome with additional power and fuel.

Pumping losses occur under most normal driving conditions. Moreover, the larger the engine, the greater the pumping losses. Why? A midsized car cruising at 65 mph on level ground with a partially closed throttle might achieve 30 percent efficiency.

A 200 hp motor under the same conditions would need to close its throttle even further. This would create a more powerful vacuum and increase drag even more. In our highway example, a 200 hp motor would achieve only 15 to 18 percent efficiency and have about half the fuel efficiency of the car with the smaller engine.

Diesels, on the other hand, do not premix fuel and air, so they have no throttles. Instead, they inject fuel directly into the combustion chamber only when needed. This is an elegant way to control power output, but it tends to produce lots of particulate matter (soot) and nitrogen oxide emissions.

The second flaw in spark engines is their low compression ratio. This ratio describes the extent that a piston compresses its air:fuel mixture. Squeezing the mixture into a smaller space produces a more powerful explosion

Higher compression ratios maximize the amount of power generated by a given amount of fuel, but only up to a point. After that, they cause knocking, premature combustion in the cylinder. This can sap an engine's power or, in severe cases, shake it apart.

Antiknock additives, measured by octane rating, suppress knock. The higher a gasoline's octane, the more compression it can withstand. Performance cars generally require high-octane premium gasoline for their high-compression engines.

Decades ago, when refiners added tetraethyl lead to gasoline, regular gasoline had octane ratings above 90. This enabled compression ratios of greater than 10:1. As the industry phased out leaded additives, regular gasoline fell to 87 octane and compression ratios fell to 9:1 or even 8.5:1 to prevent knocking for all customers in all markets.

Spark engine developers have several workarounds to boost effective compression ratios. Turbochargers, for example, use hot exhaust gases to drive air pumps that boost air intake pressure. Unfortunately, this strategy makes knocking more likely, which is why turbocharged spark engines tend to have compression ratios of about 7:1 and require 93 octane gasoline.

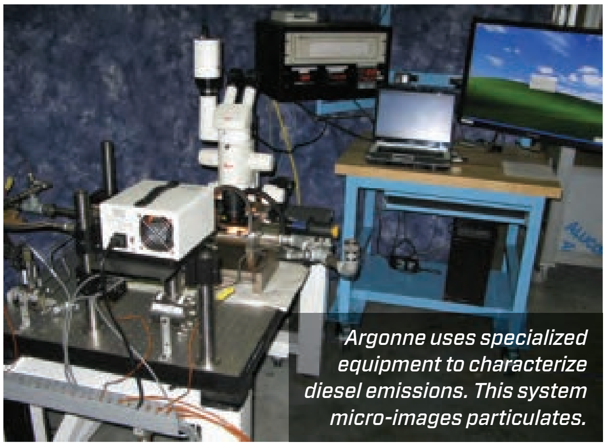
A second strategy is cam phasing, controlling the lift of intake and exhaust valves to boost effective compression ratios. This yields higher compression ratios under low throttle conditions, where the propensity to knock is somewhat reduced.

Unfortunately, both turbochargers and cam phasing increase complexity and cost but yield only modest improvements in efficiency.

Diesels, on the other hand, are designed to burn fuel almost as soon as it is injected, so they have no knock limitations. As a result, their compression ratios range from 15:1 with a high turbocharged intake pressure boost (45 pounds per square inch absolute) to 18:1 with a modest (30 psia) boost. Their combination of high compression ratios and turbochargers achieve significant efficiency advantages.

The third flaw in spark engines involves heat transfer loss. Spark engines generate lots of excess heat, and require relatively oversized cooling systems to remove it.

The problem here goes back to spark engine's fixed air:fuel ratio. It not only improves combustion efficiency and minimizes emissions, but it also yields the highest possible combustion temperatures. Since the expansion ratio of hot gases in the cylinder matches the compression ratio, the gases expand by only a factor of eight to nine and remain rather hot. It takes an oversized cooling system and radiator to manage this excess heat.


Argonne uses specialized equipment to characterize diesel emissions. This system micro-images particulates.

