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Naturally aspirated gasoline engines and cylinder deactivation

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Introduction

In 2012, the U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) finalized a joint rule establishing new greenhouse gas and fuel economy standards for vehicles.[1] The new standards apply to new passenger cars, light-duty trucks, and medium-duty passenger vehicles, covering model years 2012 through 2021, with a mid-term review in 2017.

Assuming the fleet mix remains unchanged, the standards require these vehicles to meet an estimated combined average fuel economy of 34.1 miles per gallon (mpg) in model year 2016, and 49.1 mpg in model year 2025, which equates to 54.5 mpg as measured in terms of carbon dioxide emissions with various credits for additional climate benefits factored in. The standards require an average improvement in fuel economy of about 4.1 percent per year.

The technology assessments conducted by the agencies to inform the 2017–2025 rule were conducted five years ago. The ICCT is now collaborating with automotive suppliers to publish a series of working papers evaluating technology progress and new developments in engines, transmissions, vehicle body design and lightweighting, and other measures. Each paper in the series will evaluate:

- How the current rate of progress (cost, benefits, market penetration) compares to projections in the rule
- Recent technology developments that were not considered in the rule and how they impact cost and benefits
- Customer acceptance issues, such as real-world fuel economy, performance, drivability, reliability, and safety.

This paper provides an analysis of developments and trends in naturally aspirated gasoline engine technology over approximately the past five years. A collaboration between ICCT, BorgWarner, Eaton, and the ITB Group, the paper relies on data from publicly available sources and data and information from the participating automotive suppliers.

Background

The internal combustion engine (ICE) is designed to convert chemical energy (fuel) into kinetic energy (motion of the vehicle). Direct losses in engine efficiency are due to the inherent thermal efficiency, intake and exhaust pumping losses, friction within the engine, and engine-driven accessory losses. The biggest inefficiencies arise from thermal efficiency limits and intake and exhaust pumping losses. Reducing the impact of these sources of loss is the focus of this briefing.

ICEs are heat engines. Gas heated by combustion in the cylinder is used to do work in turning a crankshaft that powers the vehicle. Heat losses are by far the largest losses in the engine, with roughly 60% of the energy from the fuel lost to heat; about half of that heat is lost to the cooling system and the other half to the exhaust. A wide variety of technologies and engine designs can increase thermal efficiencies—i.e. decrease heat loss—by modifying the gas pressure, temperature and volume. Two major examples of this are increasing compression ratio (or expansion ratio), and using alternative thermodynamic cycles (such as Atkinson).

Gasoline engines use a spark to ignite the hot, high-pressure gas for

1 US. EPA & NHTSA. *EPA/NHTSA Final Rulemaking to Establish 2017 and Later Model Years Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards.* Oct. 2012. Web. Jun. 2016. https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025

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combustion. Controlling the air and fuel flow regulates load. When the engine is not driven at its designed maximum power, it requires less air, and the engine's throttle regulates air mass flow. The throttle is almost always at least partially closed to ensure the proper amount of air is aspirated, and it takes work to force air past the partially closed throttle and into the cylinders. This work is referred to as pumping losses. There are a multitude of ways to reduce pumping losses, such as increasing exhaust gas recirculation, variable valve timing, cylinder deactivation, and downspeeding the engine.

All moving parts inside the engine exhibit friction at their interfaces, which must be overcome. The main frictional losses in the engine are due to the valvetrain, the crankshaft, and piston contact with cylinder walls. Better lubrication, surface coatings, and part redesign reduce friction. Additionally, a number of control strategies offer friction and pumping loss reductions.

Accessory losses are due to devices which are powered by the engine but do not contribute to vehicle motion, such as the air-conditioning compressor, fans, pumps, and alternator. Except for the air-conditioning compressor, which is only used during hot weather, these losses typically are relatively low compared to other losses in efficiency. There are many ways to reduce these losses; another working paper planned for this series, on thermal management, will discuss some of those methods.

An engine's valves control the flow of air, fuel, and exhaust into and out of an engine's combustion chambers. During normal operation, these valves open and close from 10 to 100 times per second. Historically, controlling such rapid valve movement required a rotating metal camshaft with fixed lobes. The camshaft timing and lift determines when and by how much the intake and exhaust valves open and close.

Variable valve timing (VVT) and variable valve lift (VVL) offer greater control over the air entering the engine. VVT allows the timing of valve opening and closing to be varied. More sophisticated systems also allow the length and/or height of the valve opening to be varied (VVL). At low engine loads they permit the throttle to open further, reducing pumping losses. At high loads they increase airflow for more power, enabling engine downsizing and/or engine downspeeding for additional efficiency improvements. VVT can also be used to control levels of residual exhaust gases, providing additional combustion improvements and pumping loss reductions.

VVL/VVT also facilitate the use of more efficient combustion cycles, such as the **Atkinson cycle**. An Atkinson-cycle engine trades off decreased power for increased efficiency. Essentially, the intake valve remains open for a longer duration on the intake stroke and closes during the normal compression stroke. This results in an effective compression ratio that is less than the expansion ratio during the power stroke, and allows the geometric compression ratio to be increased. This allows more work to be extracted per volume of fuel as compared to a typical Otto-cycle engine. However, due to a smaller trapped air mass (a consequence of air being forced out of the cylinder through the intake valve early in the compression stroke), the power density in the Atkinson cycle is lower than in the Otto cycle. Increasing the compression ratio can partially compensate for this drawback.

Cylinder deactivation allows the engine to significantly reduce pumping losses, as well as some reduction in heat transfer losses,[2] at lower engine loads by reducing the number of running active cylinders and increasing the load on these cylinders. This reduces active displacement, thus increasing manifold pressure and reducing pumping losses through a lower pressure differential across the engine. It also increases the load on the cylinder, or brake mean effective pressure (BMEP), which reduces the heat transfer to the cylinder walls and head as a percent of the fuel energy.[3]

Since these and other technologies and design changes, such as turbocharging or adding transmission gears, can all reduce pumping and friction losses, the specific engine configuration determines the effectiveness of individual technologies. For example, implementing cylinder deactivation on an engine already equipped with VVT will not necessarily achieve the same efficiency gains as implementation on an engine without VVT.

TECHNOLOGY HISTORY AND MARKET PENETRATION TRENDS

Naturally aspirated gasoline engines have been used for well over a hundred years. The traditional Otto-cycle gasoline engine gradually improved over time, but the basic design remained remarkably similar from the 1890s to the 1970s. All parts were controlled mechanically. A fixed, single camshaft drove the

2 Increased load in the cylinder, or brake mean effective pressure (BMEP), reduces the heat transfer to the cylinder walls and head as a percent of the fuel energy. See, for example, Cheng, Wai. "Engine Heat Transfer." Document posted in MIT Internal Combustion Engines online course. MIT course number 2.61. Slide 19. Spring 2008. Accessed June 2016. http://web.mit.edu/2.61/www/Lecture%20notes/Lec.%2018%20Heat%20transf.pdf

3 Wilcutts, M., Switkes, J., Shost, M. and Tripathi, A., "Design and Benefits of Dynamic Skip Fire Strategies for Cylinder Deactivated Engines," SAE Int. J. Engines 6(1):2013, doi:10.4271/2013-01-0359.

Table 1. Penetration rates of select technologies in cars and light trucks.

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
GDI	—	—	—		2.3%	4.2%	8.3%	15.4%	22.6%	30.7%	37.7%	45.6%
VVT	38.5%	45.8%	55.4%	57.3%	58.2%	71.5%	83.8%	93.1%	96.7%	97.7%	97.9%	98.2%
DEAC	—	0.8%	3.6%	7.3%	6.7%	7.3%	6.4%	9.5%	8.1%	7.7%	10.7%	12.8%
Multi-valve	62.3%	65.6%	71.7%	71.7%	76.4%	83.8%	85.5%	86.4%	91.9%	93.1%	89.4%	89.4%
Stop-start	—	—	—	—	—	—	—	—	0.6%	2.3%	5.1%	6.6%

Notes—GDI = gasoline direct injection. VVT = variable valve timing. DEAC = cylinder deactivation. Multi-valve = 3 or more valves per cylinder. 2015 values are estimates. Source: U.S. EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 - 2015," www3.epa.gov/otaq/fetrends-complete.htm.

valves, a carburetor mixed fuel with air before the intake manifold, and a coil delivered electricity to the spark plugs, with spark timing controlled by a distributor. Most engines were four-stroke engines, with separate intake, compression, expansion, and exhaust phases over two revolutions of the engine.

The first major changes were driven to a large extent by emission standards in the 1960s and 1970s. Initially, exhaust gas recirculation (EGR) was introduced to reduce engine-out NO_x emissions (i.e., emissions at the exhaust manifold, as opposed to at the tailpipe or anyplace else downstream from the manifold). With the invention and subsequent availability of microprocessors, rudimentary computers were introduced to improve control of fuel delivered to the carburetor and reduce hydrocarbon (HC) and carbon monoxide (CO) emissions. The next step was development of the oxygen sensor, which was needed to improve air/fuel control and optimize three-way catalyst efficiency. This was followed by development of fuel injection to replace the carburetor. Fuel injection allowed much more precise control of the fuel delivered to the engine and balancing of cylinder-cylinder fueling. Not only did it decrease emissions and improve catalyst efficiency, it offered opportunities to optimize combustion chamber design and increase compression ratio. Computer controls also enabled the rapid penetration of fuel injection, from only 6% of vehicles in 1980 to virtually all vehicles by 1990.[4]

Technology improvements have been coming at an ever-increasing rate, enabled by the development of computer-aided design and electronic controls. In the last thirty years, four-valve engines, turbocharging, hybrids, cylinder deactivation, variable valve timing and lift, gasoline direct injection and stop-start systems have all seen introduction and growth in the mass market. Several of these improvements are summarized in Table 1.

