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SERIES: U.S. PASSENGER VEHICLE TECHNOLOGY TRENDS

Naturally Aspirated Engines

In the technology analyses for the 2025 corporate average fuel economy (CAFE) and greenhouse gas standards, the National Highway Transportation Safety Administration and the U.S. Environmental Protection Agency projected that naturally aspirated engines would have little or no place in the 2025 vehicle fleet. Instead, the fleet would feature a combination of downsized-turbocharged engines and hybrids, with a small number (~2%) of electric vehicles. (A naturally aspirated engine relies on ambient air pressure within and around the engine to provide the oxygen necessary for fuel combustion. Until the 1990s, nearly all passenger vehicle gasoline engines were naturally aspirated.)

But since their analyses were completed in 2012, naturally aspirated engines have improved in terms of fuel efficiency more, and more rapidly, than the agencies projected, thanks to innovative technologies such as high-compression engines with cooled exhaust gas recirculation, improved start-stop systems, and dynamic cylinder deactivation. And the cost of those technologies is tending to fall below the agencies' projections.

This is a significant trend, because while naturally aspirated engines cannot fully match the efficiency gains of downsized-turbocharged engines or hybrids and electric vehicles, the recent innovations in more conventional engine designs do provide considerable efficiency benefits that were not fully factored into the 2017–2025 CAFE standards, and at much lower costs than more advanced technologies. As part of a diverse vehicle fleet, improved naturally aspirated vehicles offer manufacturers additional options for maximizing fleet average fuel economy while minimizing technology costs. This is particularly true for 4-cylinder vehicles, which made up about one-half the total U.S. light-duty fleet in 2015. There are substantial cost savings in replacing the two cylinder heads of a V-configuration engine with an inline 4-cylinder turbocharged engine, but the cost savings of engine downsizing are greatly reduced when starting with an inline engine.

Manufacturers are already using these technologies in varied combinations, with each other and with many other innovations in vehicle design. That heterogeneity in engineering and design choices makes it impossible to pin a precise number on the contribution that developments in naturally aspirated engines will make to overall gains in vehicle efficiency in the next decade. But it is certainly reasonable to expect that future naturally aspirated engines should be able to reduce passenger vehicle fuel consumption by close to 20%.

ABOUT THIS SERIES Under efficiency standards adopted in 2012, the U.S. passenger vehicle fleet must achieve an average fuel economy of 49.1 miles per gallon in 2025. or 54.5 mpg as measured in terms of carbon dioxide emissions with various credits for additional climate benefits factored in. While the fleet-average targets may change—the regulation provides for recalculating the fuel economy targets annually based on the mix of cars, pickups, and SUVs actually sold—they will still represent an average energy-efficiency improvement of 4.1% per year.

Automakers have responded by developing fuel-saving technologies even more rapidly and at lower cost than the U.S. EPA and NHTSA projected in 2011–2012, when the supporting analyses for the 2017–2025 rule were developed. In particular, innovations in conventional (as opposed to hybrid or electric) power trains and vehicle body design are significantly outpacing initial expectations. These technical briefs highlight the most important innovations and trends in those conventional automotive technologies.

For other papers in this series, as well as the more detailed technology surveys on which these briefs are based, go to www.theicct.org/series/us-passenger-vehicle-technology-trends.

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

It now seems likely that naturally aspirated engines will offer lower-cost technology alternatives for up to a quarter of the U.S. vehicle market (or roughly half of current 4-cylinder vehicles) in 2025. While different manufacturers will adopt different technology pathways to compliance, the effect will be to multiply the practical technology choices available to manufacturers for raising average fuel economy, and bring down the costs of meeting the 2025 CAFE standard.[1]

FUEL-SAVING INNOVATIONS

A number of key design innovations factor into the continued viability of naturally aspirated engines as a cost-effective technology option for fuel-efficient passenger vehicles.

HIGH-COMPRESSION ENGINES

Compression ratio—the measure of how much the fuel-air mixture in a combustion chamber is compressed before combustion—is a key determinant in fuel economy. Greater compression extracts more useable energy and reduces heat losses, permitting the engine to produce the same amount of power using less fuel.