Diesel engines, on the other hand, tend to run lean, meaning there is more oxygen in the mix than fuel. This reduces in-cylinder average temperatures. Why? The cylinder holds extra air (not just oxygen) per unit of fuel. This lowers the temperature per unit volume of air. Since the gases in the cylinder expand nearly twice as much as those in a spark engine, this results in significantly cooler exhaust temperatures. Moreover, nearly all diesels recover some exhaust to power their turbochargers, further enhancing their efficiency.

LOW-TEMPERATURE COMBUSTION

So, why don't we all drive diesels? The answer involves pollution. The same direct fuel injection system that discards the throttle, eliminates knock, and runs lean also produces toxic emissions—specifically soot and NO_x.

In fact, according to the U.S. Environmental Protection Agency, mobile diesels in 2009 discharged 300,000 tons of soot and 6.4 million tons of NO_x into the atmosphere. NO_x contributes to smog, forming both ozone and fine particles. Soot triggers asthma and worsens heart and lung disease.

Both types of emissions are inherent in diesel operation. Soot forms because air and fuel do not have time to mix fully prior to combustion. Upon ignition, fuel-rich regions of mixture that do not fully burn form fine particulates.

NO_x forms at high temperatures when excess oxygen—a byproduct of high compression ratios and direct injection—combines with atmospheric nitrogen to form nitrogen oxides.

Unlike conventional gasoline engines, treating diesel exhaust is expensive. Spark engines use a passive three-way catalyst. Diesels require an actively controlled particulate filter and NO_x catalysts that cost thousands of dollars.

This leaves us with an interesting conundrum: Gasoline spark engines have fatal efficiency flaws but comply easily and relatively inexpensively with emissions requirements. Diesels are more efficient, but carry a heavy penalty for emissions compliance.

Is there any way out of this box? Many of the latest approaches to these efficiency/emissions problems try to hybridize the best aspects of both combustion systems.

We definitely want to retain the diesel's efficiency by eliminating the throttle, operating at high compression ratios, and reducing heat transfer losses. And we want to do this in ways that do not create an emissions problem.

Generally, we refer to strategies that use efficient compression ignition combustion cycles but suppress emissions as "low temperature combustion," because they rely upon low peak combustion temperatures to reduce NO_x formation and heat transfer losses.

Researchers have explored different approaches to low-temperature combustion for decades. As worldwide emissions regulations have tightened, the picture has begun to come into focus.

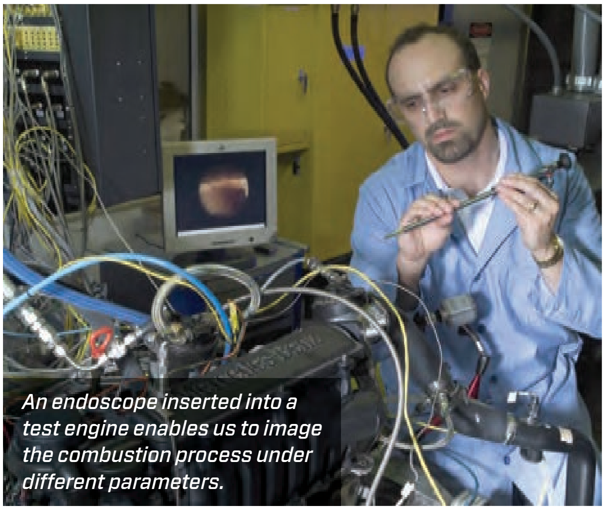
The first generation of high-efficiency, low-emission technologies included HCCI (homogeneous charge compression ignition), M-K (modulated kinetics, also called smokeless rich), and UNIBUS (uniform bulky stratified combustion).

They all borrowed a strategy from spark ignition engines—premixing fuel and air—to reduce soot and NO_x formation. They also recycled exhaust gases, whose free oxygen had already been consumed during combustion, to reduce the concentration of oxygen in the combustion chamber to 15 percent or lower, from 21 percent (ambient).

Lowering oxygen levels did two things. First, it delayed fuel ignition until the piston was closer to top dead center. This improved combustion cycle efficiency even at less-than-peak combustion temperatures, which slashed NO_x formation and heat transfer losses without giving up power.

The catch? Ignition relies solely upon the chemical kinetics of fuel, air, and exhaust gas in the combustion chamber at any given time. Controlling power in a repeatable and reliable way has proven very difficult, especially when engine speed or load needs to change. While research continues on these types of combustion systems, none of them appears a serious contender for creating breakthrough transportation engines.