According to the 2015 EPA fuel economy trends report,[5] gasoline direct injection exhibited a rapid increase in market penetration, from virtually zero vehicles to 45.6% of the market in just 7 years, replacing port fuel injection. Growth is expected to continue, since GDI offers several benefits over port injection (most notably cylinder cooling through fuel vaporization inside the cylinder, which enables higher compression ratios with reduced risk of knocking). Indeed, GM and Ford each have GDI in well over 50% of their respective production (see fig. 4.1 of the EPA FE Trends report), and Toyota and FCA are increasing their shares.[6]

The decrease in market share of multivalve cylinders since 2013 is largely due to the increase in truck sales using two-valve GDI engines with VVT (see Fig. 5.1 of the EPA FE Trends report).

By 2012, virtually all passenger vehicles used variable valve timing. And the vast majority of VVT was on multivalve cylinders.

Cylinder deactivation (DEAC) also grew in market share. GM and Honda both project DEAC in over 25% of their respective production. Fleetwide, approximately 27.4% of light trucks are estimated to use DEAC in 2015, although only 2.7% of cars used the technology. This is likely because conventional cylinder deactivation is easier to implement on cam-in-block V6 and V8 engines, widely used on light trucks, than on the four-cylinder engines that dominate car sales. Conventional cylinder deactivation involves shutting off half, or an even number of, an engine's cylinders. As described below, advances in cylinder deactivation strategies that are in development will permit a much wider range of engines to reap its fuel economy benefits and will also increase those benefits.

4 U.S. Environmental Protection Agency. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015.* Dec 2015. Accessed June 2016. https://www3.epa.gov/fueleconomy/fetrends/1975-2015/420r15016.pdf

5 US. EPA. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015.* Dec 2015.

6 Greimel, Hans. "14 new Toyota engines seek 10% gain in mpg." *Auto News* April 14, 2014. Web. Accessed June 2016. Greimel, Hans. "Toyota's massive engine overhaul." *Auto News* July 14, 2014. Web. Accessed June 2016.

Historical estimates of technology costs and benefits

A National Academy of Sciences (NAS) Committee issued an excellent report on fuel economy in 2002, including projected technology benefits and cost.[7] The report was widely used for many years, and served as the starting point for NHTSA's light truck CAFE standards for 2005–2011.[8] We utilize it here because it captured the status of technology development in 2002 and, thus, serves as background for the technology innovations that have occurred since then.

According to the NAS 2002 report, cylinder deactivation (DEAC) would realize a 3%–6% decrease in fuel consumption at a cost of $112–$252. The NHTSA 2008–2011 RIA used this estimate virtually unchanged. Note that the 2025 rulemaking estimated cost for DEAC is within the range predicted in the NAS 2002 report, but near its lower bound. In that report, the predictions were made out to 2015. In the EPA/NHTSA joint TSD[9], the cost for DEAC in 2015 was $146–$165, squarely within the range estimated in NAS 2002.

Gasoline direct injection requires new injector designs, high pressure fuel pump and rails, new piston crown/cylinder head design, and other changes to improve mixing (or stratification). GDI can improve knock resistance, allowing higher compression ratios.

Table 2. Historical estimates of selected technology fuel consumption reduction benefits and direct manufacturing costs (DMC)

	NAS 2002		NHTSA 2008-2011		EPA/NHTSA 2017-2025	
GDI	4%-6%	—	1%-3%	$200-$250	1%-3%	$164-$296
DEAC	3-6%	$112-$252	3%-6%	$116-$262	0.5%-6.5%	$118-$133
VVT	2%-3%	$35-$140	2%-3%	$36-$146	1%-5.5%	$31-$124
VVL	1%-2%	$70-$210	1%-2%	$73-$218	2.8%-4.9%	$99-$296
IVT	3%-6%	$210-$420	3%-6%	$218-$437	—	—
CVA	5%-10%	$28-$560	5%-10%	$291-$582	—	—

Notes—GDI = gasoline direct injection. DEAC = cylinder deactivation. VVT = variable valve timing. VVL = variable valve lift. IVT = electromechanical intake valve throttling. CVA = camless valve actuation

NAS 2002 did not estimate costs for GDI, but did estimate that it would have a 4%–6% decrease in fuel consumption. The 2008–2011 RIA cut the fuel consumption reduction to 1%–3% and estimated a cost of $200–$250. This reduced benefit of GDI may be due to the increased part-load intake pumping losses incurred with direct injection. GDI requires more energy to pump the fuel to higher pressure for in-cylinder injection. Also, combustion efficiency can decrease compared to port fuel injection (PFI). Consequently, the main benefit of GDI by itself over PFI on naturally aspirated engines is control over injection timing, which provides cooling of the air/fuel mixture in the cylinder and enables faster catalyst light-off. There are additional benefits when GDI is combined with VVT/VVL and, especially, turbocharging.

VVT and VVL encompass a number of different methods to vary valve duration, occurrence and lift. For example, cam phasing, the simplest form of VVT, changes the relationship of the rotation (angle) of the camshaft with respect to the rotation of the crankshaft. But even here there are various versions with different benefits and costs, from a simple change of all timing for an engine with a single camshaft (coupled cam phasing, CCP), to varying just the intake phasing for an engine with dual camshafts (intake cam phasing, ICP), to varying both the intake and exhaust phasing for an engine with dual camshafts (dual cam phasing, DCP). For VVL, one option is to use multiple lobes/cam profiles fixed to the camshaft with multiple finger followers that lock together or work separately based on the engine's load. Alternatively, a single follower may be used with a multi-lobe cam that axially slides on the camshaft to select the appropriate lobe/profile (cam profile switching, CPS). According to NAS 2002, VVT would result in a fuel consumption reduction of 2%–3% at a cost of $35–$140. Both the 2008–11 and 2017–25 rulemaking estimates were similar. NAS 2002 also estimates that VVL would result in 1%–2% fuel consumption reduction over cam phasing (VVT) on four-valve engines (5%–10% on two-valve engines) at a cost of $70–$210. While the 2008–11 RIA appears to have used the NAS estimates, the estimated benefits for the 2017–25 rule were over twice as high, although at a somewhat higher cost.

Intake valve throttling (IVT), a more advanced form of VVL, could remove the need for the throttle plate entirely. IVT essentially uses the intake valves themselves to throttle intake air. The 2002 NAS report and the 2008–11 RIA estimated this would result in 3%–6% fuel consumption reduction over VVL, costing $210–$437. It is worth noting that, to date, no IVT or VVL strategy, even BMW's Valvetronic or Fiat's

7 Transportation Research Board and National Research Council. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards.* Washington, DC: The National Academies Press, 2002. doi:10.17226/10172.

8 U.S. NHTSA. *Light Truck Fuel Economy Standard Rulemaking, MY 2008–2011.* March 2006. Web. June 2016. http://www.nhtsa.gov/fuel-economy

9 U.S. EPA & NHTSA. *Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards.* Aug. 2012. Web. June 2016. https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025

MultiAir, has completely eliminated the throttle. This is due to the need for a torque reserve: additional torque must be available to the driver in case it is needed. The throttle builds up pressure for this torque reserve and improves air distribution to the cylinders.

NAS 2002 also predicted that camless valve actuation (CVA), would result in an additional 5%–10% fuel consumption reduction beyond VVT/VVL at a cost of $280–$560. The 2017–2025 rulemaking did not explicitly consider either IVT or CVA, although it did consider more advanced forms of VVL, as discussed in the next section.

EPA/NHTSA 2017–2025 projections: Market penetration, costs, and benefits

Table 3 summarizes the technology assessments in the 2017–2025 rulemaking relevant to naturally aspirated engines. These estimates are the baseline used for the technology assessments in this paper. Note that all of the agencies' cost estimates are direct manufacturing costs (DMC). The first column, labeled "2015 penetration" lists the estimated market penetration of select technologies from EPA's fuel economy trends report. Subsequent columns are projections from the rulemaking. The 2015 Atkinson penetration estimate was obtained using Ford's and Toyota's market share of hybrids, as these were the only vehicles in 2015 to use Atkinson cycle.

Stop-start reduces fuel consumption in urban driving by shutting the engine off when the vehicle comes to a stop (in traffic), and restarting when acceleration is required, effectively slashing engine idling time. In the rulemaking, the technology that actually shuts off the engine and restarts it includes an improved 12V starter (higher power and longer cycling life) and a larger and more capable battery. The resulting benefits of this improved starter are 1.8%–2.4% fuel consumption reduction, at a cost of $225–$279.

However, the agencies also considered adding two levels of accessory improvement to the 12V stop-start system ("IACC1" and "IACC2"). IACC1 replaces the vehicle's alternator with higher-efficiency (70% efficiency) alternator. IACC2 adds "mild regenerative alternator strategy" to the high-efficiency alternator and "intelligent cooling." The combination of the two was estimated to cost $97 in 2025 and have an effectiveness of 3.1%–3.9% relative to no accessory improvements. The combination of stop-start and IACC1 and IACC2 achieves 4.8%–5.9% fuel consumption reduction.

One striking aspect of the 2017–2025 rule analyses is that the agencies projected that naturally aspirated engines would be gradually displaced by "boosted" gasoline engines over model years 2017–2025. The agencies, projections followed a simple logic: In 2012, trends in technologies that improved fuel economy suggested that downsized, turbocharged engines would be the most cost-effective solution. Thus, the agencies projected that boosted gasoline engines would capture 64% of the market in 2021 and 93% in 2025. Only 5% of 2025 vehicles would have naturally aspirated engines, and these would all be Atkinson-cycle engines used in full-hybrid vehicles.