Innovations in the design of combustion chambers and cylinders are allowing engine manufacturers to achieve very high compression ratios. For example, the Mazda SkyActiv engine achieves compression ratios of 13:1 in the U.S. (For purposes of comparison, a 1.8 liter 2015 Toyota Corolla has a compression ratio of 10:1; a Formula One race car has a compression ratio of about 17:1.) Combined with enabling technologies, such as variable valve timing for a longer intake stroke and gasoline direct injection, the SkyActiv engine improves fuel economy by 10%–15%. Even though the agencies did not anticipate development of high-compression engines for 2025, this engine is in production now, and Mazda has announced development of even higher compression ratio engines in the future.

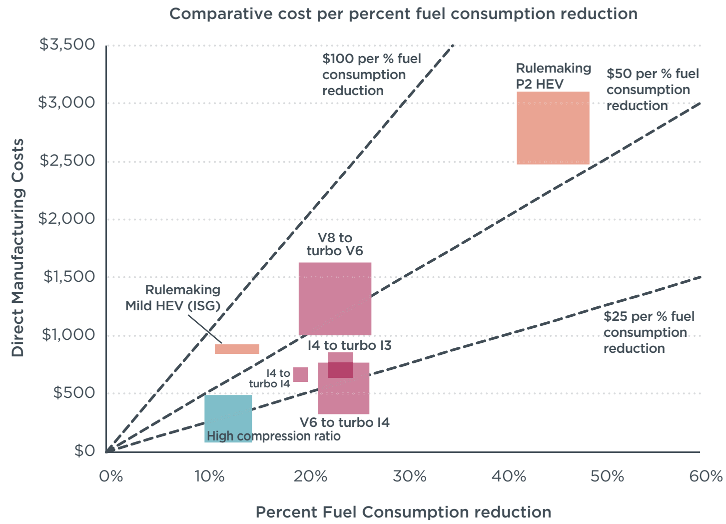

Figure 1. Cost-benefit comparison of various hybrid, downsized-turbocharged, and high-compression naturally aspirated engines. Boxes indicate the estimated range of costs.

As the chart in figure 1 shows, the fuel-efficiency gains from high-compression engines (measured in terms of percentage reduction in fuel consumption) are not as great as those possible from hybrids and downsized-turbocharged engines. But the increase in manufacturing costs for high-compression engines are significantly lower, $50 to $500 (cost estimates vary widely), so the cost-benefit ratio is quite good. And this does not include possible future improvements in efficiency from even higher compression ratios, cooled EGR, improvements in variable valve timing, and homogeneous-charge compression ignition (HCCI).

ATKINSON CYCLE

Atkinson-cycle four-stroke engines, which lengthen the intake stroke and shorten the compression stroke compared to the conventional Otto-cycle engine, have been around since the 19th century. But they have rarely been used in vehicles because, while they are inherently more fuel-efficient, they produce less power.

Some hybrid vehicles have exploited the Atkinson cycle. The electric motor on a hybrid vehicle produces maximum torque at low engine speeds. This can offset the performance tradeoff of an Atkinson-cycle internal combustion engine and obtain the fuel-efficiency benefit. Toyota and Ford have used Atkinson-cycle engines on their hybrid vehicles for over 10 years, and Hyundai recently announced its use on its Ioniq hybrid.

Recent improvements have allowed Toyota to expand the use of Atkinson-cycle engines to non-hybrid vehicles for the first time, with its ESTEC engine. Toyota uses variable

1 This technical brief is based on Aaron Isenstadt et al. “Naturally aspirated gasoline engines and cylinder deactivation,” ICCT Working Paper 2016-12, available at http://www.theicct.org/naturally-aspirated-gas-engines-201606.

valve timing and lift to design an Atkinson-cycle engine that achieves a higher compression ratio and extracts more work from the same volume of fuel while minimizing the performance penalty.

ATKINSON-CYCLE ENGINES

» 2012 EPA/NHTSA projected fuel savings: 8%–10.3%

» Supplier/OEM 2015 actual fuel savings: 3.1%–10%

» Predicted application: hybrids only

» Actual application: all passenger vehicles

Toyota's ESTEC engines, available in Lexus, Camry, and other models, use "intelligent" variable valve timing and lift to approach the combustion-cycle efficiency of the Atkinson engine.

CYLINDER DEACTIVATION

Dynamically reducing the number of cylinders firing at low engine loads, such as while cruising, significantly reduces pumping and heat losses in the engine.

The EPA and NHTSA technology analysis in 2012 did not foresee cylinder deactivation playing a significant role in the 2021 and 2025 fleets. But since 2010 the number of passenger vehicle engines using this technique has risen just under 1.5% each year, and in 2015 stood at about 13% of new vehicle sales.

