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Downsized, boosted gasoline engines

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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 standards apply to new passenger cars and light-duty trucks covering model years 2012 through 2025. A mid-term review of the standards will be conducted 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 air conditioning refrigerant credits factored in. The standards require an average improvement in fuel economy of about 4.1 percent per year.

The technology assessments performed by the agencies to inform the 2017–2025 rule were conducted four to five years ago.[2] The ICCT is collaborating with automotive suppliers on a series of working papers evaluating technology progress and new developments in engines, transmissions, vehicle body design and lightweighting, and other measures that have occurred since then. Each paper 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 turbocharged, downsized gasoline engine technology developments and trends. It is a joint collaboration between ICCT, Eaton, Ricardo, JCI, BorgWarner, Honeywell, and the ITB Group. The paper relies on data from publicly available sources and data and information from the participating automotive suppliers.

Background

TURBOCHARGER TECHNOLOGY AND EFFICIENCY IMPACTS

Internal combustion engines produce power in proportion to the amount of air that flows through them when the appropriate amount of fuel is added to that air and burned. For a naturally aspirated engine, that airflow is roughly proportional to the displacement of the engine and the engine speed.[3] Turbochargers increase engine power by increasing intake charge air density, thus increasing the mass flow of air to the engine. This extra air simultaneously requires additional fuel (to maintain stoichiometric conditions

1 U.S. Environmental Protection Agency & National Highway Traffic Safety Administration, "EPA/NHTSA Final Rulemaking to Establish 2017 and Later Model Years Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards" (2012). https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025

2 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" (2012). https://www3.epa.gov/otaq/ climate/regs-light-duty.htm#2017-2025 U.S. NHTSA, "Corporate Average Fuel Economy for MY 2017-MY 2025 Passenger Cars and Light Trucks: Final Regulatory Impact Analysis" (2012). http://www.nhtsa.gov/fuel-economy

3 Aaron Isenstadt, John German, Mihai Dorobantu, *Naturally aspirated gasoline engines and cylinder deactivation.* (ICCT: Washington DC, 2016). http://www.theicct.org/naturally-aspirated-gas-engines-201606

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desirable for modern exhaust aftertreatment technology). Consequently, the direct impacts of turbocharging are to increase engine power and fuel flow for a given engine displacement volume.

Higher output results in higher combustion pressures which increase the temperature of the unburned gases being compressed ahead of the flame front, and this leads to increased knock and detonation. Historically, manufacturers reduced compression ratios in turbocharged engines to control knock and detonation, leading to efficiency reductions. Thus, until recently, turbochargers were used primarily to increase performance in sporty vehicles. Even though gasoline turbocharged vehicles were introduced in the United States in 1961, their sales were only 3.3% of the market as recently as 2010.

Improvements in turbocharger materials, electronic controls, and, especially, the introduction of gasoline direct-injection (GDI) have transformed the use of turbocharger technology. Previous fueling systems, from carburetors to throttle body fuel injection to port fuel injection, all mixed the air and fuel before the mixture entered the cylinder. Direct injection injects the fuel directly into the cylinder so that only air flows through the intake valves. Evaporation of the injected fuel creates a cooling effect, reducing compression temperatures and, hence, knock and detonation. It also allows valve timings that promote scavenging of the cylinder during high-load operation, further reducing charge temperatures while increasing trapped air mass. With GDI, the compression ratio in a turbocharged engine can be higher than with port fuel injection (PFI) and engine efficiency is improved.

Turbochargers reduce fuel consumption indirectly, by enabling engine downsizing. The increased power density provided by a turbo allows the entire engine to be downsized while maintaining the same level of performance. At a constant vehicle demand for performance, a smaller displacement engine operates at higher loads, resulting in lower throttling losses under normal driving conditions, as well as some reduction in heat transfer losses.[4] Smaller engines typically also have lower friction losses due to smaller bearings and cylinders.

Weight reduction from the smaller engine decreases the work necessary to move the vehicle. This effect is compounded by mass reduction in the vehicle due to less structure required to support and house the engine.

Turbochargers are typically driven by exhaust gas pressure. This process recovers some of the energy remaining in the exhaust gases that would otherwise be lost, but there is a delay between the throttle being opened and boost pressure building up, due to the inertia of the turbo. This lag in turbo response is generally noticeable only at low engine speed and is mitigated with automatic transmissions that allow engine speed and flow rate to rise rapidly. Another common strategy to reduce turbo lag is to run the engine at higher rpm, even though this increases fuel consumption. Turbocharger suppliers are constantly working on improving the efficiency of the turbocharger system and reducing the inertia of the rotating components to further reduce turbo lag. These improvements are driven by peer pressure and competition between suppliers, and by vehicle manufacturers whose desire is to replace a larger displacement naturally aspirated engine with a smaller displacement turbocharged engine with no discernable penalty in vehicle performance feel.

Mechanically driven superchargers can be used to reduce or eliminate lag, but they are driven directly off of the engine and, thus, lose the efficiency benefit of using waste exhaust heat to drive the compressor. In addition, without decoupling they have higher friction losses.

Use of low-weight materials for turbine or compressor wheels, or bearing systems with lower friction, like ball bearings, can decrease the lag in turbo response. Pulse energy usage—especially for 4-cylinder engines—like Twinscroll or BorgWarner's DualVolute technology, shows potential not only to improve boosting system characteristic but also boundary conditions for the internal combustion process.

Two-stage boosting systems also improve the lag in engine response. Parallel and serial arrangement of turbochargers is feasible. Very recently, electrically-driven superchargers, especially when a small electric motor is coupled with a compressor stage (e-boost), have shown promise. They provide fast compressor pressure build up and reduce turbo lag, like conventional superchargers, without losing the waste heat recovery benefit of the turbocharger. By reducing turbo lag, these systems allow further engine downsizing and engine downspeeding without loss of performance. For practical component scale, the e-boost systems generally require higher voltage, 48V, electric architectures, but the 48V system offers a greater potential to recover and use regenerative braking energy.

4 Increased load in the cylinder, or brake mean effective pressure (BMEP), reduces the heat transfer to the cylinder walls and head as a percentage of the fuel energy. See, for example, slide 19 of Cheng, Wai. *Engine Heat Transfer* [PDF document]. Retrieved from MIT Course Number 2.61 Lecture Notes website: http://web.mit.edu/2.61/www/Lecture%20notes/Lec.%2018%20Heat%20transf.pdf

There is also potential to improve combustion. LP-EGR (low-pressure exhaust gas recirculation)—already well known in Europe for diesel engines as a NOx reduction measure—further reduces knock tendency. Variable gas exchange (like Miller or Atkinson valve timing), or variable geometry turbo technology, reduce pumping losses as well as increase combustion efficiency. The combination of both—increased EGR and variable gas exchange—is likely to enhance the next generation of ultra high efficiency gasoline engines.[5]

MARKET PENETRATION TRENDS (PASSENGER VEHICLES, INCLUDING LIGHT TRUCKS)

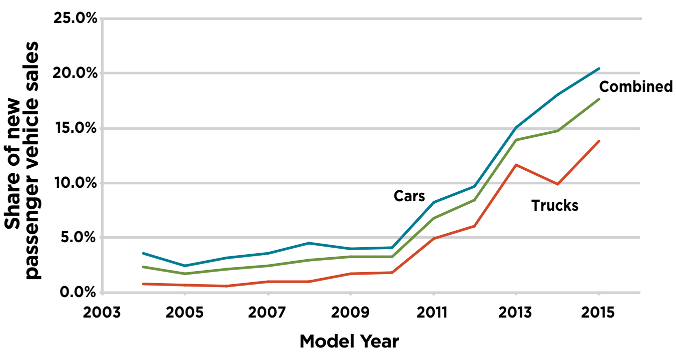

Figure 1 Market share of turbocharged light duty vehicles. (Source: EPA 2015 Fuel Economy Trends Report[6])

In the last five years, turbocharged vehicle sales have increased from 3.3% to (an estimated) 17.9% of the market. As shown in Table 1, EPA states that 73% of turbocharged engines in 2015 were 4-cylinder engines, of which 60.8% were on 4-cylinder cars.[6]

All of the world's 10 largest automakers produce downsized and turbocharged engines. In the U.S. market, most automakers' lineups offer light-duty vehicles with this technology combination.

Well-conceived and implemented downsized & turbo-charged concepts have led to favorable market acceptance that has exceeded expectations of many automotive industry observers. Based on product planning estimates, the market share for these engines is expected to continue to increase. Fundamental to their adoption is the relatively low incremental cost compared to their fuel efficiency benefit.

Table 1 Distribution of MY2015 gasoline turbochargers.

Category	Turbo Share
Car	
4-cylinder	60.8%
6-cylinder	4.5%
8-cylinder	2.5%
Other car	1.8%
Truck	
4-cylinder	11.9%
6-cylinder	17.9%
8-cylinder	0.5%
Other truck	0.1%

Source: U.S. EPA. 2015 Fuel Economy Trends Report.

HISTORICAL ESTIMATES OF COSTS AND BENEFITS

A National Academy of Sciences (NAS) committee issued an extensively referenced report on fuel economy in 2002, including projected technology benefits and costs.[7] The report was widely used for many years, including serving 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 (see Table 2).

According to the NAS 2002 report, engines with variable geometry turbochargers (VGT)[9] or mechanical superchargers reduce turbo lag and would cost $350-560 more than a conventional naturally aspirated, fixed valve (two valves/cylinder) engine, and would reduce fuel consumption 5-7%; or up to 10% when paired with multivalve technology.

5 For a good example of automobile manufacturer efforts to achieve higher thermal efficiency in gasoline engines with lean burn, cooled EGR, turbocharging & supercharging, and variable gas exchange, see: Nakata, K., Nogawa, S., Takahashi, D., Yoshihara, Y. et al., "Engine Technologies for Achieving 45% Thermal Efficiency of S.I. Engine," SAE Int. J. Engines 9(1):2016, doi:10.4271/2015-01-1896.

6 U.S. EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015" (2015). https://www3.epa.gov/fueleconomy/fetrends/1975-2015/420r15016.pdf

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" (2006). http://www.nhtsa.gov/fuel-economy

9 Variable geometry turbochargers are also referred to as variable turbine geometry (VTG).

Table 2 Historical estimates of technology fuel consumption reduction (%) and costs ($).