As shown in Table 3, above, GDI already occupies a large market share and the 2017–2025 rulemaking projected the share would continue to grow through 2025 to 94%. This is consistent with the projected increase in boosted engines, as all boosted engines are expected to use GDI.

Depending on the valvetrain configuration already present in a vehicle, the agencies determined that cylinder deactivation could

Table 3. EPA/NHTSA market projections and direct manufacturing costs

	2015 penetration	2021 penetration	2025 penetration	Direct Manufacturing Cost (2025)	Fuel consumption reduction
GDI	46%	65%	94%	$164 (I3/4), $246 (V6), $296 (V8)	1%–3%
DEAC	13%	1%–9%	1%–5%	$118 (V6), $133 (V8)	0.5%–6.5%
VVT - ICP	98%	2%	2%	$31(OHC-I4), $63(OHC-V6/8)	2.1%–2.7%
VVT - CCP		11%	11%	Same as above	1%–3%
VVT - DCP		70%	70%	$58(OHC-I4), $124(OHC-V6/8)	4.1%–5.5%
DVVL	n/a	12%–52%	11%–52%	$99(OHC-I4), $143(V6), $204(V8)	2.8%–3.9% (VVT)
CVVL		16%	16%	$148 (I4), $271 (V6), $296 (V8)	3.6%–4.9% (VVT)
Stop-start	7%	8%	15%	$225-279	1.8%–2.4%
IACC	n/a	68%	67%	$97	3.1%–3.9%
Atkinson cycle	2.5%	4%	5%	n/a	8.0%–10.3%

Notes—GDI = gasoline direct injection. DEAC = cylinder deactivation. VVT = variable valve timing. ICP = intake cam phasing. CCP = coupled cam phasing. DCP = dual cam phasing. DVVL = discrete VVL. CVVL = continuous VVL. IACC = electric accessory improvement.

deliver between 0.5% and 6.5% reduction in fuel consumption. The low end of the range is mainly due to the overlap in the reduction of pumping losses inherently present in advanced valvetrains, such as dual-overhead cam (DOHC) engines with dual cam phasing (DCP), DVVL and EGR. However, according to the rulemaking, the cost of adding cylinder deactivation to these advanced valvetrains is also very low: as low as $32 when added to an engine with VVL, which accounts for active engine mounts to improve noise, vibration, and harshness (NVH). For engines with no application of VVT or VVL, DEAC benefits increase to 4.7%–6.5% at a cost of $118–$131. These estimates are all for conventional cylinder deactivation that shuts off half, or an even number of, an engine's cylinders. More advanced systems were not considered.

The rulemaking considered two main methods of cylinder deactivation. For overhead-cam engines, the rocker arm (finger-follower) has one part that follows a cam lobe/profile, and another that opens its respective valve (termed "DEACS" for single overhead cams in the rulemaking, "DEACD" for dual overhead cams). A lashing or latching mechanism either connects or disconnects these two parts, thereby activating or deactivating the valve and its cylinder.[10,] For overhead valve engines (pushrod), solenoids release hydraulic oil pressure in the tappet, collapsing the lifters and deactivating the respective pushrods and valves (termed "DEACO" in the rulemaking). The rulemaking cost estimation given in Table 3 for DEAC assumes these two technology options. The agencies also mention, but do not consider, a third method, which is to use a zero-lift cam lobe and switch to this lobe to deactivate the valves.

The agencies considered three types of VVT: intake cam phasing (ICP), coupled cam phasing (CCP), and dual cam phasing (DCP). All three use a cam phaser to adjust the phase (angular position) of the camshaft(s) relative to the crankshaft. Most cam phasers in production are hydraulically-actuated: a solenoid controls engine oil pressure applied to the cam phaser.

- ICP is generally applicable only to DOHC engines and controls only the intake valve timing, while exhaust valve timing is fixed.
- CCP controls intake and exhaust valve timing in equal amounts. The agencies assumed that overhead valve (OHV) engines cannot use any other cam phasing strategy, but this is not strictly true; OHV engines can use a special cam and phaser, as evidenced by the Dodge Viper (albeit at a much higher cost.)
- DCP is generally applicable only to DOHC engines, but allows for greater flexibility in valve timing control.

The rulemaking also considers two types of variable valve lift: discrete VVL (aka cam profile switching [CPS]), and continuous VVL.

- DVVL switches between two, or possibly three, discrete camshaft profiles. It is considered a mature technology with low risk, and is applied only on overhead cam (OHC) vehicles.
- CVVL offers greater effectiveness than DVVL since it can be optimized for any load. BMW Valvetronic and Fiat MultiAir are two systems currently in production that offer CVVL.

Atkinson cycle efficiency was modeled by Ricardo for EPA. EPA post-analyzed Ricardo's simulation runs and apportioned the losses and efficiencies to six categories: engine thermal efficiency, friction, pumping losses, transmission efficiency, torque converter losses, and accessory losses. These losses and efficiencies were incorporated into EPA's Lumped Parameter Model (LPM).[11] Ricardo did not model a baseline Atkinson-cycle engine, so the only estimates in the LPM are for a 2025 Atkinson-cycle engine. Selecting Atkinson cycle in the LPM results in a reduction in fuel consumption of 8.0%–10.3% for the 2025 Atkinson cycle compared with a baseline conventional engine, depending on the vehicle class. Unfortunately, the agencies did not break out the cost of the Atkinson-cycle engine, but there is no technical reason why the cost should be significantly different from an engine with VVT and VVL.

Status of current production versus Agency projections

HIGH COMPRESSION RATIO ENGINES

Increasing compression ratio improves thermal efficiency. High compression ratios are necessary on naturally aspirated engines to reduce fuel consumption without the additional costs of turbocharging and supercharging. However, increasing compression ratio also increases the risk of knocking, where unburned fuel mixture ahead of the flame front ignites before the propagating flame engulfs it.

Mazda SkyActiv-G (gasoline) engines resolve the knocking problems and achieve one of the highest advertised compression ratios of any

10 "Cylinder Deactivation." *Eaton Products & Services: Vehicle Engine Valves, Lifters & Valve Actuation.* 2016. Accessed June 2016.

11 "Lumped Parameter Model (LPM) for Light-Duty Vehicles." *EPA OTAQ: Transportation and Climate.* Feb 23, 2016. Accessed June 2016. https://www3.epa.gov/otaq/climate/lpm.htm

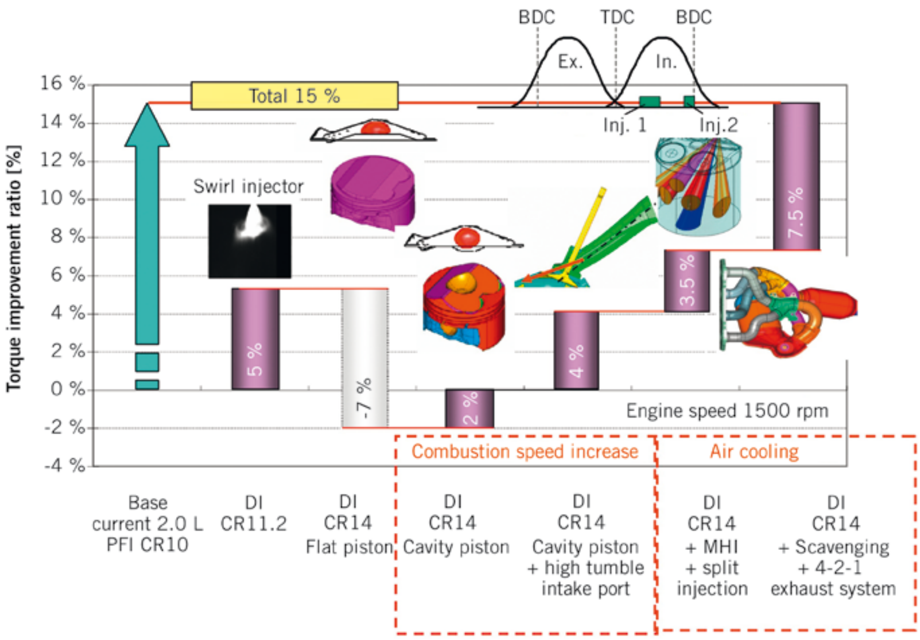

Figure 1. Several engine improvements in the Mazda SkyActiv-G lead to a net 15% increase in torque with lower fuel consumption. (Source: Goto et al. "The New Mazda Gasoline Engine Skyactiv-G." MTZ worldwide Issue no.: 2011-06: 40-46.)

production gasoline engine.[12] In the United States, the advertised compression ratio (CR) is limited to 13.0:1 due to lower octane fuel, but in the European Union the engine achieves an advertised 14.0:1 CR.

This remarkably high compression ratio and fuel-efficient[13] 2.0L four-cylinder engine was achieved by combining a series of incremental design improvements into the engine. These improvements allowed Mazda's SkyActiv-G engine to achieve a 15% reduction in fuel consumption on the NEDC (New European Driving Cycle) at a relatively low cost. The U.S. Federal Test Procedure (FTP) city cycle is considerably more stringent than the NEDC and the U.S. highway cycle is quite different, so the fuel consumption reduction on the U.S. cycles may differ substantially. In the United States, the MY2014 Mazda6 achieved about 25% reduction in fuel consumption compared to the MY2013 Mazda6 (and the MY2016 Mazda6 already meets MY2021 fuel economy standards[14]), although this dramatic reduction includes other, non-engine, technologies implemented by Mazda in their full redesign. For example, the road load horsepower at 50mph dropped by 23%–32% from 2013 to 2014, depending on which coefficients from the EPA data you use. The test weight also dropped from 3625 to 3500lbs. These load reductions likely account for about half of the fuel economy improvements, leaving 10%–15% for the engine improvements.