The second-generation approach to low-temperature combustion attempted to control fuel auto-ignition by blending together two different fuels.


An endoscope inserted into a test engine enables us to image the combustion process under different parameters.

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The best known of these techniques is RCCI (reactivity controlled compression ignition). It starts with a mixture of gasoline, which has very low reactivity (it does not ignite easily without a spark), and recirculated exhaust gas. Injecting a small amount of high-reactivity diesel fuel initiates combustion.

Injecting diesel fuel early in the stroke reduces soot and NO_x formation because it gives the diesel fuel sufficient time to mix with air. RCCI is reliable and efficient throughout the engine's entire speed and load range. It achieves quite low emissions levels. Its downside is that a vehicle must store two separate fuels and invest in potentially complex and expensive equipment to regulate the proportion of gasoline, recycled exhaust, and diesel fuel precisely.

THE ARGONNE APPROACH

At Argonne National Laboratory, our team is developing an approach pioneered by Gautam Kalghatgi of Shell Oil. It attempts to simplify what we have learned from second-generation low-temperature combustion research.

Instead of two fuels and complex equipment to control their mixture, it uses an off-the-shelf diesel engine and only one fuel, low-octane gasoline, to achieve dramatic reductions in soot and NO_x. For lack of a better alternative, we call it MSCI, for multizone stratified compression ignition. It is named after our air/fuel mixing strategy, and we'll get to that in a moment.

The reason diesels produce soot and NO_x is that ignition takes place almost as soon as they inject fuel into the engine. This does not give the fuel enough time to disperse evenly, and so oxygen-rich regions form NO_x and fuel-rich regions form particulates.

We attack this problem in several ways. Let's start with our choice of fuel. One thing we do differently is that we use gasoline with a slightly lower octane than pump gasoline. We're burning fuel in the 80 to 85 RON (research octane number) range, compared with standard 87 RON regular gasoline.

Our low-RON gasoline is a little easier to auto-ignite than pump gasoline. Yet low-RON gasoline is still difficult to ignite. This is especially true when we mix in some recycled exhaust gas to keep temperatures low. So how do we do it?

First, we operate at higher compression ratios than other low-temperate combustion engines. This generates the higher pressures and temperatures needed to set off our fuel mixture—but only at the top dead center of the compression stroke.

Second, we inject fuel two or three times during each compression cycle, starting early in the stroke. Using a fuel that is difficult to auto-ignite gives us more time to stratify layers of well-mixed fuel, air, and exhaust gases before the pressure buildup ignites the mixture.

Our mixing strategy gives us more levers to control combustion timing. Not only can we optimize the number of fuel injections, but also their timing, pressure, droplet size, and several other factors.

Our work to date shows near-zero particulate matter emissions and 66 to 80 percent reductions in NO_x compared with conventional diesels.

There are, however, trade-offs. They come in the form of power density. When we use exhaust gas to lower combustion temperatures, we reduce the violence of our combustion reactions. As a result, peak power drops roughly 25 percent.

How significant is that? Standard vehicle operation rarely requires peak power. After all, how often do you have the accelerator pedal mashed to the floor?

Moreover, the new system's torque profile is essentially the same as that of a conventional diesel, and it provides excellent performance in the powerband where most people actually drive. We believe the impact on most drivers will be negligible.

Our challenge is to ensure robust, reliable operation during transient operation. In this regard, multizone stratified compression ignition is not as robust as traditional spark ignition or diesel combustion. Still, our stratification strategy provides more control over engine power than most dual-fuel systems, which require two fuel tanks and complex and costly injection equipment.

In fact, we believe MSCI could provide all of the advantages of diesel engines (no throttle, high compression ratio, low heat transfer) with a significantly reduced soot and NO_x signature. Equally important, we can do it with conventional, off-the-shelf components and low-octane gasoline that should cost less to refine than conventional gasoline or diesel. We may be able to greatly simplify emissions control, resulting in vehicles that are more economical, more efficient, and less costly to buy and operate.

We will continue to work with our industrial and academic research partners around the globe to explore this combustion system and test its possibilities. ■