	NAS 2002	NHTSA 2008-2011	EPA/NHTSA 2017-2025
GDI	4-6%, n/a	1-3%, $200-250	1-3%, $164-296
Turbo	5-7%, $350-560	3-6%, $116-262	0-6.5%, $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
CVA	5-10%, $280-560	5-10%, $291-582	-
Higher volt.*	1-2%, $70-280	1-2%, $73-291	12.1-24.6%†, $310-1307

Notes: GDI = Gasoline Direct Injection. VVT = Variable Valve Timing. VVL = Variable Valve Lift. CVA = Continuous Valve Actuation. *NAS/NHTSA 2008-2011 considered 42V systems, EPA/NHTSA 2017-2025 considered >42V systems. † Higher pressure turbos generate the highest fuel consumption reductions, but with cooled EGR.

NAS 2002 did not consider direct injection (DI) likely without improved lifetime emissions control systems. Although NHTSA's analyses in support of the 2008-2011 light-truck CAFE standards were largely based upon the NAS 2002 report, NHTSA updated the DI estimates to a 1-3% reduction in fuel consumption at a cost of $200-250.

NAS 2002 estimated a 42V electrical system to replace mechanically driven accessories and to enable integrated starter/generators (ISG) would reduce fuel consumption by 1-2% at a cost of $70-280, while ISG would reduce fuel consumption by 4-7% (5-10% with regenerative braking/launch assist) at a cost of $210-350. The NHTSA 2008-2011 estimates were almost identical.

NAS 2002 estimated that variable valve timing (VVT) would cost $35-140 for a 2-3% fuel consumption reduction. Again, the NHTSA 2008-2011 estimates were almost identical.

EPA/NHTSA 2017-2025 PROJECTIONS: MARKET PENETRATION, COSTS, AND BENEFITS

In the 2017-2025 rulemaking analyses, the costs and benefits of turbocharged and downsized engines are in comparison to a naturally aspirated, fixed valve engine. The greater the boost, the more an engine was downsized to maintain equivalent performance: an engine with 18 bar brake mean effective pressure (BMEP) performance density was considered to have 33% downsizing ratio compared to a naturally aspirated engine with typical 12 bar BMEP value, 24 bar BMEP equates to 50% downsizing, and 27 bar to 56% downsizing. As shown in Table 3, EPA/NHTSA predict 64% of the new car fleet will have some level of turbocharging & downsizing in 2021. That market share increases to 93% in 2025; 24bar BMEP (with variable geometry turbo) makes up the majority (64%).

Furthermore, the agencies estimated the additional costs and effectiveness of adding cooled EGR systems to conventional downsized turbo DI engines.

The direct manufacturing costs (DMC) utilized by the agencies in the 2017-2025 rulemaking were estimated based on teardowns, bills of materials, and public literature. They were designed to include all potential costs associated with the application or installation of a given technology on a vehicle, and not just the actual physical parts of the technology. However, the actual costs were based on studies conducted prior to MY 2012-2016 rulemakings. In the present rulemaking, the agencies adjusted the costs determined in those earlier studies to 2010 dollars. Additionally, the agencies estimated the DMCs to decrease over time due to manufacturer learning. Learning decreases costs over time due to a number of reasons: simplified machining/assembly, lower material costs, reduced complexity or number of components, increased production volume, etc.

Learning was based on a simple curve with two main sloped sections indicating learning is occurring. In the steep section: costs are reduced by 20% after 2 full years of implementation; there are two consecutive steep sections. In the flatter section: agencies estimate a 3% reduction per year for 5 years; then 5 years at 2%/year and then 5 years at 1%/year. Several key technologies enabling downsized & turbocharged engines were determined to be on the flat portion of the learning curve from 2012-2025. These include GDI, turbocharging, cooled EGR, and VVT.

Table 3 EPA/NHTSA estimated future market penetration, direct manufacturing costs (DMC), and technology fuel consumption reduction.

	Market Share		2025 direct manufacturing cost			Estimated fuel consumption reduction	Relative to
	2021	2025	I3/4	V6	V8		
GDI (stoich.)	65%	94%	$164	$246	$296	1.5%	PFI
TRB 18bar	46%	23%	$310	$523		10.7-13.6%	GDI
TRB 24bar*	15%	64%	$465	$784		15.0-18.9%	GDI
TRB 27bar**	3%	6%	$775	$1307		16.4-20.6%	GDI
Cooled EGR	12%	68%	$180			3.6%	GDI+TRB
DCP+DVVL+ LUB+EFR2	>64%	>93%	$210-259	$410		4.3-8.8%	GDI+TRB+ cooled EGR
Downsizing (savings)	I4▸I3	I4▸I4	V6▸I4	V8▸I4	V8▸V6		
	($148)	($65)	($420)	($690)	($210)		

* Most 24bar BMEP turbochargers are projected to include cooled EGR, although the agencies considered a variant without it.

**27bar BMEP turbocharger is two-stage, and includes cooled EGR.

PFI = Port Fuel Injection, TRB = turbocharger, GDI = gasoline direct injection (stoichiometric), Cooled EGR = cooled exhaust gas recirculation, DVVL = discrete variable valve lift, DCP = dual cam phasing, LUB = low friction lubricants, EFR2 = engine friction reduction level 2

Source: EPA/NHTSA Joint TSD[10], NHTSA 2017-2025 FRIA.[11]

A summary of all the agency-estimated costs associated with turbocharging and downsizing engines is presented in Figure 2. Note that some combinations are not allowed, due to performance considerations. For example, downsizing from a V8 to an I4 requires a turbocharger that can provide peak BMEP of 27 bar to maintain equivalent performance (thus, no 18 or 24 bar columns).

As shown in Figure 2, the savings of decreasing the number of cylinders (especially V6 to I4) often drastically offsets the increased costs of turbocharging (turbocharger itself + charge air cooler + hoses + water and oil lines). Thus, the market potential for such downsized and turbocharged vehicles is quite large.

Status of current production versus agency projections

CURRENT TURBOCHARGER MARKET PENETRATION AND LATEST PROJECTIONS

Turbocharged engine market share increased by about 3 percentage points per year from 2010 (3%) to 2015 (18%), as shown in Figure 1. Extrapolating this increase to 2020, market share would be 33% in 2020 and 48% in 2025.

Suppliers agree that engine downsizing is one of the most important pathways to reduced emissions of future vehicles. BorgWarner estimates that by 2019-2020, 3-cylinder engines will sell at more than twice the level of today, 4-cylinder engines will increase their market share by 13 percentage points, and 6- to 8-cylinder engines will decrease their overall share. The vast majority of these downsized future engines will have displacement between 1.0-2.9L.[12] Of course, these engines all require boosting to meet the same (or greater) levels of performance.

Honeywell predicts that sales of new turbocharged vehicles in North America will reach 39% of all new passenger vehicle sales by 2020.[13] Globally, approximately three quarters of the turbo market in 2020 will be for 4-cylinder engines,

10 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" (2012). https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025

11 U.S. NHTSA, "Corporate Average Fuel Economy for MY 2017-MY 2025 Passenger Cars and Light Trucks: Final Regulatory Impact Analysis" (2012). http://www.nhtsa.gov/fuel-economy

12 Nahra, Paul (2014). *Downsizing…it's not just smaller engines* [PowerPoint slides]. Presented at Automotive World Megatrends USA 2014, 18 March 2014. Slides 8-9.

13 Mike Stoller, "Honeywell's 2015 turbocharger forecast signals increased expectations of turbo technology as global penetration nears 50 percent by 2020." Honeywell News Release, September 16, 2015, https://turbo.honeywell.com/whats-new-in-turbo/press-release/honeywells-2015-turbocharger-forecast-signals-increased-expectations-of-turbo-technology-as-global-penetration-nears-50-percent-by-2020/

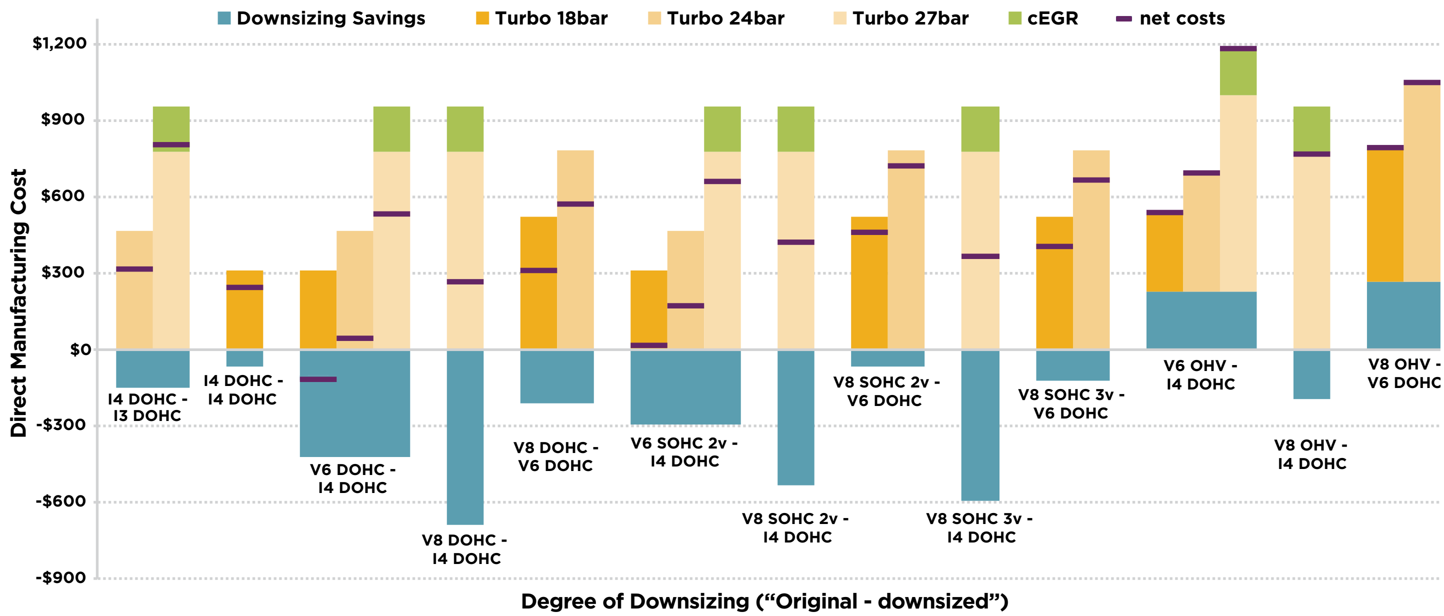

Figure 2 Rulemaking estimated 2025 direct manufacturing costs of turbocharging and downsizing.