The Mazda SkyActiv engine utilizes the Atkinson cycle concept with direct injection and a combustion chamber optimized with high-tumble flow and a small bore. A fabricated 4-2-1 exhaust manifold is used to minimize residual fraction and ensure a cool in-cylinder charge. Combined with other engine improvements, torque was increased by 15% (figure 1). Delayed intake valve closing and dual VVT reduce pumping losses 20%.

Mazda's new engines are designed around the specific combustion chamber of each engine, to ensure the most efficient combustion process. This maximizes efficiency and reduces the time it takes to calibrate each engine, but it eliminates interchangeable parts among different sized engines (a common industry practice). To rebalance this tradeoff, Mazda uses advanced robots to create their new engines. These highly capable machines, which other manufacturers are also starting to use, cut engine production time by 4.7 hours compared with fixed assembly lines (from 6.0 to 1.3 hours) and decrease initial investment by 70%.[15]

While the agencies considered Atkinson cycle engines in the rulemaking, the Mazda SkyActiv engine meets, if not exceeds, the agencies' efficiency targets for Atkinson cycle engines a full decade early.

ATKINSON-CYCLE ENGINES

As described above, the Atkinson cycle is a simple way in which to improve fuel economy of a conventional engine at relatively little cost, using clever valve timing. By delaying intake valve closing, compression of the fuel-air mixture begins late. This method effectively separates compression ratio from the expansion ratio and allows the combustion gases to expand beyond the point at which compression began, extracting more work from the gases. Although the higher expansion ratio improves

12 Goto et al. "The New Mazda Gasoline Engine Skyactiv-G." MTZ worldwide Issue no.: 2011-06: 40-46. Accessed June 2016. http://www.atzonline.com/Artikel/3/13208/The-New-Mazda-Gasoline-Engine-Skyactiv-G.html.

13 Ellies, B., Schenk, C., and Dekraker, P., "Benchmarking and Hardware-in-the-Loop Operation of a 2014 MAZDA SkyActiv 2.0L 13:1 Compression Ratio Engine," SAE Technical Paper 2016-01-1007, 2016, doi:10.4271/2016-01-1007.

14 US. EPA Fuel Economy Guide 2014 Datafile. Updated June 3 2016. Accessed June 2016. https://www.fueleconomy.gov/feg/download.shtml

15 Weissier, Paul. "Mazda's new system machines blocks with different bore centers." *Automotive Engineering* Feb 4, 2013. Accessed June 2016. http://articles.sae.org/11783/

efficiency, the late intake closing allows an increase in the geometric compression ratio because it reduces the trapped mass of charge, which also lowers the maximum torque and power of the engine. Thus, to retain vehicle performance, Atkinson-cycle engines are generally increased displacement or are paired with full-hybrid systems, where the electric propulsion motor adds significant torque and returns the system to an equivalent level of performance. All Ford and Toyota hybrid systems use Atkinson-cycle engines, with a 2015 market penetration of 2.5% (table 3).

The agencies did not explicitly estimate the cost of Atkinson-cycle engines. The National Academy of Sciences published a recent report analyzing the costs and benefits of technologies available to manufacturers to meet 2017–2025 regulations.[16] Although many of the estimates in this report mirror the agencies', additional estimates were made for high compression ratio and Atkinson-cycle engines. These are incorporated here as a reference for estimated costs in these two types of improved engines.

NAS 2015 estimated that increasing the compression ratio, while maintaining the same regular octane fuel, would cost between $50 and $100. For high compression ratio engines that also use the Atkinson cycle (such as Mazda's SkyActiv and Toyota's ESTEC engines, see below), the NAS 2015 cost estimate is $250–$500. This cost increase includes enabling technologies that are also found on non-Atkinson cycle engines, specifically increased compression ratio, a 4-2-1 scavenging exhaust manifold, direct injection, and redesigned piston crowns (VVT is also necessary, but is already present in the baseline engine used by NAS). These technologies are found on Mazda's SkyActiv engine and Toyota's ESTEC engines (although the ESTEC engine does not have direct injection), discussed below.

At a minimum, Atkinson requires VVT, at least intake cam phasing (where the intake valve timing alone can be adjusted), whose costs the agencies estimated at $31–$63 in 2025. VVT is already quite cost effective, as evidenced by its near 100% market penetration. Atkinson cycle engines also have higher compression ratio, the cost of which was estimated by NAS 2015 to be $50–$100 (for just the increased CR). Finally, the NAS estimate included the cost of direct injection, estimated by the agencies at $164–$294. Thus, the cost of Atkinson cycling itself is likely to be low.

To improve power and performance while achieving high fuel efficiency, Toyota plans to improve its Atkinson-cycle engines by increasing compression ratio (in much the same way Mazda utilizes valve control and high CR to reduce fuel consumption), coupled with in-cylinder modifications and enhanced valve and temperature control strategies. For the 2016 Prius, Toyota has increased peak thermal efficiency of the Atkinson-cycle engine to over 40%, a significant improvement over the 38.5% peak thermal efficiency of its predecessor.[17]

The improved engine also reduces the performance loss, enabling Toyota to expand use of the Atkinson-cycle engine to non-hybrid vehicles for the first time. Toyota will implement these improvements on 14 new engines starting in 2015, affecting 30% of Toyota's lineup, and boosting fuel efficiency by 10%.[18]

To achieve the Atkinson cycle on conventional gasoline engines, Toyota expanded the range of their hydraulic VVT (VVT-iW, "intelligent-Wide range" variable valve timing). Conventional valve timing was used for performance and extreme valve timing was used for the Atkinson-cycle for efficiency. Other technologies added to improve efficiency were cooled EGR, variable fuel injection pressure, and upper and lower water jackets for faster engine and catalyst warmup. Thermal efficiency was improved by increasing the compression ratio to 13:1 and the low-load, high-efficiency region was expanded through use of the Atkinson cycle.[19]

Hyundai has also introduced a highly thermally efficient production engine for its Ioniq hybrid. The powertrain system includes a 1.6-liter Atkinson cycle engine with a peak thermal efficiency of 40%—essentially matching the improved 2016 Prius hybrid engine efficiency.[20,]

In its 2016 draft report[21], FEV found that implementing the Atkinson cycle would cost nothing on top of the cost of a VVT/VVL system (in that report, "Miller cycle" is used to refer to both Atkinson cycle on a naturally aspirated engine and Miller cycle on turbocharged engines). The costs of a VVL system, in the FEV report, were between $92 and $120 when installed on engines already equipped with VVT. The particular VVL system

16 National Research Council. *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles.* Washington, DC: The National Academies Press, 2015. doi:10.17226/21744.

17 Greimel, Hans. "Prius greener, but will it be meaner?" Auto News October 19, 2015. Web accessed June 2016. http://www.autonews.com/article/20151019/OEM03/310199973/prius-greener-but-will-it-be-meaner

18 "Toyota claims record gasoline efficiency." *Ricardo Quartlery Review* Q2 2014, p. 4. Accessed June 2016 http://www.ricardo.com/Documents/RQ%20pdf/RQ%202014/RQ%20Q2%202014/RQ_Q2_2014_English.pdf.

19 Yamada, T., Adachi, S., Nakata, K., Kurauchi, T. et al., "Economy with Superior Thermal Efficient Combustion (ESTEC)," SAE Technical Paper 2014-01-1192, 2014, doi:10.4271/2014-01-1192. Matsui, J., Koyama, H., Goto, Y., and Kawai, H., "Development of 3.5L V6 Gasoline Direct Injection Engine - ESTEC 2GR-FKS/FXS -," SAE Technical Paper 2015-01-1972, 2015, doi:10.4271/2015-01-1972.

20 Greimel, Hans. "Hyundai: Ioniq highway mpg to top Prius." *Auto News.* Jan 10, 2016. Accessed June 2016. http://www.autonews.com/article/20160104/OEM05/301049996/hyundai:-ioniq-highway-mpg-to-top-prius.

21 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis.* Draft: Sept. 2015. Forthcoming report for ICCT.

assessed by FEV was one very similar to VW's Active Cylinder Management Technology (ACT) system (see below) in structure and operation.

In general, fuel consumption of Atkinson-cycle engines is lower than that of Otto-cycle engines. On BSFC engine maps, Atkinson-cycle engines exhibit a wider area of low fuel consumption, with VVT, primarily, enabling the late intake valve closing characteristic of the Atkinson cycle. High geometric compression ratio offsets the otherwise lower effective CR of Atkinson.[22]

Estimates for the benefits of Atkinson cycle were determined, from suppliers, using information disclosed by Toyota[23] as well as information gathered from simulations for the Miller cycle conducted by FEV in their analysis[24] (albeit on a downsized turbocharged engine), and from NAS 2015 (which drew from Mazda and Toyota sources). Toyota's non-hybrid Atkinsons are not simple substitutions of Atkinson cycle for Otto cycle, but include a more complete technology package. Nevertheless, the greatly reduced fuel consumption under a wider range of engine loads is possible with Atkinson cycling. Overall fuel consumption reductions ranged from 3.1%–10%.[25]

COOLED EGR

Cooling the recirculated exhaust gas reduces combustion temperature, which reduces heat losses and also enables higher compression ratio and other combustion improvements. This is a key enabler for continued increases in naturally aspirated engine efficiency. Modeling of cooled EGR on turbocharged engines in FEV's draft report[26] yielded 2.5% efficiency improvements. This is lower than the agencies' estimate of 5% improvement. The benefits of cooled EGR on naturally aspirated engines may be somewhat different.