The agencies also assumed that where cylinder deactivation was used it would be on larger (V6 and V8) engines, and involve a fixed group of cylinders. But electronic engine controls have since improved to such an extent that engines with as few as three cylinders, using dynamic cylinder deactivation, can deactivate individual cylinders every compression stroke to increase fuel efficiency.

Estimates for fuel savings from dynamic cylinder deactivation range from 2.0% to 10.5%, which is almost twice the potential benefit estimated by EPA/NHTSA in the rulemaking.

CYLINDER DEACTIVATION

» 2012 EPA/NHTSA projected fuel savings: 0.5%–6.5%

» Supplier/OEM actual fuel savings: 2.0%–10.5%

» Predicted vehicle application: V6 and V8 engines only

» Actual vehicle application: all passenger vehicle engines

GM's "Dynamic Skip Fire" engine uses cylinder deactivation to improve fuel economy by as much as 14%, with no reduction in power output.

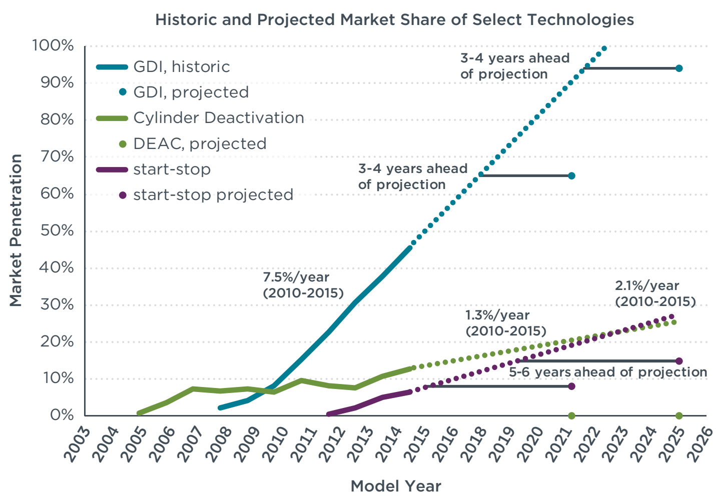

Figure 2. Market penetration of key fuel-efficiency technologies in naturally aspirated engines, actual (as reported by U.S. EPA, Fuel Economy Trends) and as projected in the 2012 EPA/NHTSA technology analysis for the 2016–2025 CAFE standard.

GASOLINE DIRECT INJECTION

Injecting fuel directly into the combustion chamber allows for more precise variation of both the amount of fuel being delivered and the point in the combustion cycle at which it is delivered. That can reduce fuel consumption during low-demand operation (e.g., cruising or decelerating), while at the same time improving engine responsiveness and therefore vehicle driveability. There is also a charge cooling effect, as evaporation of the fuel injected into the cylinder reduces combustion temperatures.

By itself, gasoline direct injection (GDI) offers modest fuel consumption gains. But it also enables high-compression engines due to the charge cooling effect and better fuel control. Manufacturers are adopting GDI systems for new engines at a pace exceeding the EPA/NHTSA 2012 projections. If present trends continue, nearly all new passenger vehicles (approximately 98%) will be equipped with GDI systems by 2022.

GASOLINE DIRECT INJECTION (GDI)

- Up to 3% fuel savings
- Supplier/OEM estimated 2025 cost: $28–$52/cylinder
- 2012 EPA/NHTSA projected 2025 costs: $37–$55/cylinder

Mazda's SkyActiv engine, a high-compression engine using gasoline direct injection, achieves up to 15% reduction in fuel consumption. All of Mazda's 2016 vehicles with SkyActiv engines are several years ahead of CAFE standards.

START-STOP

Start-stop systems automatically shut off the engine when a vehicle comes to a stop, and restart it when the driver lifts their foot off the brake or engages the clutch. The engine thus burns no fuel (and emits no CO_2) while idling. In real-world urban driving, start-stop can reduce fuel consumption in naturally aspirated engines between 3% and 7%. On the combined city and highway test cycles, fuel savings of current start-stop systems is about 2%. Start-stop systems are in development that turn the engine off while the vehicle is decelerating, not just when it stops, which could substantially increase the benefit. And the benefits of start-stop systems may be larger yet in the real world, which manufacturers can capture by applying for off-cycle credits.