Note that V8 to I4 costs represent first V8 to V6 downsizing, then V6 to I4.

while sales of turbo 3-cylinder engines will reach 7 million by 2020, which represents a compound average growth rate of 30%.

BorgWarner has similar estimates: 7.2 million turbocharged systems (in total) by 2020, at a compound average growth rate of 29% from 2015 (~2m sales).[14]

The projections from Honeywell and BorgWarner are noticeably higher than the 33% market share derived from linearly extrapolating the 2010–2015 trends to 2020. Nevertheless, these increases, while impressive, are still short of the agencies' projection of 64% turbocharger market share in 2021.

A potential reason for these projections of somewhat slower market introduction of downsized turbocharged engines is the successful introduction of other technology paths to achieve the mandated fuel efficiency levels. Improvements to naturally aspirated engines, reductions in vehicle mass, improvements in rolling resistance, and technically advanced transmissions have contributed to improved vehicle fuel economy.

CURRENT PRODUCTION COSTS AND BENEFITS

Turbochargers are continuously improving: response time (lag, time to torque) decreases, max torque and low-end torque increase, high-end backpressure decreases, bearing losses decrease, wastegates improve, and overall efficiencies improve.

There are numerous developments that have enabled these improvements in turbo performance and efficiency. These include new, high temperature materials, water cooling jackets to minimize the need for high temperature materials, new manufacturing processes opening the design space for turbine wheels, extensive computational fluid dynamics to optimize the efficiency where it matters, and introduction of mixed-flow turbine wheels. Those latter developments are also aimed at reducing rotating inertia. Other improvements in turbochargers include axial flow turbines and smaller radius double-sided compressors.[15] Honeywell estimated that using axial flow turbines (similar to designs in the aerospace industry) increases the transient response by 25-35% while maintaining the same torque

14 BorgWarner (2015). *Technologies for enhanced fuel efficiency with engine boosting* [PDF slides]. Presented at Automotive Megatrends USA 2015, March 17 2015. Slide 5.

15 J. Lotterman et al. "New Turbocharger Concept for Boosted Gasoline Engines." Honeywell Turbo Technologies & Ford Research Center. June 3, 2013. Houst et al. "DualBoostTM Twin-Flow: An ultra-low inertia turbocharger compatible with exhaust pulse separation." Honeywell Transportation Systems. October 2013.

curve as conventional turbos.[16] Honeywell also estimated that highway and city fuel economy increases by 1.8-2.7% by switching from a conventional turbo to their axial flow turbine/double-sided compressor turbo.

In their technology analyses and simulations, EPA/NHTSA assumed that turbocharged engines would reach 95% torque in about 5 seconds, whereas naturally aspirated engines achieve the same level of torque in 1.5 seconds.[17] However, third generation gasoline turbochargers generate 10% more low-end torque, can reach 95% torque in 1.5 seconds, and improve fuel economy by 1% with 3% more power.[18] This time-to-torque is just 30% of the 5-second spool time assumed by the agencies in 2012 and matches the agency-assumed 1.5s time-to-torque of naturally aspirated engines.

Improved turbochargers and reduced turbo lag permit greater engine downsizing and downspeeding, which results in lower fuel consumption and reduced weight. Modern designs now incorporate new turbocharger layouts with one or more turbos specifically suited for different engine speeds and loads.[19]

For a mid-sized SUV, BorgWarner estimated that downsizing and turbocharging a naturally aspirated 5.0L V8 to a 3.5L V6 and a 1.9L I4 would reduce fuel consumption by 30% and 38%, respectively, when simulated on the FTP driving cycle (fuel consumption reductions on the highway were smaller).[20] Reaching these levels of downsizing requires fast spool up, avoiding knock, and minimizing increased turbine backpressure. These problems can be addressed by more efficient turbos and reduced friction bearings, such as ball bearings, as well as variable turbine geometry (VTG).[21] Ball bearings improve low-end torque, and also efficiency, as shown in Figure 3.

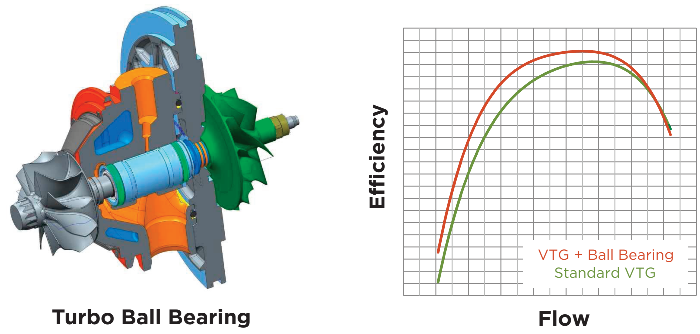

Figure 3 Left - turbocharger with ball bearing; Right - improvement in efficiency of standard VTG with ball bearing. (Source: BorgWarner[22])

In a report commissioned by the ICCT, FEV provided detailed cost assessments for turbochargers, which are summarized in Table 4.[23] Note that FEV found the cost savings of downsizing from a V6 to an I4 engine would be much larger than the cost of the turbocharger system, resulting in large cost reductions for replacing a V6 engine with a turbocharged I4.

Table 4 FEV turbocharger cost estimates.

Baseline Naturally Aspirated	Downsized Turbo	FEV Cost Estimate
1.3L, 4-cyl	1.0L, 3-cyl	$297
1.8L, 4-cyl	1.4L, 4-cyl	$454
1.8L, 4-cyl	1.0L, 3-cyl	$333
2.4L, 6-cyl	1.8L, 4-cyl	-$463
2.6L, 6-cyl	2.0L, 4-cyl	-$391
Variable Geometry Turbo (vs 1-stage)		$67
2-Stage Turbo (vs. 1-stage, I3/I4)		$184-$226

Source FEV Report.

IMPROVEMENTS IN DEVELOPMENT

Significant improvements are arriving for downsized boosted vehicles. Some of these developments were anticipated in the 2017-25 rule, such as cooled EGR. However,

16 K-H Bauer et al. "The Next Generation of Gasoline Turbo Technology." Honeywell Transportation Systems. June 3, 2013.

17 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" (2012). https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025

18 J-S Roux et al. "The next generation of small gasoline turbochargers to meet EU6.2." Honeywell Turbo Technologies. Feb 12, 2016.

19 K. Kuhlbach et al. "Parallel sequential twin turbo boosting system applied to a 1.6-l DI gasoline engine." Ford Research & Advanced Powertrain Europe and Honeywell Turbo Technologies. December 11, 2013.

20 BorgWarner (2015). *Technologies for enhanced fuel efficiency with engine boosting* [PDF slides]. Presented at Automotive Megatrends USA 2015, 17 March 2015. Slide 13.

21 BorgWarner (2015). *Technologies for enhanced fuel efficiency with engine boosting* [PDF slides]. Presented at Automotive Megatrends USA 2015, 17 March 2015. Slides 22-24.

22 Telephone call with Dr. Hermann Breitbach of BorgWarner. August 4, 2016.

23 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. September 2015. Report commissioned by ICCT.

there are three significant improvements that were not anticipated: Miller cycle, e-boost, and variable compression ratio. These technologies are being enabled, in part, by in-cylinder flow improvements for knock limitations, and higher injection pressure.

MILLER CYCLE

The Miller cycle is a special variant of the Otto cycle, which is a simplified representation of the most common thermodynamic cycle used in light-duty vehicles today. The Miller cycle decouples expansion and compression ratios by using early or delayed intake valve closing (see Figure 4).

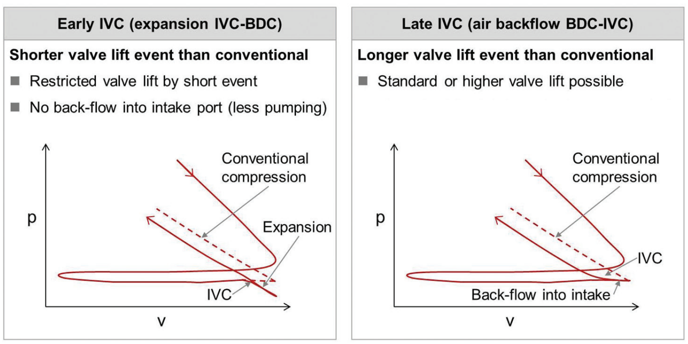

Figure 4 Miller cycle early and late Intake Valve Closing (IVC). (Source: FEV 2015 report.)

This decoupling creates a higher relative expansion ratio compared to the compression ratio, which has several efficiency benefits. The higher expansion ratio increases work extracted from combustion. Also, knock risk is reduced, allowing higher compression ratio, due to displacing some of the compression work outside the cylinder (i.e. to the turbo), where the charge air goes through the intercooler, reducing charge air temperature in the cylinder.

The downside is that the Miller cycle potentially decreases specific engine power and torque unless higher boost pressures with effective intercooling is adopted. Thus, Miller cycle engines achieve the greatest benefits by relying on significant amounts of intake manifold pressure from the boost system, in order to compensate for the reduced compression stroke.[24]

FEV estimates that the Miller cycle reduces fuel consumption by 3.9%-5.7% over a baseline downsized turbocharged engine with variable valve lift and timing. Part of the efficiency increase was an increase in geometric compression ratio from 10.0:1 to 12.0:1. On an engine already equipped with variable valve lift and timing, the cost of the Miller cycle is effectively zero in the simplest implementations, although in some cases a variable geometry turbo, e-booster, or 2-stage turbo may be needed to maintain performance, which comes with additional cost.