FEV also conducted updated cost estimates for a cooled EGR system, to $113–$143 (compared to no EGR system). These are lower than the estimate in the 2017–2025 rule of $180.

STOP-START, GDI, AND CYLINDER DEACTIVATION COST ESTIMATES

Supplier cost estimates can be difficult to come by, as suppliers are reticent about revealing costs. Thus, FEV's forthcoming report was used to estimate costs for stop-start, GDI, and cylinder deactivation technologies.

Stop-start costs were estimated by FEV to be $76–$86. This includes the costs of more robust starter and alternator, as well as more capable battery and various additional sensors. This is only about a third of the cost estimate for stop-start in the rulemaking: $225-$279.

FEV also analyzed the cost of replacing a PFI system with GDI. The hardware for such a system requires a high-pressure pump (which is driven by the engine) and high-pressure rail, as well as new injectors. The higher the pressure of the DI system, the higher the costs. FEV found that such a system would cost $28 to $52 per cylinder. This is very close to the cost estimate for GDI provided in the rulemaking: $37–$55 per cylinder.

As described above, FEV estimated the increased cost of VVL ranges from $95 to $123 (85€–110€) depending on engine size and number of cylinders. This was based on VW's ACT system (two-stage cam profile switching), which uses two lobes—high and low—and an actuator to axially slide the cam along the camshaft.[27] VVL costs are compared to a baseline engine with discrete VVT already installed. Using one cam profile with zero lift (i.e., deactivated valve) and one with normal lift means the cost of cylinder deactivation using VW's system is the same as a more general VVL system. With the structure of ACT, implementing a Miller or Atkinson cycle with DVVT and VVL is possible at no additional cost (VVT and VVL are both present). Costs would likely be minimally higher for valve lifts that go from high, to low, to zero lift (i.e., three cam profiles).

Thus, FEV's cost for cylinder deactivation is actually an estimate of the cost of two-stage DVVL, which uses cam profile switching to switch between high- and low-profile cam lobes. Replacing the low-lift profile with a zero-lift profile permits DEAC instead of DVVL. Alternatively, simply adding a third, zero-lift cam profile maintains the VVL capabilities of the engine, but adds cylinder deactivation, at slightly increased costs. Note that the rulemaking estimated the 2025 cost of discrete VVL ("DVVL") at $24–$26

22 Feng, R., Li, Y., Yang, J., FU, J. et al., "Investigations of Atkinson Cycle Converted from Conventional Otto Cycle Gasoline Engine," SAE Technical Paper 2016-01-0680, 2016, doi:10.4271/2016-01-0680.

23 Yamada, T., Adachi, S., Nakata, K., Kurauchi, T. et al., "Economy with Superior Thermal Efficient Combustion (ESTEC)," SAE Technical Paper 2014-01-1192, 2014, doi:10.4271/2014-01-1192. Takahashi, D., Nakata, K., Yoshihara, Y., and Omura, T., "Combustion Development to Realize High Thermal Efficiency Engines," SAE Int. J. Engines 9(3):2016, doi:10.4271/2016-01-0693. Matsui, J., Koyama, H., Goto, Y., and Kawai, H., "Development of 3.5L V6 Gasoline Direct Injection Engine - ESTEC 2GR-FKS/FXS -," SAE Technical Paper 2015-01-1972, 2015, doi:10.4271/2015-01-1972.

24 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis.* Draft: Sept. 2015. Forthcoming report for ICCT.

25 Matsui et al., "Development of 3.5L V6 Gasoline Direct Injection Engine - ESTEC 2GR-FKS/FXS -." Yamada et al., "Economy with Superior Thermal Efficient Combustion (ESTEC)." Takahashi et al., "Combustion Development to Realize High Thermal Efficiency Engines."

26 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis.* Draft: Sept. 2015. Forthcoming report for ICCT.

27 "VW ACT Active Cylinder Management." *Automotive Expo.* YouTube, April 2014. Accessed June 2016. https://www.youtube.com/watch?v=_4AZbbBjqhM

per cylinder, which is between $5 and $10 less than the DVVL cost estimated by FEV. The agencies estimated DEAC costs to be $33–$39 per cylinder, but this only accounts for finger-follower de-lashing on a fixed block of cylinders (half the cylinders of a V6 or V8).

Both the rulemaking and FEV cost estimates for cylinder deactivation apply to conventional DEAC only a fixed group of cylinders can deactivate. As described below, newer, more advanced strategies permit variable numbers of cylinders to deactivate. This requires equipping all participating cylinders with the necessary hardware for deactivation (e.g., additional actuators). As such, costs per cylinder will be higher.

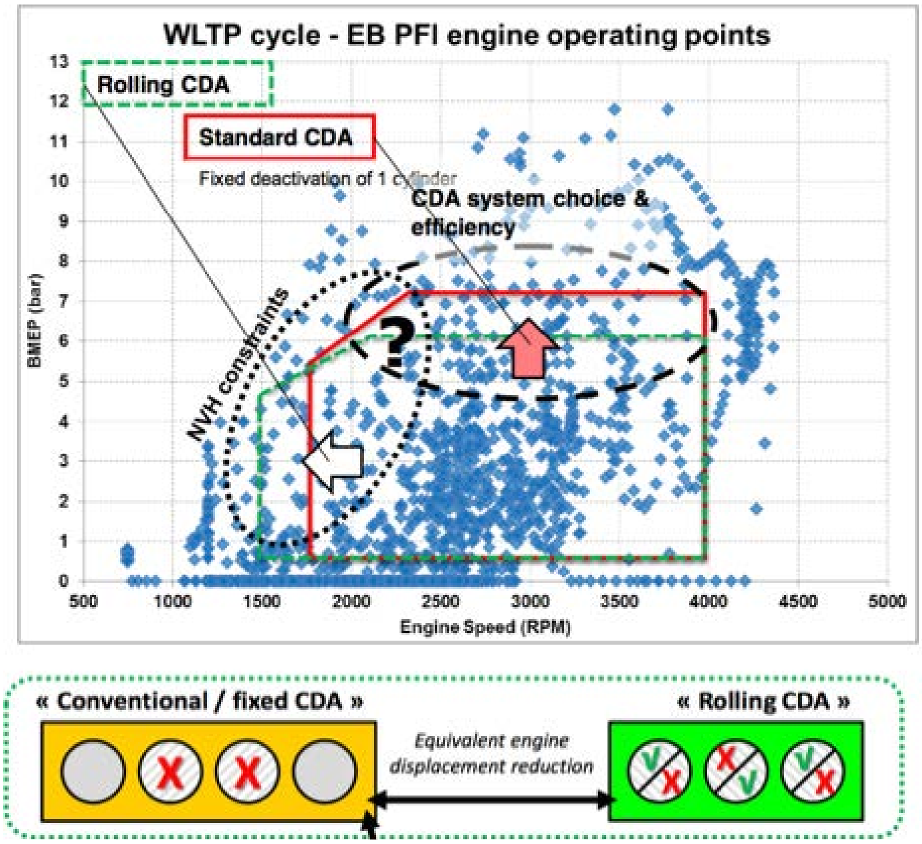

Figure 2. Eaton and PSA, Dynamic Cylinder De-Activation: System approach and performance potential. (Source: Cecur, Majo, Veiga-Pagliari, D.R. “Dynamic Cylinder De-Activation (D-CDA).” PSA & Eaton. Presented at 24th Aachen Colloquim Automobile and Engine Technology. October 7, 2015. Slides 4-5.)

Improvements in Development

CYLINDER DEACTIVATION

Conventional cylinder deactivation normally applies only to larger engines with an even number of cylinders. This allows cylinders to deactivate symmetrically in order to avoid intense torque fluctuations and vibration. The analyses in the 2017–2025 rule were limited to this type of cylinder deactivation.

There is a major area of improvement in cylinder deactivation: dynamic deactivation of individual cylinders. There are many systems currently in development. These systems continually change the active cylinders and have many potential advantages over conventional cylinder deactivation:

- Maintain uniform engine operation temperatures
- Allow the throttle to remain nearly fully open by controlling engine power by varying the firing cylinders
- Handle noise, vibration, and harshness by dynamically controlling which cylinders fire, which allows use of cylinder deactivation at lower engine rpm (figure 2, upper).
- Expand the range of applicability to smaller engines, even 3-cylinder engines with an odd numbers of cylinders (figure 2, lower).
- Theoretically capable of switching between four-stroke and two-stroke operation, potentially enabling engine downsizing without the need for boost, although this would require significant additional development (and is not considered in our estimates for 2025).

Tula’s Dynamic Skip Fire (DSF, utilized by GM) is a fast-acting cylinder deactivation strategy expected to launch within five years (as of 2015).[28] A V8 could cruise on the highway with as few as two cylinders firing. After optimizing the transmission calibration and accounting for noise and vibration features, the study found a 14% increase in miles per gallon over the combined FTP/highway cycles. Note that the V8 engine used in this study did not have variable valve timing, so the benefits would be far lower on an engine with more advanced valve timing, but this is still about twice the 6.5% improvement estimated by the agencies for a comparable engine with fixed valve timing. Cost to install would be $300–$600 ($38–$75 per cylinder for a V8), due to installation of hardware on all

28 Wilcutts, M., Switkes, J., Shost, M. and Tripathi, A., “Design and Benefits of Dynamic Skip Fire Strategies for Cylinder Deactivated Engines,” SAE Int. J. Engines 6(1):2013, doi:10.4271/2013-01-0359.

cylinders (as opposed to just four for conventional deactivation on a V8).[29,] This includes the full cost of all variable valve train components, as the baseline engine had fixed valve timing.

