Gasoline-alcohol engines for heavy-duty trucks could produce a meaningful improvement in global air quality

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Several years ago, Daniel Cohn (left) and Leslie Bromberg took on the challenge of designing a low-emissions, fuel-efficient replacement for the polluting diesel engines traditionally viewed as the only viable option for powering heavy-duty trucks. Using sophisticated computer models developed by Bromberg, they've now produced a conceptual design for an engine that should be up to the task. Credit: Stuart Darsch

Most efforts to reduce the adverse air pollution and climate impacts of today's vehicles focus on cars and light-duty trucks that are typically fueled by gasoline, with strategies that range from electrification and carpooling to autonomous vehicles.

"These strategies can be an important part of the overall solution," says Daniel Cohn, research scientist at the MIT Energy Initiative. "But it's also increasingly important to think about heavy- and medium-duty trucks. Finding a way to clean them up could actually bring a greater improvement in worldwide air quality during the next few decades."

Powered largely by diesel engines, those trucks are now the largest producer of nitrogen oxide (NOx) emissions in the transportation sector, contributing to ground-level ozone, respiratory problems, and premature deaths in urban areas. Some estimates project that diesel fuel—used for both trucks and cars —will out-sell gasoline worldwide within the next decade, threatening to further increase already-severe urban air pollution as well as greenhouse gas (GHG) concentrations.

Today's heavy-duty diesel engines provide fuel efficiency and high power, making them ideal for long-haul, high-mileage commercial vehicles. But finding another option is critical, says Cohn. "We need to replace diesel engines with other internal combustion engines that are much cleaner and produce less greenhouse gas."

Using computer simulation analysis, Cohn and his colleague Leslie Bromberg, principal research engineer at the Plasma Science and Fusion Center and the Sloan Automotive Laboratory, have designed a replacement half-sized gasoline-alcohol engine that should be not only cleaner but also lower-cost and higher-performing—and could be introduced into the fleet of vehicles on the road soon.

Replacing the heavy-duty diesel

Within the United States, pressure on the trucking industry to deal with diesel emissions has been mounting. Indeed, expected regulations in California would require that NOx emissions from medium- and heavy-duty trucks be cut by about 90 percent relative to today's cleanest diesels, which use complex and expensive exhaust treatment systems just to meet current regulations. In some parts of the world, such as India and China, those cleanup systems aren't generally used. As a result, NOx emissions are about 10 times higher, and getting them down to the level of future California regulations would require a reduction of about 98 percent.

In the United States, some trucks have begun to meet the expected strict NOx limits using large spark-ignition (SI) engines fueled by natural gas. But large-scale adoption of those engines would be problematic. Storing and distributing a gaseous fuel raises vehicle cost and poses infrastructure challenges, and the use of natural gas can lead to a heightened climate impact because of the leakage of methane, a GHG with high global warming potential.

To avoid the challenges of dealing with natural gas, Cohn and Bromberg decided to pursue another approach: a heavy-duty SI engine fueled instead by gasoline. In general, gasoline SI engines produce low NOx emissions. Guided by their computer models, Cohn and Bromberg took a series of steps to increase the power and efficiency of that design without sacrificing its emissions benefits.

During normal gasoline SI engine operation, the process of translating the combustion of gases into torque (rotational force) at the wheels progresses smoothly—until there's a need for high-torque operation, for example, to pull a heavy load at high speed or up a hill. Then, pressures and temperatures inside the cylinder can rise so much that the unburned combustion gases spontaneously ignite. The result is knock, which causes a metallic clanging noise and can damage the engine. The need to prevent knock has up to now limited improvements in efficiency and performance that would be needed for gasoline engines to compete with diesels.