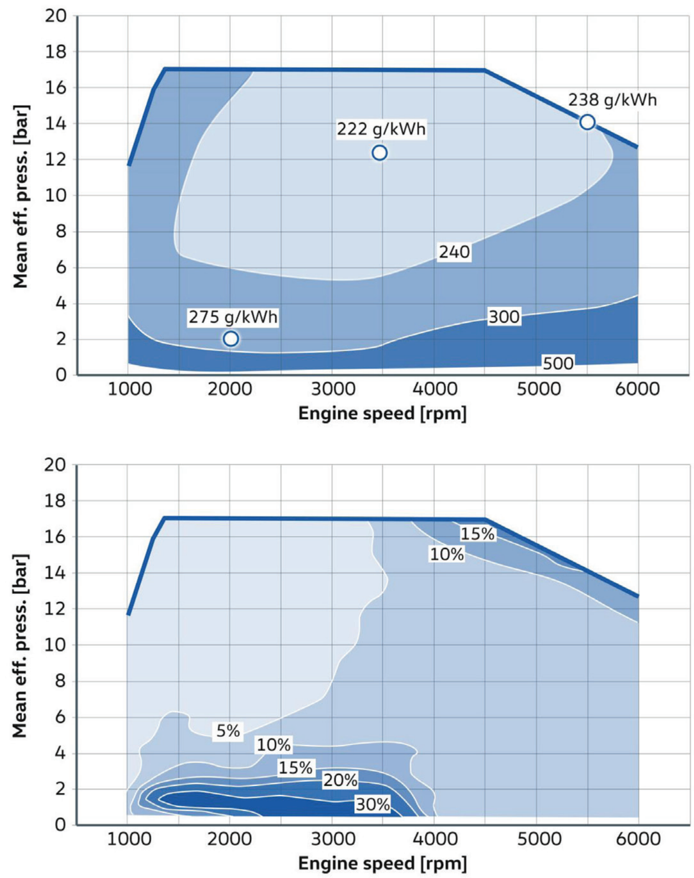

Figure 5 Top - VW EA 211 1.5-L TSI evo specific fuel consumption engine map. Bottom – Percent reduction in fuel consumption versus baseline turbocharged engine. (Source: Eichler et al. 2016.)

Figure 5 shows the specific fuel consumption engine map of VW's EA211 TSI evo engine family, scheduled to begin production in late 2016.[25] VW implemented the Miller cycle on these new engines without making any fundamental hardware changes. The claimed efficiency improvement is 10% compared with the previous generation, although this is not due to just adding the Miller cycle. VW also incorporated

24 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. September 2015. Report commissioned by ICCT.

25 Eichler, F. et al (2016). *The New EA211 TSI® evo from Volkswagen*. Presented at the 37th International Vienna Motor Symposium, 28-29 April 2016.

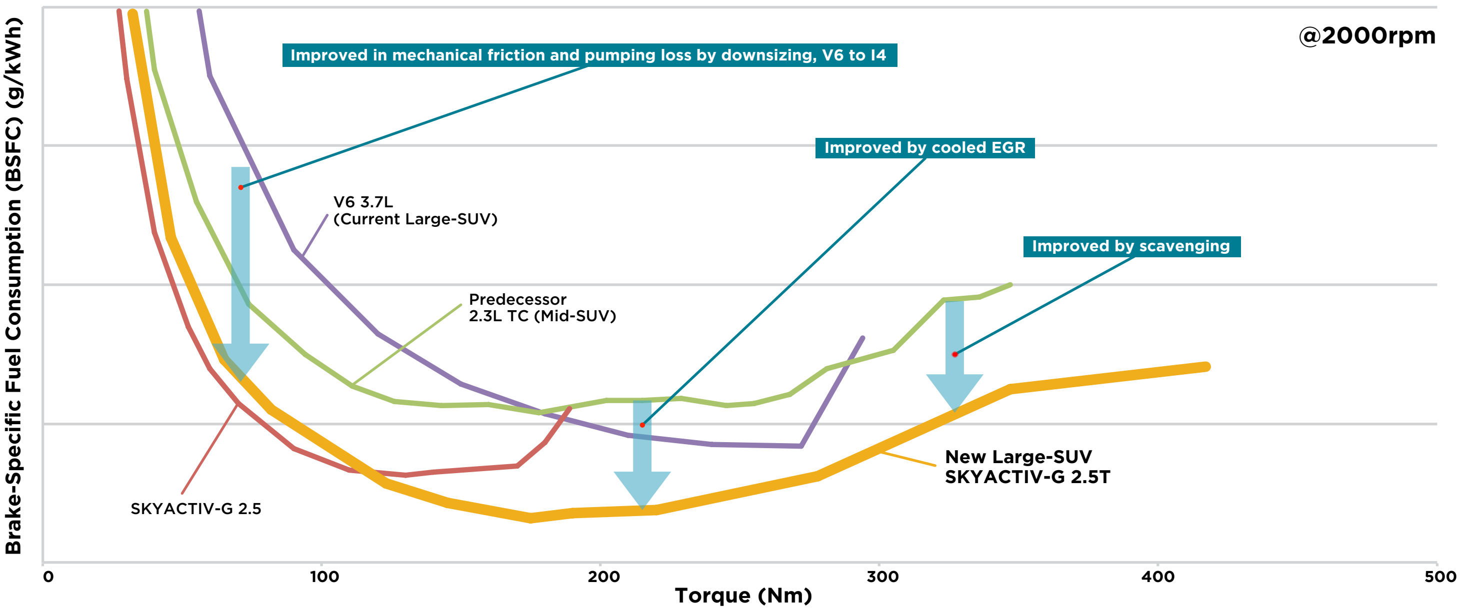

Figure 6 Reduction in fuel consumption of SKYACTIV-G 2.5T at 2000 rpm. (Source: Ichiro Hirose 2016.)

a variable geometry turbocharger and other in-cylinder improvements to improve engine efficiency. However, the reduction in brake specific fuel consumption (BSFC) is due to the Miller cycle implementation and its 12.5:1 compression ratio, likely contributing at least half of the overall benefit. The new engine shows between 5-10% reduction in fuel consumption compared to the previous generation over most of its engine map. However, for a significant portion of the low load region, the Miller cycle enables 10-30% reduction in fuel consumption (see Figure 5).

The 1.5-L TSI evo 96kW engine is also the first production implementation of a variable turbine geometry turbocharger in a gasoline engine. Very efficient VGTs have been developed for diesel engines, but they do not work well on conventional gasoline turbos, as the exhaust temperature is too high. The lower exhaust temperatures from Miller cycle engines will likely allow these efficient diesel VGTs to be used with Miller cycle engines, for additional efficiency benefits beyond those modeled by FEV. Indeed, VW's TSI gasoline Miller cycle engine reaches maximum exhaust temperatures of 880°C, slightly above diesel exhaust temperatures. Thus, VW was able to use the slightly modified VGT technology of their TDI engines on the new TSI. The new turbocharger reaches target torque 35% faster than its predecessor, and, with charge-air cooling, enables the engine to operate at stoichiometric conditions across the entire engine map.

Starting with the A4 in MY2017, using an improved 2.0-L TFSI engine, Audi will also offer vehicles that use the Miller cycle to reach high levels of fuel economy.[26] In the case of the 2.0 TFSI, intake valves close early. Thus, some additional gas expansion occurs, which helps reduce in-cylinder temperatures. To help maintain performance using the Miller cycle, the engine's compression ratio was increased from 9.6:1 to 11.7:1.[27] Compared to the previous model, fuel consumption is reduced up to 21% (on the New European Driving Cycle, which is less stringent than the US test cycles) while power output is increased up to 25%.[28]

Mazda now offers a 2.5-L turbocharged I4 (SKYACTIV-G 2.5T) that uses the Miller cycle across all engine speeds at relatively low loads. For higher loads, high-pressure cooled EGR improves knock resistance at high engine speeds, while

26 Audi USA. (2016). 2017 Audi A4 ultra offers highest EPA-estimated fuel economy in competitive segment. Retrieved from https://www.audiusa.com/newsroom/news/press-releases/2016/08/2017-audi-a4-ultra-with-best-in-segment-fuel-economy

27 "2017 Audi A4 ultra with Millerized 2.0 TFSI offers 31 mpg combined; highest EPA-estimated fuel economy in competitive segment," Green Car Congress, accessed 17 August 2016, http://www.greencarcongress.com/2016/08/20160817-audi.html

28 "Audi launches next-gen A4 with new Millerized TFSI engine; g-tron model w/ Audi e-gas," Green Car Congress, accessed 17 August 2016, http://www.greencarcongress.com/2015/06/20150629-audi.html "Audi introduces new high-efficiency 2.0L TFSI based on Miller cycle; 190 hp, 47 mpg," Green Car Congress, accessed 18 August 2016, http://www.greencarcongress.com/2015/05/20150708-audi.html

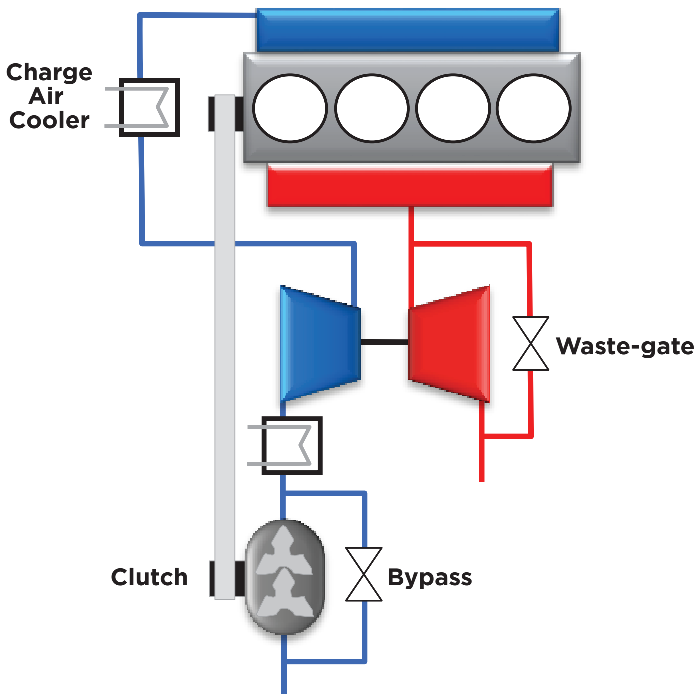

Figure 7 Ricardo concept boost system layout. (Source: Pendlebury et al. 2016)

scavenging does so at lower speeds.[29] Intended primarily to replace V6 engines in SUVs and other larger vehicle classes, downsizing to an I4 resulted in a 30% reduction in both friction and pumping losses. As with VW's Miller cycle engine, Mazda's engine achieves lower fuel consumption, greater maximum torque and faster turbine response, as compared to its predecessor. Figure 6 illustrates how Mazda achieved fuel consumption reductions over the full load range of the engine. On the US Consumer Reports' highway test mode, the SKYACTIV-G 2.5T realized a 23% reduction in fuel consumption (30% increased fuel economy). Mazda argues that the reduced size, weight and fewer engine components that result from the switch to four cylinders from six, led to an overall lower cost engine (even when considering the additional high-pressure cooled EGR and turbo systems).