Dynamic Skip Fire, like all DEAC systems, seeks to keep the combustion process in the engine at a point of peak efficiency. At part/reduced load, DSF reduces throttling by using only a portion of the cylinders for combustion. Thus, these active cylinders may operate at high load, where they are most efficient. Dynamically controlling which cylinders fire handles noise, vibration, and harshness (NVH) systematically.[30]

VW implemented Active Cylinder Management Technology on its Polo model in the EU and has plans for the Passat (U.S.) and Golf.[31] The system deactivates cylinders 2 and 3 (inline-4), and can operate over 1400–4000 rpm at 25–100Nm.[32] ACT uses a slightly modified camshaft. It is fitted with sleeves/bushings ("cam pieces") that permit cam profile switching, and simple actuators to engage the cam pieces. Thus, ACT enables discrete/dual VVL (i.e., valve open or closed). To implement this technology (discrete/dual VVL), the engine requires a new camshaft, one actuator per cylinder, and some cylinder head modifications to mount the actuators. Thus, total costs generally depend on the number of cylinders on an engine. The Polo saw fuel consumption reduced by 0.4L/100km on the NEDC, from 5.0L/100km to 4.6L/100km, or about 8%. The report did not say if the baseline engine had variable valve timing or not and the efficiency gains on the U.S. cycles might be somewhat less than on the NEDC.

Eaton, partnering with PSA (Peugeot), developed its Dynamic-Cylinder Deactivation system (D-CDA, or "rolling cylinder deactivation").[33] It enables engines with odd numbers of cylinders to reap the benefits of cylinder deactivation. Conventionally, deactivation with odd numbers of cylinders leads to irregular torque output and engine vibration. Eaton solves this problem by deactivating each cylinder every second cycle, effectively converting a three-cylinder into a one and a half cylinder engine.[34] According to PSA simulations, their improved dynamic or rolling CDA reduces fuel consumption by at least 1.5% compared to fixed cylinder deactivation. Furthermore, Eaton's D-CDA can be applied to cold start because it is less sensitive to oil temperature than conventional hydraulic actuated systems.[35] Overall, PSA estimates a fuel consumption benefit of 3.5%–4.0% on the WTLP cycle for their EB port fuel-injected engines (engines specific to PSA). Eaton expects further developments in the form of two- and three-way axial cam shifting to enable Miller cycling, improved VVL, and two/four-stroke operation.

In 2013, Honda brought together their three-stage variable valve timing and lift electronic control (VTEC) system and their Variable Cylinder Management system on a DI 3.5L V6 (Acura RLX). Vibration of the (deactivated) engine when running on three-cylinders was controlled with an active engine mount, resulting in an increased range over which cylinder deactivation operated. Later versions of the system used in the Honda Odyssey were able to switch from six-cylinder to four-cylinder to three-cylinder, depending on the load. Essentially, the VTEC system permits high, low, and no valve lift, while the VCM system manages when and which cylinders undergo zero lift. To achieve this, Honda consolidated cam lobes and maintained compact cam width, thereby improving and simplifying manufacturing.

Overall, it is difficult to estimate the benefit of dynamic cylinder deactivation, as it is highly dependent on the sophistication of the variable valve system on the comparable vehicle. Most of the benefits of cylinder deactivation are reductions in pumping losses, which are also reduced by a variety of other technologies. Still, dynamic cylinder deactivation can reduce pumping losses even further, and it also reduces heat transfer due to the higher BMEP in the cylinder. Benefits versus fixed cylinder deactivation are likely to be in the range of 1.5% to 4%, as estimated by Eaton/PSA.

HIGH-COMPRESSION AND ATKINSON-CYCLE ENGINES

Mazda's second-generation SkyActiv-G petrol engines could emerge by 2018 with compression

29 Truett, Richard. "Cylinders take turns to deliver proper power." *Auto News* September 21, 2015. Accessed June 2016. http://www.autonews.com/article/20150921/OEM06/309219978/cylinders-take-turns-to-deliver-proper-power

30 Wilcutts et al., "Design and Benefits of Dynamic Skip Fire Strategies for Cylinder Deactivated Engines."

31 Gillies, M. "The New Polo—A Parade of Premieres at Geneva." VW US Media Newsroom press release. Feb 24, 2014. Accessed June 2016. http://media.vw.com/release/696/

32 "VW ACT Active Cylinder Management." *Automotive Expo.* YouTube, April 2014. Accessed June 2016. https://www.youtube.com/watch?v=_4AZbbBjqhM

33 Cecur, Majo, Veiga-Pagliari, D.R. "Dynamic Cylinder De-Activation (D-CDA)." PSA & Eaton. Presented at 24th Aachen Colloquim Automobile and Engine Technology. October 7, 2015.

34 "Cylinder Deactivation." *Eaton Products & Services: Vehicle Engine Valves, Lifters & Valve Actuation.* 2016. Accessed June 2016. http://www.eaton.com/Eaton/ProductsServices/Vehicle/valves-lifters-actuation/cylinder-deactivation/index.htm#tabs-2

35 Cecur, Majo, Veiga-Pagliari, D.R. "Dynamic Cylinder De-Activation (D-CDA)." PSA & Eaton. Presented at 24th Aachen Colloquim Automobile and Engine Technology. October 7, 2015.

ratios between 16:1 and 18.0:1.[36] This engine would use homogeneous charge compression ignition (HCCI) as the next step. HCCI works by using the heat and pressure inside the cylinders to ignite the air/fuel mixture without requiring a spark plug for ignition. It has been the subject of research and development since the 1970s, with production applications generally stymied by control issues. The advantage that has motivated the research is the promise of unthrottled highly dilute operation at light load.

Mazda is already working on third-generation SkyActiv technology, which will include adiabatic combustion chamber technology, reduced combustion duration, and lean HCCI.[37] If successful, this could lead to another reduction in fuel consumption by improving low-speed efficiency and reducing exhaust energy and cooling losses (figure 3).

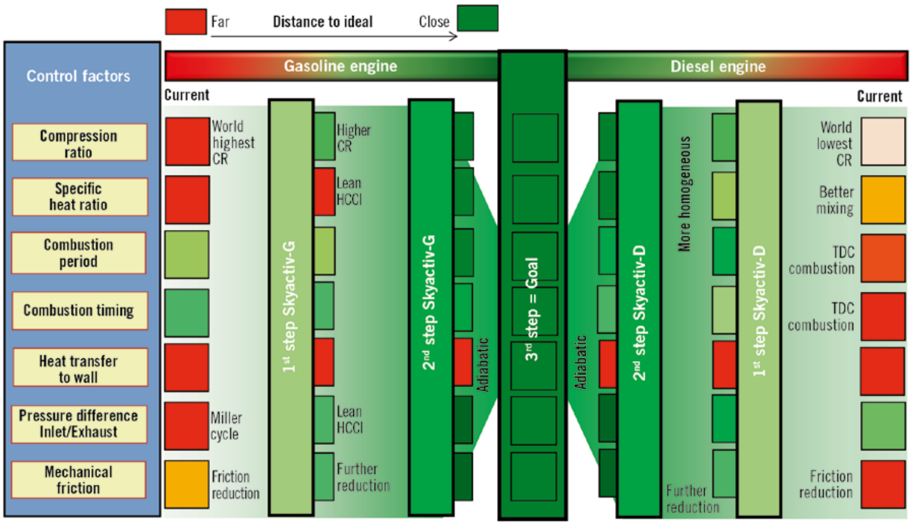

Figure 3. Mazda map for incremental improvements in gasoline (and diesel) engines. (Source: Hirose, Ichiro, Hitomi, Mitsuo. "Mazda's Way to More Efficient Internal Combustion Engines.")

Because the benefits and production potential of HCCI and adiabatic technology are still speculative, these have not been included in the technology summaries in this report. Still, it is interesting to note that further improvements are being actively pursued.

Subaru has set the goal of developing engines with thermal efficiency greater than 40% by 2020.[38] Subaru will improve its engines' efficiency by adding cylinder deactivation, Atkinson cycle, and lean combustion (although lean burn may prove difficult given the stringent NOx standards in the United States, and the higher NOx output of lean burn). This level of engine efficiency would be higher than the engine currently available in the Prius Hybrid.

IMPROVED STOP-START SYSTEMS

Stop-start was estimated by the agencies to have 1.8%–2.4% benefit. Improved stop-start systems are in development that also turn the engine off while the vehicle is decelerating (sometimes referred to as sailing), not just when it stops. According to the draft FEV analysis, between 2.3% and 4.3% reduction in fuel consumption is possible with such an advanced stop-start system. Also, NAS 2015 estimates that the benefits of conventional stop-start in real-world driving may be higher than on test cycles (up to 5% instead of 2.1%), which manufacturers can capture by applying for off-cycle credits.

Due to the more advanced stop-start system considered by FEV, costs may not be directly comparable. However, FEV estimated that their stop-start system would cost \$76–\$86, significantly cheaper than the agencies' estimated \$225–\$279. This may be partially due to the fact that the FEV stop-start system does not have the same regenerative-braking capability of the stop-start system considered in the rulemaking. (FEV considers regenerative braking in their P0 hybrid, which uses 48v.)

CONSUMER-ACCEPTANCE ISSUES

Variable valve timing and lift provide improved vehicle performance, in addition to the efficiency benefits. Thus, there are no consumer acceptance issues for these technologies.