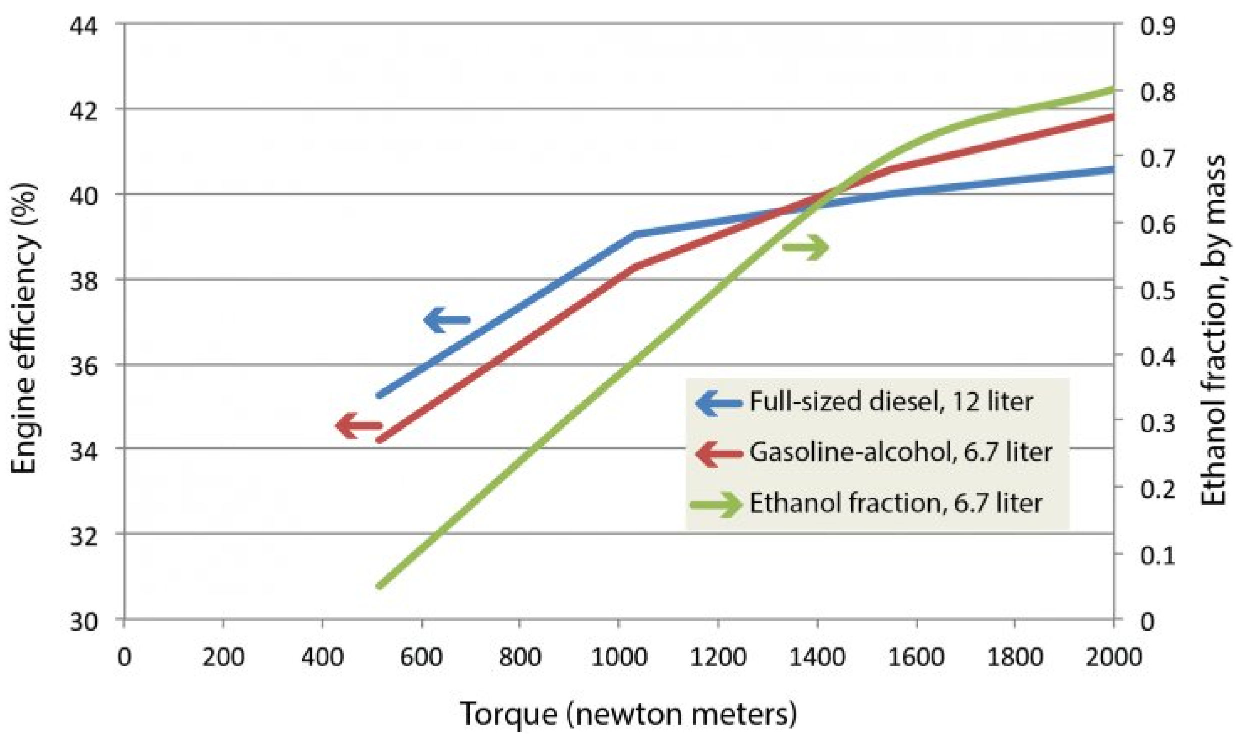
Cohn and Bromberg dealt with that problem using alcohol. When the SI engine is working hard and knock would otherwise occur, a small amount of ethanol or methanol is injected into the hot combustion chamber, where it quickly vaporizes, cooling the fuel and air and making spontaneous combustion much less likely. In addition, because of alcohol's chemical composition, its inherent knock resistance is higher than that of gasoline. The alcohol can be stored in a small, separate fuel tank—as exhaust-cleanup fluid is stored in a diesel engine vehicle. Alternatively, it could be provided by onboard separation of alcohol from gasoline in the regular fuel tank. (Almost all gasoline sold in the United States is now a mix of 90 percent gasoline and 10 percent ethanol.)

With concern about knock removed, the researchers were able to take full advantage of two techniques used in today's passenger cars. First, they used turbocharging, but at higher levels. Turbocharging involves compressing the incoming air so that more molecules of air and fuel fit inside the cylinder. The result is that a given power output can be achieved using a smaller total cylinder volume. And second, they used a high compression ratio, which is the ratio of the volume of the combustion chamber before compression to the volume after. At a higher compression ratio, the burning gases expand more in each cycle, so more energy is delivered for a given amount of fuel.

The researchers also made use of an important feature of the low-NOx heavy-duty SI engine fueled by natural gas: They assumed that the mixture of air and fuel inside their engine contained just enough air to burn up all the fuel—no more, no less. That stoichiometric operation permitted important changes not possible in the diesel, which must run with lots of extra air to control emissions. With stoichiometric operation, they could utilize a three-way catalyst to clean up the engine exhaust. A relatively inexpensive system, the three-way catalyst removes NOx, carbon monoxide, and unburned hydrocarbons from engine exhaust and is key to the low NOx achieved in today's SI engines.

Then, given stoichiometric operation combined with a higher level of turbocharging and a high compression ratio, the researchers were able to shrink their whole engine. The SI engine doesn't contain all the excess air that's in a diesel, so the total volume of its cylinders can be smaller.

"Because of that difference, you can replace a diesel engine with an SI engine about half as big," says Bromberg.



This figure shows engine efficiency at various levels of torque (rotational force) in the 12-liter diesel engine (blue) and the 6.7-liter gasoline-alcohol engine (red) assumed in the analysis. Efficiencies of the two engines are comparable, though the gasoline-alcohol engine is somewhat less efficient at lower torque and more efficient at higher torque. The amount of ethanol used in the gas-alcohol engine (green) increases with increasing torque, as pressures and temperatures inside the cylinder rise and more alcohol is needed to suppress knock. Credit: Massachusetts Institute of Technology

With that reduction in size comes an increase in fuel efficiency. In any engine, the process of pumping air into the cylinders and various sources of friction inevitably reduce fuel efficiency. Those pumping losses depend on engine size. Make an engine smaller, and there's less friction and less wasted fuel.