Ricardo has been developing a "deep" Miller cycle concept with high (13:1) compression ratio and central direct injection in a downsized boosted engine (termed "Magma").[30] An advanced boosting system with intake-valve closing strategies is used to mitigate knock while maintaining specific output. The concept places particular demands on the boosting system, as high-pressure boost ratios are required. The turbo-supercharging layout, shown in Figure 7, uses a mechanical supercharger in the low-pressure position and a fixed-geometry turbocharger in the high-pressure position. This layout provides the required boost pressures across the engine speed range and—depending on operating condition—can provide the positive pumping mean effective pressure contribution of the original Miller concept.

Peak knock amplitude from single-cylinder engine development testing is compared in Figure 8. If the CR is increased from 10.2:1 in the baseline engine to 13.0:1 without any change to intake valve cam (IVC) timing, it is impossible to avoid a significant increase in knock amplitude, even with very retarded combustion phasing. When electronically controlled IVC is employed, knock is reduced back to the baseline level. This supports the hypothesis that the unburned gas temperatures are lower in the Magma case than the baseline engine, compensating for the higher cylinder pressures.

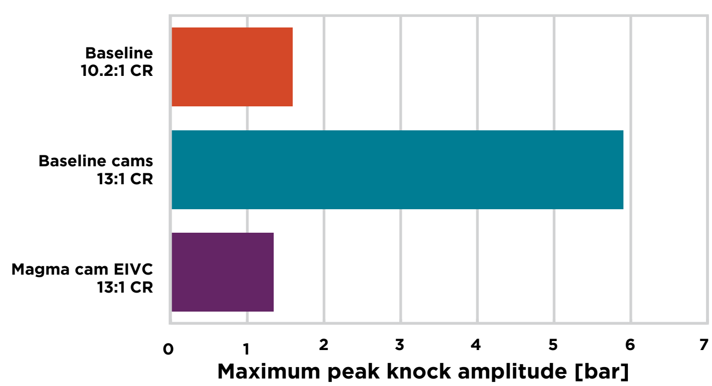

Figure 8 Comparison of knock amplitude and combustion phasing at 2000 rpm, 20 bar BMEP. (Source: Pendlebury et al. 2016.)

29 Ichiro Hirose (2016). *Mazda 2.5L SKYACTIV-G Engine with New Boosting Technology*. Presented at the 37th International Vienna Motor Symposium, 28-29 April 2016.

30 Pendlebury, K., Osborne, R. J., Downes, T. and O'Brien, S.: Development of the Magma Combustion System – A High Compression Ratio Miller Cycle Engine, JSAE Annual Congress (2016). Osborne, R. J., Pendlebury, K., Stokes, J., Dalby, J. and Rouaud, C.: The Magma Engine Concept – A Downsized Turbocharged Gasoline Engine with High Compression Ratio, JSAE Annual Congress (2015). Pendlebury, K., Stokes, J., Dalby, J. and Osborne, R. J.: The Gasoline Engine at 2020, 23rd Aachen Colloquium (2014). Osborne, R. J., Rouaud, C., Pendlebury, K., Anderssson, J., Keenan, M., Hametner, T., Bowen, P. J., Walters, D.: Lean Stratified Turbocharged Gasoline Engines to Meet Emissions and Fuel Economy Targets in 2018, Stuttgart International Symposium (2014).

The impact on full-load indicated specific fuel consumption (ISFC) is shown in Figure 9. With the CR increased to 13:1 but with standard valve events there is a small increase in fuel consumption. In this case the high knock intensity, unfavorable combustion phasing and combustion stability counteract the increased expansion ratio. By contrast, the Magma engine shows a full-load ISFC benefit of nearly 8% compared with the baseline. Although not shown in the figure, testing also found an 18% reduction in fuel consumption at the low speed light load condition of 2000 rpm/2 bar BMEP and an 8% reduction at a moderate load of 8 bar, over the baseline engine.

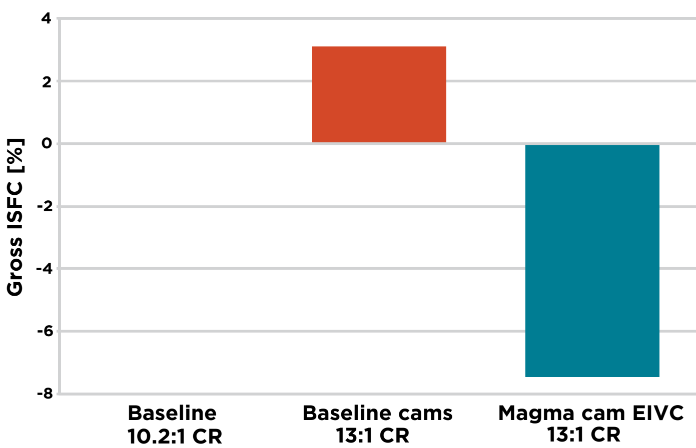

Figure 9 Comparison of gross ISFC at 2000 rpm, 20 bar BMEP relative to the baseline engine. (Source: Pendlebury et al. 2016.)

In summary, implementing Miller cycle for maximum efficiency requires variable valve timing and lift, along with updated control systems and algorithms. These advanced controls also allow manufacturers to use the Otto cycle, or alternative valve lift and timing, for particular engine loads and speed. Thus, enhanced valvetrains are key to achieving better control over engine efficiency, while minimizing the performance tradeoff. Continuous valvetrain improvement and innovation from OEMs and suppliers enable early intake valve opening, late intake valve closing (for Miller cycling), internal EGR, turbulence control, and thermal management.[31]

Due to the improvement in knock resistance and efficiency provided by the Miller cycle, downsized-turbocharged, high compression ratio engines, like VW's and Mazda's, will likely be produced in increasing numbers.[32]

E-BOOSTING AND 48 VOLT HYBRID SYSTEMS

Perhaps the most significant advancement in downsized-turbocharged engines is the explosion in development of 48V e-boosting systems or electric supercharging. These systems comprise a higher voltage electrical system (48 volts) used to provide power for small electric compressor motors within or without a turbocharger. These either directly boost the engine, or spin up the turbocharger to greatly reduce turbo lag. Improved boosting and reduced lag increase the ability to downsize and downspeed the engine and also reduce backpressure.[33] E-boost allows the use of larger turbines with lower backpressure, for a direct reduction in BSFC in addition to the benefits from engine downspeeding/downsizing.[34] It is worth noting that a 12V e-booster is possible, but provides about half the benefits of a 48V system.[35]

A larger battery or other energy storage device (typically a lithium ion battery, although improved 12V batteries paired with ultracapacitors are also being evaluated) helps deliver the power needed for the e-booster. And, as long as the powertrain already has a 48V system and a larger battery pack, upgrading the alternator to a 48V BAS (belt-alternator-starter) system to capture the additional benefits from a mild hybrid system is relatively inexpensive. As with conventional hybrids, higher voltage and greater energy storage capacity shifts the burden of powering certain accessories to the electrical system, which reduces engine accessory losses, captures regenerative braking energy, and permits accessory operation with the engine off. 48V hybrids also enable more robust start-stop systems, in particular start-stop-coasting (or sailing). Here the engine is shut off at higher speeds, and the 48V system maintains power to all electronics and electrical devices.[36] Thanks to the enhanced starter-generator, the restart of the engine is extremely quick and seamless.

31 "Variable Valve Lift," Eaton Vehicle Products & Solutions, accessed June 2016, http://www.eaton.com/Eaton/ProductsServices/Vehicle/valves-lifters-actuation/variable-valve-lift/index.htm. Richard Truett, "Chrysler plans new I-4 family, plug-ins, diesels," Auto News, May 12, 2014, http://www.autonews.com/article/20140512/OEM01/305129953/chrysler-plans-new-i-4-family-plug-ins-diesels

32 Stuart Birch, "Audi evolves the Miller cycle in its new 2.0-L spark-ignition engine," *Automotive Engineering*, May 11, 2015, http://articles.sae.org/14140/

33 BorgWarner (2015). *Technologies for enhanced fuel efficiency with engine boosting*. Presented at Automotive Megatrends USA 2015, 17 March 2015. Slide 26.

34 Telephone call with Dr. Hermann Breitbach of BorgWarner. August 4, 2016.

35 BorgWarner (2015). *Technologies for enhanced fuel efficiency with engine boosting*. Presented at Automotive Megatrends USA 2015, 17 March 2015. Slide 29.

36 Li Jiang (2015). *Advanced and System Engineering: Gasoline Systems*. Presented at ARPA-E Powertrain Innovation Workshop, 15 May 2015. Slides 12-15.

Unlike more expensive full hybrids, 48V systems are not designed to power the vehicle. The lack of a large electric motor and the correspondingly smaller battery greatly reduce the cost for this level of hybridization. It also improves safety by staying below the 60V lethal threshold.[37]

The major turbocharger manufacturers, including BorgWarner, Hitachi, Valeo, and Honeywell, all have prototypes under customer evaluation.[38] The first e-boost system is already in production, although on a diesel engine, the Audi V8 diesel SQ7.[39] Developed out of continued research,[40] this engine integrates a compressor driven by a 48V electric motor with a more conventional turbocharger system. Audi has stated that the fuel consumption of the SQ7 will be at the level of V6 diesel. This is a potential alternative to two-stage turbocharger systems and delivers boost instantaneously. The efficiency benefits are enhanced if the e-booster is integrated with a 48V hybrid system with regenerative braking.