Cylinder deactivation can lead to increased vibration and noise from the engine. Manufacturers have successfully addressed these issues by

36 Pettendy, Marton. "Mazda eyes 18:1 petrol compression." *Motoring* November 27, 2013. Accessed June 2016. http://www.motoring.com.au/mazda-eyes-181-petrol-compression-40237/. Greimel, Hans. "Mazda pin improved mpg on Skyactiv 2". Auto News Jan 6, 2014. Accessed June 2016. http://www.autonews.com/article/20140106/OEM06/301069997/mazda-pins-improved-mpg-on-skyactiv-2. Hirose, Ichiro; Hitomi, Mitsuo. "Mazda's Way to More Efficient Internal Combustion Engines". MTZ worldwide Issue no.: 2016-05. pp 28-33. May 2016. http://www.atzonline.com/index.php;do=show/id=18433/alloc=3

37 Hirose, Ichiro; Hitomi, Mitsuo. "Mazda's Way to More Efficient Internal Combustion Engines". MTZ worldwide Issue no.: 2016-05. pp 28-33. May 2016. http://www.atzonline.com/index.php;do=show/id=18433/alloc=3

38 Greimel, Hans. "High-flying Subaru to add models, capacity." *Auto News* May 12, 2014. Accessed June 2016. http://www.autonews.com/article/20140512/OEM01/305129943/high-flying-subaru-to-add-models-capacity. Kurylko, Diana. "Subaru moves to 1 platform, new generation of engine technology." *Auto News* August 25, 2014. Accessed June 2016. http://www.autonews.com/article/20140825/OEM04/308259973/subaru-moves-to-1-platform-new-generation-of-engine-technology

improving motor mounts and adding noise cancelling systems. Dynamic deactivation of individual cylinders will further reduce noise and vibration from the engine.

Atkinson-cycle engines have historically not been used on conventional vehicles due to the loss in power. However, recent improvements have mitigated the power loss. Toyota is in the process of introducing its Atkinson-cycle engine on many conventional vehicles in its lineup. Mazda has also successfully introduced its SkyActiv engine in most of its vehicles without consumer complaints.

The primary consumer-acceptance issue has been with stop-start systems. Some systems have noticeable noise and vibration when the engine restarts, and customers can think their engine has stalled when it shuts off at a light or stop sign.[39] Still, it is expected that customers will get used to the system with experience, and in most vehicles the driver can turn the system off if they want to. The noise and vibration issues should also diminish as manufacturers gain experience with the systems and develop improved hardware and control algorithms.

Table 4: comparison of estimated costs in rulemaking and suppliers

	Supplier estimated cost in 2025	Rulemaking estimated cost in 2025
Stop-Start	$76–$86	$225–$279
GDI ($/cyl)	$28–$52	$37–$55
DEAC ($/cyl)**	$35–$36	$33–$39
Cooled EGR	$113–$145	$180
Atkinson cycle	—	$200–$400*
High CR	—	$50–$100*

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

** Conventional cylinder deactivation

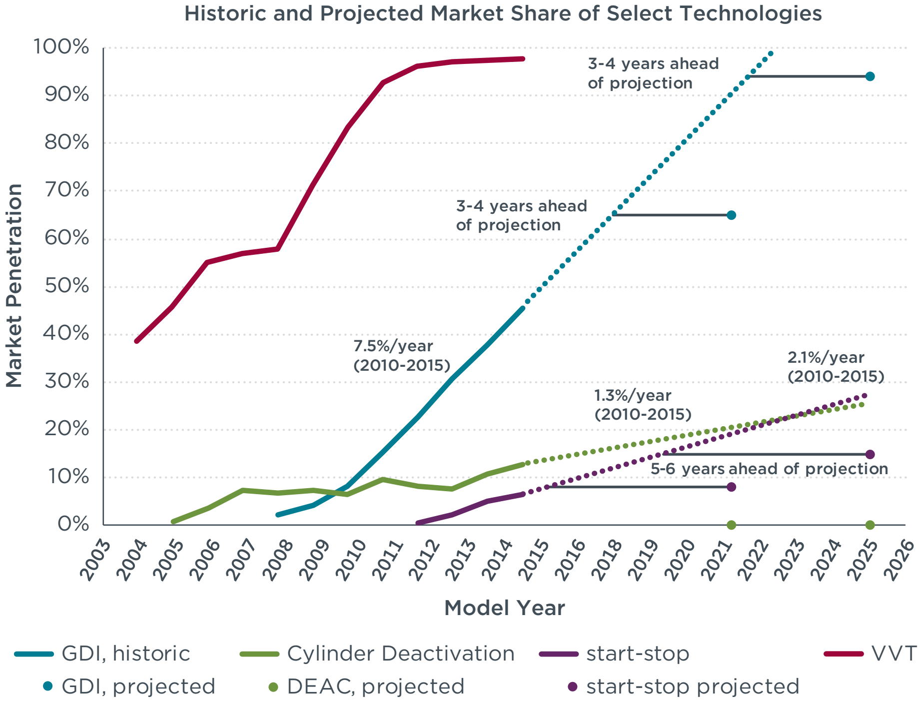

Figure 4. Market penetration of select technologies, and extrapolation to rulemaking (RM) projected penetration. Based on U.S. EPA fuel economy trends report for 2015. Note that the 2015 values are estimates.

Discussion: Comparison of current production costs, new developments, and agency projections

Many of the innovations driving efficiency gains in naturally aspirated engines build on technology that is now nearly universal in the vehicle fleet: variable valve timing and variable valve lift.

The most recent developments use VVT to facilitate the use of more efficient combustion cycles, such as the Atkinson-cycle engines from Toyota. But VVT and VVL are the cornerstones of a host of new engine innovations that are driving gains in fuel economy for all types of engines, including those that are naturally aspirated. Additional innovations enabled by VVT and VVL include cylinder deactivation and Atkinson-like engine efficiency.

Due to the suite of additional fuel efficiency gains made possible by VVT and VVL, some of the vehicles with naturally aspirated engines in the market today, such as Mazda's SkyActiv series, already meet the 2020 model year CAFE standards, four years ahead of schedule.

Figures 4 and 5 show technology penetration and fuel consumption reductions, respectively. Along with Table 4, on costs, these summarize the discussion above comparing the most recent estimates with the rulemaking projections.

The left half of figure 4 shows the market penetration of select technologies discussed in this paper from 2004 to 2015. The right half (dotted

39 Martinez, Michael. "More cars getting stop-start despite driver resistance." The Detroit News October 8, 2014. Accessed June 2016. http://www.detroitnews.com/story/business/autos/2014/10/07/autos-stop-start-driver-resistance/16893597/

lines) shows the market-penetration trends and compares these trends with predictions made by the EPA/NHTSA for the 2017–2025 rulemaking.

As figure 4 shows, VVT is nearly ubiquitous in the fleet. This indicates that improvements enabled by VVT, such as emissions control (e.g., faster catalyst light-off and engine warm-up) and fuel efficiency (e.g., Otto cycle for high torque, Atkinson for high efficiency) no longer require manufacturers to invest in additional expensive hardware. It also means that many of the benefits from these technologies are already incorporated into today's products.

GDI market share increased approximately linearly at a rate of 7.5 percentage points per year from 2010 to 2015. As indicated by the dotted blue line, if this trend continues GDI will reach 65% market penetration sometime between 2017 and 2018, and 94% penetration between 2021 and 2022. As shown, the agencies predicted 65% and 94% market penetration by 2021 and 2025, respectively. Thus, the current rate of market penetration puts **GDI 3 to 4 years ahead of schedule**. An updated assessment of GDI cost by FEV and fuel consumption reduction by NAS 2015 are both similar to the projections in the 2017–2025 rulemaking.

The agencies predicted 8% market penetration in **stop-start** systems by 2021 and 15% by 2025. However, since 2012, the market share of stop-start has grown steadily at 2.1 percentage points each year. This means that **stop-start is 5 to 6 years ahead of schedule**, assuming the rate of growth continues (purple line in figure 4). Also, General Motors announced in May 2016 that nearly every GM light vehicle produced globally will have at least one powertrain combination available with stop-start, putting it far ahead of the agencies' projections of market share.[40] Stop-start is not only ahead of schedule in market penetration but also is estimated to be more efficient, due to increased capabilities such as stopping the engine during deceleration, and to cost significantly less than estimated by the agencies.[41]

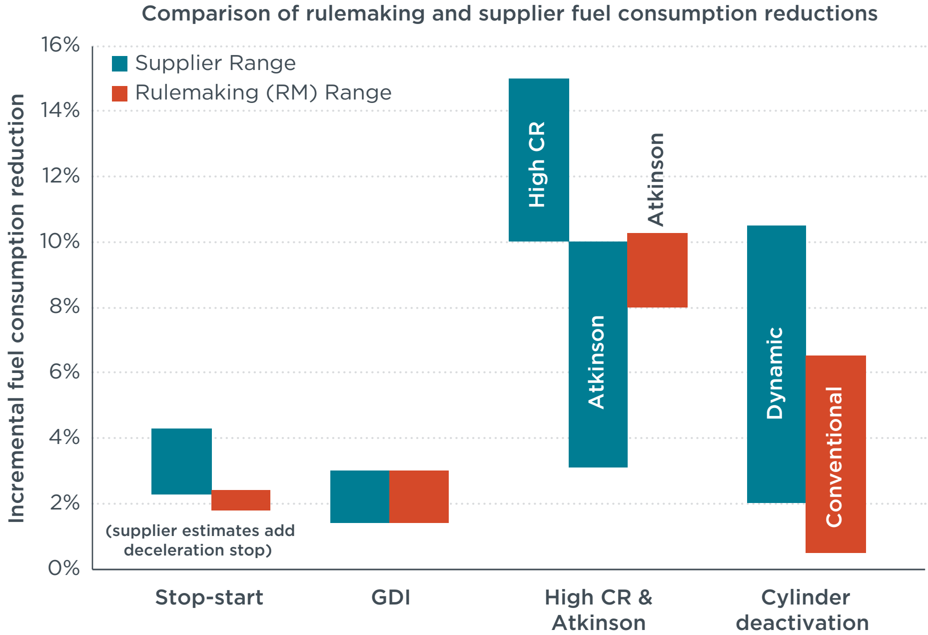

Figure 5. Comparison between rulemaking (orange) and supplier estimated (blue) incremental fuel-consumption reductions.