Start-stop is a standard feature on all hybrid vehicles, but the rate at which conventionally-powered vehicles are being equipped with this technology exceeds the 2012 EPA and NHTSA projections. Since 2012, the share of new conventionally-powered vehicles sold with start-stop capability has grown by about 2.1% each year, and in 2016 should reach about 8%—a share of the market that EPA and NHTSA anticipated start-stop would not achieve until 2021. One likely reason is that the cost of start-stop systems is rapidly falling; auto parts suppliers project the cost per vehicle in 2025 will be about one-third what EPA and NHTSA estimated.

START-STOP

- 2012 EPA/NHTSA projection, 2025 fuel savings: 1.8%–2.4%
- Supplier/OEM 2015 improved stop/start fuel savings: 2.3%–4.3%
- 2012 EPA/NHTSA projected 2025 costs: $225–$279
- Supplier estimated 2025 cost: $76–$86

As of model year 2016, all new Chevy Malibus are equipped with start-stop, contributing to an increase in city fuel economy of up to 15%.

IMPLICATIONS FOR THE MIDTERM EVALUATION

In a diverse vehicle fleet, moderate-cost, moderate-benefit naturally aspirated engines multiply the technology avenues available for manufacturers to reach the 2017–2025 fuel economy targets. Up to a quarter of the U.S. vehicle fleet may be able to use more cost-effective naturally aspirated engines, even in 2025. As Figure 3 illustrates, the benefits of high-compression engines already exceed the estimates for Atkinson-cycle engines in the CAFE rulemaking technology analyses. Improved start-stop systems and dynamic cylinder deactivation both are almost double the rule's estimated improvements. Synergies among these technologies, and between them and other aspects of vehicle design, will depend on a wide variety of engineering and design choices. Nevertheless, it is entirely reasonable to project at this point that naturally aspirated high-compression engines combined with Atkinson cycle, improved start-stop, dynamic cylinder deactivation, and other improvements, such as cooled EGR, are likely to achieve 20% reductions in fuel consumption by 2025, and perhaps more.

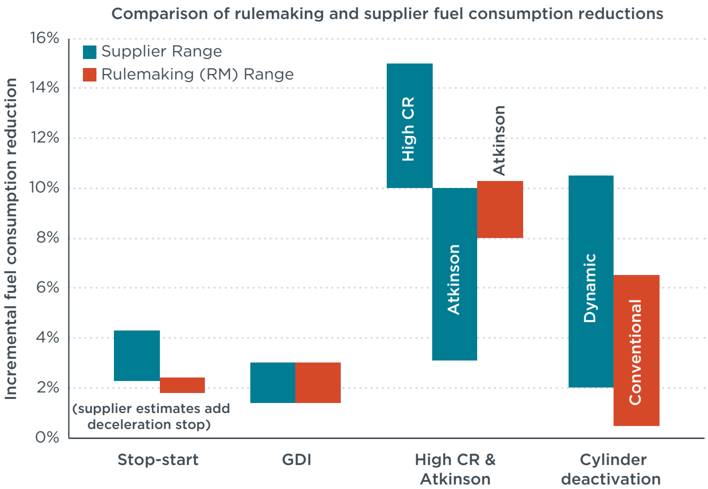

Figure 3. Comparison between rulemaking and supplier estimated incremental fuel consumption reductions.

These improvements are not coming with increased costs. As table 1 shows, the latest cost estimates are similar to or lower than those in the CAFE rule, despite the efficiency improvements. Thus, the cost-benefit of naturally aspirated engines will be substantially better than estimated in the rule. While different manufacturers will adopt different technology pathways to compliance, improved naturally aspirated engines will multiply the practical technology choices available to manufacturers for raising average fuel economy, and bring down the costs of meeting the 2025 CAFE standard.

Table 1. Comparison of naturally aspirated engine technology costs as estimated for the 2017–2025 CAFE rulemaking and by automotive suppliers in 2016.

	Supplier estimated cost in 2025	Rulemaking estimated cost in 2025
Start-Stop	$76–$86	$225–$279
Gasoline direct injection ($/cyl)	$28–$52	$37–$55
Cylinder deactivation ($/cyl)**	$35–$36	$33–$39
Cooled exhaust gas recirculation	$113–$145	$180
Atkinson cycle	—	$200–$400*
High compression ratio	—	$50–$100*

*From NAS 2015. Atkinson-cycle costs in that report include 4-2-1 scavenging exhaust manifold, GDI, and redesigned piston crowns, none of which are required for Atkinson-cycle engines.

** Conventional cylinder deactivation for rulemaking costs, dynamic cylinder deactivation for supplier costs.