Numerous turbocharger manufacturers have prototypes of these 48V e-boost systems that are undergoing customer evaluation. These systems typically realize dramatic increases in efficiency at a fraction of the cost of deeper hybridization/electrification. Some examples are:

(1) Ricardo's prototype "HyBoost" engine (a modified 1.0-L EcoBoost) adds a low cost 6kW BSG (belt starter generator, another term for BAS) and an improved 12V battery plus ultracapacitors for recovering regenerative braking energy, and powering the engine's e-boost and start-stop system. Even though the ultracapacitors operate at voltage levels up to 27V, a Valeo 48V electric supercharger augments the conventional turbocharger.[41] The 1.0-L engine demonstrated by Ricardo's HyBoost dramatically increased the torque compared to a baseline 2.0-L, 4-cyl, PFI, naturally aspirated 2009 Ford Focus, while eliminating turbo lag. The Focus' efficiency improved from 39 mpg to 59 mpg (on the EU NEDC). Ford, working closely with Ricardo, has stated that a Focus with an electric turbocharger sees a 40-50g reduction in CO_2 on the NEDC, without any degradation in performance.[42] It is worth noting that the electric supercharger does not benefit the engine as much when exhaust flow sufficiently spins the turbo.[43] JAC and Ricardo are currently working on a production version of the HyBoost vehicle intended for the Chinese market.[44]

(2) Continental and Schaeffler teamed up in 2014 to demonstrate the fuel saving benefits of a 48V system on a Ford Focus 1.0-L EcoBoost.[45] Through e-boosting, regenerative braking, downspeeding, combustion optimization, and improved thermal management systems and strategies, the Focus reduced fuel consumption by 17% (the report did not discuss the cycle, but likely on the NEDC) compared with the base 1.0-L EcoBoost. Schaeffler is also nearing road testing of a 48V system on an Audi TT.[46] This system offers some fully electric driving in certain conditions, and strives to stop the engine whenever possible.

(3) Valeo is working on all types of micro- and mild-hybrid systems, which are claimed to be more cost effective than full hybrids, diesels, or plug-in hybrids. Their electrically driven compressor reduces fuel consumption 7-20%, if used with regenerative braking.[47] In a presentation given at The Battery Show in 2014, Valeo showed that an optimized 48V hybrid system should be able to achieve more than 15% efficiency improvement against a baseline turbocharged

37 Alex Serrarens (2015). *Overview of 48V technologies, deployment and potentials*. Presented at Automotive Megatrends USA 2015, 17 March 2015.

38 "E-boosting for VW-Audi's 2015 V6 diesel," *Automotive Engineering*, November 4, 2014. Page 24.

39 Stuart Birch. "Audi claims first production-boosting on 2017 SQ7," *Automotive Engineering*, March 6, 2016, http://articles.sae.org/14662/

40 Stuart Birch, "Testing Audi's new e-booster reveals turbocharging's future," Automotive Engineering, Aug 4, 2014, http://articles.sae.org/13421/. "Audi SQ7 features new V8 TDI, 48V system, electric compressor," Green Car Congress, March 3, 2016, accessed June 2016, http://www.greencarcongress.com/2016/03/20160303-audisq7.html

41 Jorg Christoffel, Tony Lewin, "HyBoost: the win-win option," Ricardo Quarterly, Q3, 2012, pp 13-17. http://www.ricardo.com/PageFiles/21730/RQ_Q3_2012.pdf King, J., Boggs, D., Heaney, M., et al, "HyBoost – An Intelligently Electrified Optimized Gasoline Engine Concept," Emissions 2012 conference proceedings, June 12, 2012. "HyBoost – Intelligent Electrification," Ricardo, accessed June 2016. http://www.ricardo.com/en-GB/What-we-do/Technical-Consulting/Research--Technology/HyBoost---Intelligent-Electrification/

42 Lindsay Brooke, "Ford accelerates research on 48-V mild hybrid systems," *Automotive Engineering*. Feb 12, 2015, accessed June 2016, http://articles.sae.org/13908/

43 Don Sherman, "Blowing Your Way to Savings: How Electric Superchargers Boost MPG," *Car and Driver*, October 8, 2014, accessed June 2016, http://blog.caranddriver.com/blowing-your-way-to-savings-how-electric-superchargers-boost-mpg/

44 Anthony Smith, Ricardo. (2015). JAC and Ricardo develop production version of 'HyBoost' concept. Ricardo, September 29, 2015. Retrieved from http://www.ricardo.com/News--Media/Press-releases/News-releases1/2015/JAC-and-Ricardo-develop-production-version-of-HyBoost-concept/

45 Continental. (2014). Continental and Schaeffler Present Innovative Mild Hybrid. May 8, 2014. Retrieved from http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2014_05_08_gtc_en.html

46 "Schaeffler preparing 48V mild hybrid Audi TT for road testing," Green Car Congress, September 30, 2015, accessed June 2016, http://www.greencarcongress.com/2015/09/20150930-schaeffler.html

47 Richard Truett, Jens Meiners, "Electric turbocharger eliminates lag, Valeo says," *Auto News*, August 3, 2014, accessed June 2016, http://www.autonews.com/article/20140803/OEM10/308049992/electric-turbocharger-eliminates-lag-valeo-says

engine at a direct manufacturing cost of less than $1,000.[48] The benefits increase to 20% if a 48V electric supercharger is included.

(4) Volvo developed a concept for a 225hp/L engine that uses an electrically powered compressor to spool up two twin turbos.[49] The inline 2.0-L four-cylinder engine is unique in its use of a separate electrical supercharger to spin two conventional turbochargers. Due to the cost of the system, however, it is unclear whether such an engine will move into production.[50] But the concept of a separate electrical supercharger presents yet another take on the e-boosting trend.

(5) In late 2015, IDTechEx published a report on mild hybrid vehicles (48V), including forecasts through 2031. In this report, it was estimated that CO_2 emissions could be reduced by 15-20% (50-75% of the benefit of full hybrid), at 25% of the cost. These vehicles will have brief electric drive for smooth launch, parking, creeping and sailing. IDTechEx expects production volume sales to begin in 2017. The performance of the vehicles is close to that of strong hybrids at half the cost, and further enhancements arise often, such as CPT switched reluctance motor generators replacing DC-DC converters and enabling pure electric take-off.[51] The report concludes that manufacturers will sell over 300 million equipped vehicles by 2030 and 48V mild hybrids are expected to successfully cope with "onerous emissions legislation planned for 2030."

(6) Speedstart is an example of an enabling technology for 48V systems. It eliminates permanent magnets (which can potentially be an expensive part of an electric motor, due to rare earth minerals) in a belt integrated starter generator (BISG, yet another name for BAS). The 48V machine aids the engine at low engine speeds. It is capable of 20% reduction of CO_2 (presumably on NEDC).[52] Other companies offer improved permanent magnet motor e-superchargers at reduced costs.[53]

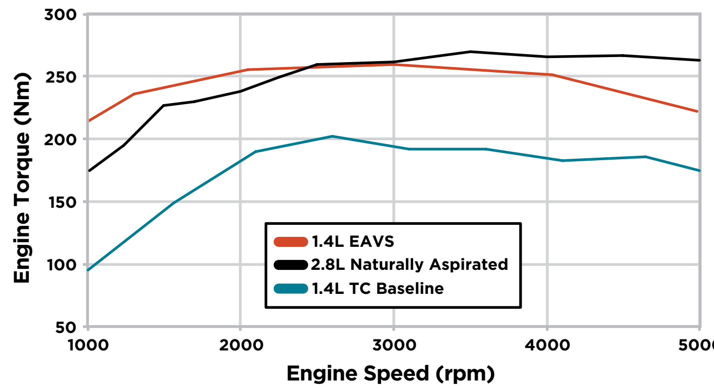

Figure 10 Torque improvement of EAVS over two baseline engines. (Source: Eaton 2015.)

(7) The electrically assisted variable speed (EAVS) supercharger from Eaton is a production-ready e-booster.[54] Like the systems from other suppliers, it reduces parasitic losses, recovers braking energy, and enables start-stop, downsizing, downspeeding, and instant boost. The EAVS supercharger reduces turbocharger backpressure and can create boost even at low engine speed, generating 230kPa peak intake pressure even at idle speeds. This greatly boosts torque, as shown in Figure 10.[55] The instant boost also eliminates particulate matter (PM) and NOx spikes during transient conditions (engine start). Overall, Eaton found the EAVS supercharger decreased fuel consumption by 14-32% (depending on previous degree of turbocharging). Eaton's analyses found 48V hybrid systems can reduce CO_2 by 10%–20% (depending on the test cycle and the inclusion of e-boost superchargers), are 50%–75% cheaper than a full hybrid, and improve safety by staying below the 60V lethal threshold.[56]

48 Matti Vint (2014). *Optimizing the Value Proposition of Low Voltage Electrified Powertrain Systems*. Presented at The Battery Show, 16 September 2014, Novi, Michigan. Slides 5-6.

49 Richard Truett, "Volvo 'triple boost' engine cranks up the power," *Auto News*, October 13, 2014, http://www.autonews.com/article/20141013/OEM06/310139959/volvo-triple-boost-engine-cranks-up-the-power

50 Brad Lord, "Triple Boost: Volvo's 450hp 2.0L Four," *Speed Hunters*, October 10, 2014, http://www.speedhunters.com/2014/10/triple-boost-volvos-450hp-2-0l-four/

51 Raghu Das, "Over 300 million mild hybrid 48V vehicles in prospect," IDTechEx, 2015, http://www.idtechex.com/emails/6528.asp

52 "SpeedStart," Controlled Power Technologies, accessed June 2016, http://www.cpowert.com/Products/SpeedStart "CPT SpeedStart Product Brief," Controlled Power Technologies, accessed June 2016, http://www.cpowert.com/assets/Speedstart_A4_4pp_04.15_ proof4.pdf

53 "Aeristech launches new 48V electric supercharger," Green Car Congress, July 31, 2015, http://www.greencarcongress.com/2015/07/aeristech-launches-new-48v-electric-supercharger.html

54 "EAVS Supercharger," Eaton Vehicle Products & Solutions, accessed June 2016, http://www.eaton.com/Eaton/ProductsServices/Vehicle/Superchargers/EAVS-supercharger/index.htm

55 Eaton (2015). *Fuel savings technologies for LD*. Presentation given by Eaton April 17, 2015.

56 Eaton (2015). *Lighter, Better, Greener: Powering Tomorrow's Vehicles with Advanced Valvetrain and Engine Air Management Systems*. Presented at Automotive Megatrends USA 2015, 17 March 2015.

(8) The Advanced Lead Acid Battery Consortium (ALABC) announced in January 2016 that 48V systems with lead-carbon batteries reduced the "T-hybrid" (Kia Optima) fuel consumption by 16%. The effectiveness of the 48V system is that it permits engine downsizing at equivalent performance. The lead batteries used are 99% recyclable and system production costs remain low because of the low cost of lead-carbon batteries.[57]

(9) BorgWarner's eBOOSTER can be used in a 48V or 12V system (although the 12V system only generates half the benefits).[58] The response time of this eBOOSTER is 170ms, which accelerates the vehicle 15% faster. Combined with standard or larger turbochargers, the 48V system reduces CO_2 by 4-8g. The biggest benefit, however, is that the assist provided by e-boosting broadens the beneficial operating range of the turbocharger system (i.e. increases the max speed over which compressor outlet pressure is greater than turbine inlet pressure). This permits increased engine compression ratio and implementing Miller cycle.[59] Furthermore, with 56.6 million start-stop sales globally by 2024, the 48V system of the eBOOSTER profoundly improves effectiveness, as it enables regeneration and sailing.