Taken together, the low-cost three-way catalyst and smaller overall size help make the gasoline-alcohol engine less expensive than the cleanest diesel engine with a state-of-the-art exhaust-cleanup system. Indeed, according to the researchers' estimates, the cost of the gasoline-alcohol engine plus its exhaust-treatment system would be roughly half that of the cleanest diesel engine.

Power, efficiency, and alcohol use

How does the half-sized gasoline-alcohol SI engine compare to today's cleanest full-sized diesel on efficiency and power? To answer that question, the researchers used a series of sophisticated engine and vehicle simulations and chemical kinetic models developed by Bromberg.

For the comparison, they used an illustrative version of their engine based on a 6.7-liter engine that's now manufactured and could—with relatively small alterations—be converted to the gasoline-alcohol configuration. Their analysis assumed that the compression ratio and engine torque were about the same in the 6.7 gasoline-alcohol SI engine as in a 12-liter diesel engine. But the SI engine can run far faster than the diesel can. (Combustion is faster with spark ignition than with the compression ignition used in diesel engines.) Because of the faster operation and the roughly equivalent torque, the small engine can produce almost 50 percent more power than the diesel can. And while the gasoline-alcohol engine is somewhat more efficient than the diesel at high torque and less efficient at low torque, in general the small SI engine is about as efficient as the diesel.

However, as more torque is required, knock becomes more likely, so more ethanol is needed. At the highest torque, about 80 percent of the total fuel must be ethanol to prevent knock. That estimate raises a concern: In the United States, ethanol is widely used in a low-concentration mixture with gasoline, but pure ethanol or a high-concentration ethanol-gasoline blend may not be available or may be too costly. So how much ethanol is likely to be required for a given trip?

As an example, the researchers considered a trip taken by a long-haul, heavy-duty vehicle that requires high torque most of the time. Depending on the compression ratio, ethanol could make up 20 to 40 percent of its total fuel consumption. In contrast, a delivery truck might operate at low torque most of the time and do just fine with ethanol as 10 percent of its total fuel over a driving period.

"Such levels of ethanol consumption are doable," notes Cohn. "But the system would be more attractive to people if you had a case where you could use less ethanol."

One way to reduce ethanol use would be to dilute the ethanol with water. Using the knock model, Cohn and Bromberg determined that knock resistance is actually higher when water makes up as much as a third of the secondary fuel. "And in some cases where you don't need any ethanol for antifreeze, you might be able to run with water alone as the secondary fluid," says Cohn.

Another approach to reducing alcohol use—called upspeeding—involves operating the engine at a higher speed. Running the engine faster and adjusting the gearing in the transmission to increase the ratio of engine rpm to wheel rpm make it possible to use less engine torque in the gasoline engine to achieve the same torque at the wheel as in the diesel. According to the researchers' calculations, that reduction in engine torque could reduce ethanol use over a driving period to less than 10 percent of the total fuel consumed, an amount that could be supplied by onboard fuel separation.

Reducing climate impacts

Cohn points out one more benefit of the gasoline-alcohol SI engine: a pathway to reducing GHG emissions.

"A somewhat under-recognized aspect in evaluating the environmental impacts of transportation vehicles is that GHG emissions from trucks worldwide will overtake GHG emissions from cars sometime between 2020 and 2030," he notes.

The gasoline-alcohol SI engine can be operated in a flexible-fuel mode where it uses only pure alcohol if desired. Right now, looking at the life cycle of the fuels and assuming comparable engine efficiency, using ethanol produced from corn by state-of-the-art methods generates about 20 percent lower GHG emissions than using gasoline or diesel fuel. Even greater reductions in GHG emissions could come when ethanol and methanol fuels are produced from agricultural, forestry, and municipal waste or specialty biomass.

"Reducing GHG emissions from trucks by finding an alternative source of power—for example, through electrification—could take a long time," says Cohn. "But if you can operate your engine partially with ethanol or entirely with ethanol, that's a good way to make a start right away."

More information: Daniel Cohn et al. Dual-Fuel Gasoline-Alcohol Engines for Heavy Duty Trucks: Lower Emissions, Flexible-Fuel Alternative to Diesel Engines, *SAE Technical Paper Series* (2018). DOI: 10.4271/2018-01-0888

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