Cylinder deactivation, shown in green in figure 4, was not expected to play any significant role in the 2021 and 2025 fleets. Since 2010, it has seen approximately 1.3% market share growth each year, and is currently at 12.8% (estimated). Some implementations of cylinder deactivation (such as VW's) are simply VVL with zero-lift cam profiles (essentially deactivating the cylinder by not lifting valves). Thus, the increased market share of cylinder deactivation may be a sign that OEMs and suppliers are prepared for other and additional (discrete) VVL systems. An updated assessment of conventional cylinder deactivation cost by FEV is similar, if slightly lower than, the projections in the 2017–2025 rulemaking. Importantly, the agencies assumed that a fixed group of cylinders would deactivate (for example, a V6 would have three inactive cylinders, the V8 four). However, improvements in cylinder deactivation control (Dynamic Skip Fire by Tula/GM, and rolling or dynamic cylinder deactivation by EATON/Peugeot) permit engines with as few as three cylinders to take advantage of deactivation benefits, with lower NVH and additional deactivation at lower engine speeds. As a result, all cylinders may be equipped with the necessary hardware, implying that costs scale with the number of cylinders. Supplier estimates of fuel consumption reduction with active cylinder deactivation range from 2% to 10.5%, significantly higher than the estimates for conventional cylinder deactivation in the 2017–2025 rulemaking of 0.5% to 6.5%.

The share of **Atkinson-cycle** engines is currently limited to hybrid vehicles, and the agencies projected that this would remain true through 2025, with Atkinson-cycle engines only used on strong hybrids (4% market share in 2021 and 5% in 2025). However, Toyota has announced that they

40 GM plans stop-start fleetwide by 2020, Automotive News, May 23, 2016. http://www.autonews.com/article/20160523/OEM06/305239970/gm-plans-stop-start-fleetwide-by-2020

41 FEV 2015 (see above)

have reduced the trade-off between Atkinson-cycle efficiency and reduced torque, thereby expanding the application of the Atkinson cycle to non-hybrid vehicles with its ESTEC engines. Hyundai and Subaru are also introducing improved, higher-efficiency Atkinson-cycle engines. In addition, Mazda's SkyActiv engine has a number of technologies enabling a **high compression ratio**, which was not separately considered in the agencies' projections (Atkinson-cycle engines also have high compression ratio). While naturally aspirated engines may still be replaced by downsized turbocharged engines in the future, it is clear that some manufacturers have a lot of interest in Atkinson cycle and other high compression ratio concepts and these engines will be much tougher competitors than projected by the agencies.

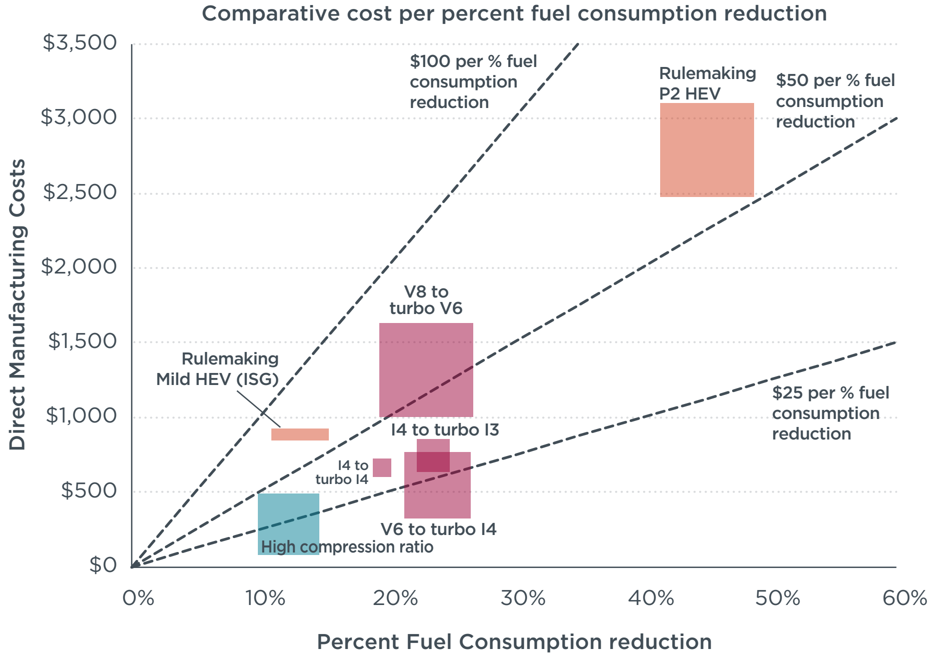

Figure 6. Comparison of overall costs for high compression ratio engines (such as the Mazda SkyActiv) and turbocharged and downsized and hybrid (HEV) as estimated by NAS 2015 and EPA/NHTSA for the 2017–2025 rulemaking.

As the rulemaking did not anticipate Atkinson-cycle engines in non-hybrids, the agencies did not estimate those costs. But Atkinson requires VVT, at a minimum intake cam phasing (where the intake valve timing alone can be adjusted), whose costs the agencies estimated at $31–$63 in 2025. VVT's market share supports that it is already quite cost effective, as evidenced by its near 100% market penetration. Atkinson-cycle engines also have higher compression ratio, the cost of which was estimated by NAS 2015 to be $50–$100. Thus, the cost of Atkinson cycling is unlikely to be more than $100. This is supported by FEV's updated cost estimates in their draft report, which found zero cost for Atkinson/Miller cycle engines.

Atkinson-cycle engines were projected by the agencies to reduce fuel consumption by 8% to 10.3%. It appears that manufacturers are on track to match or exceed these improvements. Mazda's current production SkyActiv engine already matches or exceeds the agencies' efficiency estimates for Atkinson-cycle engines in 2025. And this does not include technologies currently in development, such as cooled EGR, Miller-cycle engines, HCCI, and adiabatic engines. Except for cooled EGR, these technologies are more speculative and, thus, have not been included in the summaries in this report, but they still illustrate that additional improvements are highly likely.

Figure 6 compares the estimated 2025 fuel consumption reduction and direct manufacturing costs for high compression ratio naturally aspirated engines (blue box) with downsized and turbocharged engines (red boxes) and hybrids (orange boxes). Boxes indicate the estimated range of costs per percent fuel consumption reduction. The hybrid and turbocharged data were taken from the 2017–2025 rulemaking and NAS 2015.

The figure shows that 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 future improvements in efficiency from even higher compression ratios, cooled EGR, further valve timing improvements, dynamic cylinder deactivation, and improved stop/start systems.

Figure 6 also shows that turbocharging and downsizing is most cost-effective when the number of cylinders can be reduced: in particular V6 to I4, and for some I4 to I3. Naturally aspirated engines cannot compete with the substantial cost savings in replacing the two cylinder heads of a V-configuration engine with an inline four-cylinder turbocharged engine, but the cost benefits of engine downsizing are greatly reduced when starting with an inline engine. As of 2014 just over half of all light-duty vehicles (56%) had four cylinders, with a similar portion of the market estimated for 2015. While some manufacturers are committed to downsizing all, or most, of their lineup, these improved naturally aspirated engines provide an opportunity for more cost-effective solutions on perhaps up to 25% of the fleet.

Table 5 summarizes the latest assessment of future technology penetration, cost, and fuel consumption reductions compared to the technology assessments in the 2017–25 rulemaking. The main naturally aspirated technologies are all on track or ahead of the rulemaking assessments in every way. The fuel economy of naturally aspirated vehicles is improving more rapidly than was projected by the agencies in the 2017–2025 rulemaking. A continuous cycle of vehicle innovation—such as the extremely high compression ratio in Mazda's SkyActiv engine; the individual cylinder deactivation in GM's Dynamic Skip Fire engine; improved stop/start systems; and Toyota's introduction of an improved, Atkinson-cycle engine on non-hybrid vehicles—is driving these improvements.

Table 5: Naturally aspirated engine technology compared to EPA/NHTSA 2017–2025 rulemaking.

Ahead of rulemaking On Schedule Behind rulemaking	Stop-start	Gasoline Direct Injection	High Compression ratio	Cylinder Deactivation	Atkinson Cycle
Cost			n/a		n/a
Penetration					
Benefits					

Based on the success of Mazda and Toyota, it is clear that the goal of good performance and fuel economy can be reached with highly flexible valvetrains that permit increasing compression ratio. The resulting engines are capable of both Atkinson and Otto cycles, which broadens the range of efficient operation at a cost manageable by at least two major automakers.

As with the Atkinson cycle and the reduction in knock-risk for high compression ratio engines, cylinder deactivation is enabled by variable valve timing and lift control. VVT/VVL systems that already exist for Atkinson-cycle and high compression ratio engines would require only minor modifications to enable a zero-lift cam profile, or lashed finger-followers, i.e., cylinder deactivation. The resulting engine may be capable of cylinder deactivation, Atkinson cycle, and have high compression ratio. Specific engine loading would determine which strategy best optimizes fuel consumption.

Continued improvements to naturally aspirated engines suggest that there may be a larger role for these engines than previously estimated as manufacturers struggle to meet aggressive fuel economy and CO_2 standards.