(10) On January 27, 2016, FCA released a business plan update specifying future paths and investments in vehicle technologies through 2018. The update states that 48V mild hybrid systems are expected in 2018. FCA predicts one main vehicle in their lineup, the Jeep Wrangler 4-door, to be between 2018 and 2022 emissions requirements by the next generation, which includes mild hybridization.[60]

(11) Delphi detailed the configuration of a 48V mild hybrid system with an electrical supercharger.[61] The company is aiming to be production-ready within 16 months (as of June 2016).[62] Current vehicles equipped with 48V systems benefit from 7-10% reduction in CO_2 emissions, with reductions up to 15% expected as 48V alternators improve. The improved alternators essentially free the engine of power-consuming accessories. Delphi estimates 48V hybrids with e-boosting will achieve 60-70% of the CO_2 reduction benefits of higher voltage hybrid vehicles, but at 30% of the cost. The main benefits come from downsizing and (electric-)turbocharging with regenerative braking. Delphi, quoting IHS,[63] expects that due to their better cost-benefit ratio, 48V hybrids could represent more than half of all global hybrid production by 2025. Delphi and IHS estimates for the costs and benefits of 48V mild hybrids are similar to other estimates.[64]

(12) The ITB Group estimates that 48V mild hybrid systems range in cost from $800-$1350, with higher cost corresponding to greater levels of hybridization. The estimates, validated by industry participants and shown in Table 5, are roughly aligned with others' listed above and below. The lowest cost 48V mild hybrid (MHEV) topology uses air-cooled batteries, whereas the two higher-cost topologies use liquid-cooled batteries. This type of cooling may increase total battery cost by 20%. However, batteries optimized for the high power applications on hybrids are being developed and will likely require less cooling than current hybrid batteries (by generating less heat or functioning at higher operating temperatures).

(13) AVL[65] estimates nearly 300,000 mild hybrids will be produced annually in North America in 2020, which represents almost a third of the nearly 1 million projected to be produced globally (very close to Delphi's 2020 projections described above). However, AVL specifies several challenges that remain for e-boost and mild hybrid systems. These include belt durability (for BSG), high power and high cycling energy storage, and other engineering tradeoffs related to the variety of systems available to manufacturers.

57 Chip Bremer, "48V Mild-hybrids can meet Emissions Targets with CO_2 Reductions of 15-20%," The Advanced Lead-Acid Battery Consortium, accessed June 2016, http://www.alabc.org/press-releases/48v-mild-hybrids-can-meet-emission-reductions-targets-with-co2-reductions-of-15-20

58 BorgWarner (2015). *Technologies for enhanced fuel efficiency with engine boosting*. Presented at Automotive Megatrends USA 2015, 17 March 2015. Slides 25-31.

59 Nahra, Paul, "IC Engine Evolution & Effective Electrification," Racing to 54.5 MPG by 2025, SAE Detroit Section, BorgWarner, March 10, 2015.

60 "Business Plan Update 2014-2018," Fiat Chrysler Automobiles, January 27, 2016, accessed June 2016, https://www.autonews.com/assets/PDF/CA103557127.PDF

61 John Kendall, "Delphi says 48-volt mild-hybrid systems could offer 15% CO_2 reductions," *Automotive Engineering*, October 2, 2015, http://articles.sae.org/14376/

62 "Delphi unveils new 48V mild hybrid system; working with tow OEMs toward production within 18 months," Green Car Congress, April 13, 2016, accessed June 2016, http://www.greencarcongress.com/2016/04/delphi-unveils-new-48v-mild-hybrid-system-working-with-two-oems-toward-production-within-18-months.html

63 John Kendall, "Delphi says 48-volt mild-hybrid systems could offer 15% CO_2 reductions," *Automotive Engineering*, October 2, 2015, http://articles.sae.org/14376/

64 David Sedgwick, "Johnson Controls bets big on stop-start systems," *Automotive News*, July 4, 2016, http://www.autonews.com/article/20160704/OEM02/307049991/johnson-controls-bets-big-on-stop-start-systems

65 Ulf Stenzel (2014). *48V Mild Hybrid Systems: Market Needs and Technical Solutions*. Presented at AVL UK Expo 2014, https://www.avl.com/documents/10138/1379144/AVL_UK_Expo_48V_Mild_Hybrid_Systems.pdf

Table 5 ITB Group estimates of costs and benefits of hybridization.

2020 Cost Estimates ($)	12V S/S	48V-BSG	48V-BSG E-boost	48V E-drive E-boost	Strong HEV
Hybrid level		P0 hybrid	P0 hybrid	P2 hybrid	Prius
Motor size		8-10kW	10-15kW	15-20kW	
Battery size		320Wh	450Wh	700Wh	
Total Cost ($) *	275	800	1200	1350	3200
Energy Consumption Red. **	4%	9%	12%	15%	38%†
Value ($ / %CO_2 Red.)	69	89	100	90	83

* including battery, motor, power electronics
** versus Conventional ICE
† Includes benefits of Atkinson cycle engine, lower tire rolling resistance, and improved aerodynamics

(14) Infineon estimated that a 48V, 10-15kW BAS hybrid system, without e-boost, would cost 600 to 1,000 Euros and reduce fuel consumption by 10%. Adding e-boost, Infineon's estimates were 1,300 Euros and 15% fuel consumption reduction.[66]

(15) Honeywell and AVL worked closely to deliver a high performance dynamic "Sport Car" 200 kW/L demonstrator called HYPER 200. This top performance concept, based on a 1.75-L TC GDI engine reaches 474HP, and is fitted with a bi-turbo boosting system to achieve boost pressures and air mass flows without negatively impacting combustion. AVL added the 48V electric Honeywell E-Supercharger to achieve immediate response from the boosting system ("Boost on demand") ensuring a well-balanced response behavior across the full speed range and very good low-end torque. This allows the system to reach 22 bar BMEP at 2000 e-rpm and 27 bar at 3000 e-rpm, going up to more than 30 bar while keeping the minimum BSFC below 240 g/kWh. This demonstration highlights the possibility of extreme downsizing while achieving top-level BSFC. Using the same system but with only 1 turbocharger and 1 e-charger, AVL is demonstrating a path to 200g/kWh with a 1.75-L engine reaching 150HP.[67]

(16) Johnson Controls estimates that 48V mild hybridization can deliver 80% of the fuel economy benefits of a full hybrid at less than 50% of the cost. Incremental cost are in the $1200 – $1500 range at the vehicle level.[68] With 12 – 15 kW of electrical power available and a battery system with less than 1 kWh of energy, adequate power is available to enable many engine efficiency technologies such as electrically-driven boosting systems, electrically heated catalysts and electric valve actuation. 12V dual energy storage (lead-acid + small capacity lithium ion battery) coupled with a 12V BAS-type motor/generator, while not sufficient to deliver optimal electrical power for electrically-driven boosting systems, does provide the responsiveness needed (discharge and quick recharge) for powering smaller systems.

(17) New reports from Bosch indicate that their 48V boost recuperation system will be ready for production in 2017, and will decrease fuel consumption up to 15%.[69] The alternator will be replaced with a much higher power starter-generator, which provides the engine with up to 10kW of power and 150Nm of torque.

66 Dr. Dusan Graovac, Radovan Vuletic, Tom Röwe, Patrick Leteinturier (2015). *48V Hybrid Systems from Semiconductor Perspective*. Presented at EVS28 KINTEX, Korea, 3-6 May 2015, http://www.a3ps.at/site/sites/default/files/downloads/evs28/papers/D4-02.pdf

67 AVL. (2016)."Press Release: AVL Hyper 200 – Modularity and High Specific Output." Retrieved from https://www.avl.com/press-releases-2016/-/asset_publisher/AFDAj3gOfDFk/content/avl-hyper-200-modularity-and-high-specific-output?inheritRedirect=false&redirect=https%3A%2F%2Fwww.avl.com%3A443%2Fpress-releases-2016%3Fp_p_id%3D101_INSTANCE_AFDAj3gOfDFk%26p_p_lifecycle%3D0%26p_p_state%3Dnormal%26p_p_mode%3Dview%26p_p_col_id%3Dcolumn-2%26p_p_col_count%3D1

68 Dave Sedgwick, "JCI: Future of battery market isn't EVs," Automotive News, June 20, 2016, http://www.autonews.com/article/20160620/OEM10/306209982/jci:-future-of-battery-market-isnt-evs
David Sedgwick, "Johnson Controls bets big on stop-start systems," Automotive News, July 4, 2016, http://www.autonews.com/article/20160704/OEM02/307049991/johnson-controls-bets-big-on-stop-start-systems

69 Florian Flaig, Bosch Media Service. (2015). The hybrid for everyone: Bosch's 48-volt system makes sense even in compact vehicles. Retrieved from http://www.bosch-presse.de/pressportal/en/the-hybrid-for-everyone-boschs-48-volt-system-makes-sense-even-in-compact-vehicles-43066.html

FEV conducted a detailed assessment of 48V hybrid ("P0") costs for segment B and C vehicles in the EU (FEV assumed P2 hybrid systems would be used for segment D and E vehicles).[70] They found the 48V hybrid would cost about $780 more than a start-stop system. This estimate accounts for a Li-ion battery, BSG, and electronics. Compared to the costs of full hybridization (a little more than $2000), the 48V hybrid is less than half the cost.

FEV also conducted computer simulation modeling of the fuel consumption. On a downsized and turbocharged engine, P0 48V mild hybridization resulted in a 5.1-6.2% reduction in fuel consumption, whereas full P2 hybridization resulted in 7.3-7.8% reduction.[71] Thus, a 48V hybrid system achieved nearly 75% of the benefit of P2 hybridization (assuming downsizing and turbocharging), at a third to half the cost. This conclusion is in line with supplier estimates of costs and benefits, as listed above, and with research projects supported by ARPA-E.[72]

Paralleling the explosion in development (discussed above), Lux Research predicts that most of the efficiency gains in passenger vehicles in 2025 will come from 48V micro-hybridization, with significant help from lightweighting (discussed in a separate paper).[73]

VARIABLE COMPRESSION RATIO (VCR)

Higher compression ratio improves efficiency, but at high engine loads it increases detonation, which is especially a problem for boosted engines. Variable compression ratio (VCR) systems change the engine's compression ratio to suit particular speeds and loads, so that high compression ratio can be used at light loads, when detonation is not a problem, and low compression ratio can be used at high loads for increased power output. For boosted engines, VCR allows both deep Miller cycle with high compression ratio (CR), and lower CR for more performance.[74]

VCR development has been ongoing since the early 1970s with no production applications, so what is different now? Although certainly not definitive proof of production-scale technology, patent trends can indicate the level of research and investment going into a given technology. Heavy levels of research and investment are indicative of technologies that patentees (i.e. suppliers and OEMs) see as a means to meet regulations. From the early 1970s through 2000, VCR-related yearly patent filings remained relatively constant and low (well under 25 filings/year).[75] However, from 2000 to 2013, yearly filings increased rapidly, to over 100 per year in 2013. These patents may be divided into numerous VCR designs, which indicate the flexibility of VCR systems.[76] Thus, many paths are available to manufacturers, should they seek to employ VCR as a means of increasing performance and efficiency across a range of engine loads. More importantly, Nissan will put the first production VCR system in an Infiniti in 2017.

The following paragraphs focus on two methods of VCR: a new variable connecting rod length concept and Nissan's variable compression ratio turbocharged design ("VC-T").

The basic idea behind all VCR systems is to change the size of the combustion chamber depending on engine load. While there have been attempts to create this effect by moving cylinder heads[77] or changing crankshaft radius,[78] recent

70 "FEV showcasing 48V technology at 2016 SAE World Congress," Green Car Congress, April 8, 2016, Accessed June 2016, http://www.greencarcongress.com/2016/04/20160408-fev.html FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis.* September 2015. Report commissioned by ICCT.

71 FEV's hybrid assessments were compared against an advanced stop-start system with sailing on the non-hybrid engine, did not include any engine downsizing to maintain constant performance with the addition of the hybrid system, and did not include e-boost.

72 "ARPA-E awards U-M $1.9M to develop advanced low-cost high-efficiency engine; boosting, highly dilute combustion and 48V system," Green Car Congress, December 1, 2015, http://www.greencarcongress.com/2015/12/20151201-umengine.html

73 C. Laslau et al. "Building the Car of 2025: How to Cost-effectively Get to 54.5 mpg Using the Right Mix of Advanced Technologies." Lux Research State of the Market Report, December 6, 2015, https://portal.luxresearchinc.com/research/report_excerpt/20754, Carole Jacques, "Micro-Hybrids, Not Electric Vehicles or Fuel Cells, Will Drive Auto Efficiency in 2025," Market Wired, January 6, 2016, http://www.marketwired.com/press-release/micro-hybrids-not-electric-vehicles-or-fuel-cells-will-drive-auto-efficiency-in-2025-2085873.htm. "Lux: micro-hybrids will provide the most economical path for automakers to meet 2025 fuel efficiency targets," Green Car Congress, January 6, 2016, http://www.greencarcongress.com/2016/01/20160106-lux.html. "Lux: 48V microhybridization could prove to be cost-effective means of achieving 2025 CAFE targets," Green Car Congress, December 21, 2015, http://www.greencarcongress.com/2015/12/20151221-lux48v.html

74 Constensou, C. and Collee, V., "VCR-VVA-High Expansion Ratio, a Very Effective Way to Miller-Atkinson Cycle," SAE Technical Paper 2016-01-0681, 2016, doi:10.4271/2016-01-0681.

75 Thiago Hoeltgebaum, Roberto Simoni, Daniel Martins. Reconfigurability of engines: A kinematic approach to variable compression ratio engines. Mechanism and Machine Theory, Volume 96, Part 2. February 2016. Pages 308-322. ISSN 0094-114X. http://dx.doi.org/10.1016/j.mechmachtheory.2015.10.003. (http://www.sciencedirect.com/science/article/pii/S0094114X15002372).

76 For more detailed comparisons of historical and current VCR attempts, see: Asthana, S., Bansal, S., Jaggi, S., and Kumar, N., "A Comparative Study of Recent Advancements in the Field of Variable Compression Ratio Engine Technology.," SAE Technical Paper 2016-01-0669, 2016, doi:10.4271/2016-01-0669.

77 "Variable Compression Engine," Linkopings Universitet, September 2, 2013, accessed June 2016, http://www.fs.isy.liu.se/Lab/EngineLab/SVC/

78 K. Wittek, "Further Development of FEV's Fully Variable VCR System," FEV, accessed June 2016, http://www.fev.com/fileadmin/user_upload/Knowhow/Fully%20Variable%20VCR%20System.pdf

development focuses on raising/lowering the piston position at top dead center (TDC) within a fixed cylinder bore.

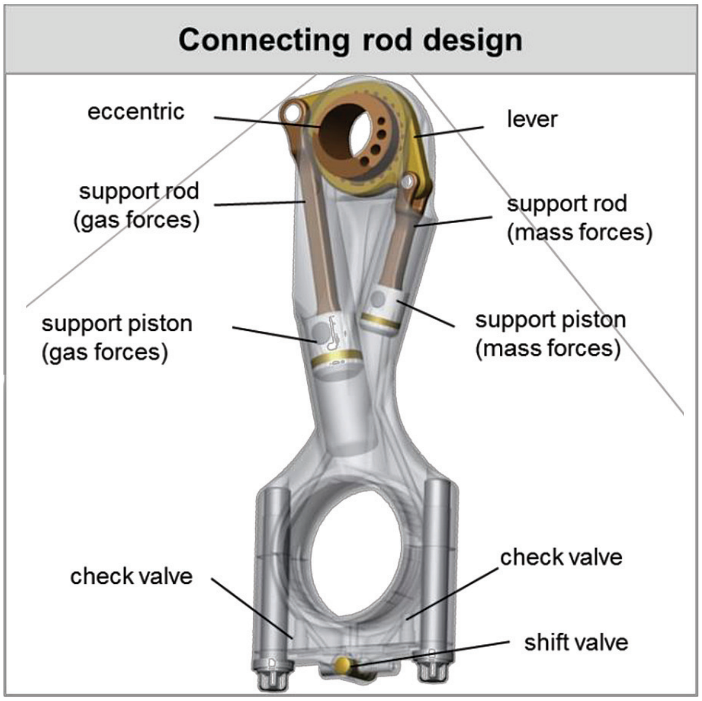

Figure 11 Two-stage connecting rod design. (Source: FEV 2015 report.)

FEV has a 2-step VCR system, which uses an eccentric bearing on the connecting rod.[79] As illustrated in Figure 11, the system uses gas and mass forces to change the compression ratio and hydraulically fix the position of the connecting rod length adjusting mechanism.

In their analysis, FEV predicts VCR availability on a commercial scale by 2030. FEV estimates that the cost of a 2-step VCR system is significantly less than a fully, or continuously, variable VCR system, while still reaping more than 80% of the fuel consumption reduction potential of a fully variable system. This is due mostly to optimizing compression ratio during part and full loads, as shown, schematically, in Figure 12.

79 Kleeberg, H., Tomazic, D., Dohmen, J., Wittek, K. et al., "Increasing Efficiency in Gasoline Powertrains with a Two-Stage Variable Compression Ratio (VCR) System," SAE Technical Paper 2013-01-0288, 2013, doi:10.4271/2013-01-0288.

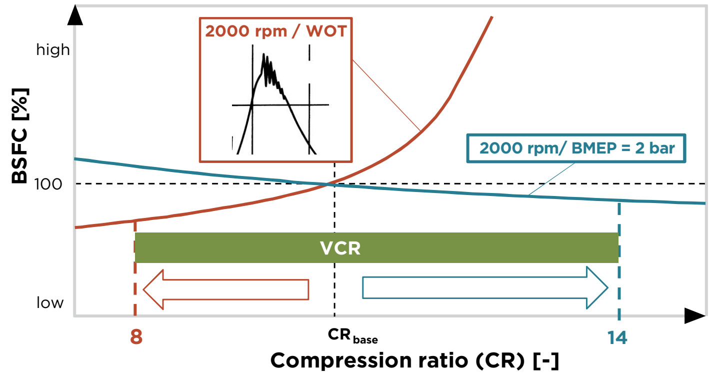

Figure 12 Fuel consumption dependence on compression ratio under part and full load operation conditions. (Source: Kleeberg, H. et al 2014.[80])

The 2-step con-rod system eliminates modifications to the engine block and permits various settings with small design changes, keeping costs down. FEV conducted a detailed assessment of the costs, which were estimated at $124-$170 compared to an engine without VCR in the corresponding segment.[81]

FEV further estimated that two-step VCR with a low pressure EGR system would reduce fuel consumption by 4.2-6.2% on the US combined cycles. Much of the efficiency benefit was due to increasing the compression ratio from 10.0:1 to 13.0:1. Note that the FEV efficiency benefits are similar to their estimated benefits for Miller cycle – and both analyses started with the same baseline engine.

Although not included in the analyses in this report for 2025, the FEV VCR system also offers the potential for a wider range of operation of gasoline controlled autoignition (GCAI), which would further reduce emissions and fuel consumption should GCAI become feasible post-2025.

A patent application in 2015 by Porsche, in association with Hilite International, shows a similar mechanism to the FEV design, with a connecting rod that changes its length with a hydraulic mechanism.[82]

To tie together variable valve actuation (VVA, i.e. VVT with some degree of VVL) and variable compression ratio,

80 Kleeberg et al. *Two-Stage Variable Compression Ratio (VCR) System to Increase Efficiency in Gasoline Powertrains*. Presented at Automotive World Megatrends USA 2014, 18 March 2014.

81 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. September 2015. Report commissioned by ICCT.

82 Mike Magda, "Porsche Working On Variable Compression Connecting Rod," EngineLabs, May 5 2015, http://www.enginelabs.com/news/porsche-working-on-variable-compression-connecting-rod/

two reports from MCE-5 highlight the overall benefits of combining these efficiency-increasing technologies. Compared to an engine with 10.5:1 fixed CR and 2-stage VVT, the combination of VCR and variable valve actuation generates potential for fuel consumption reduction greater than either technology by itself. VVA enables Miller cycle, while VCR expands optimum efficiency range of the engine.[83]

On the other hand, the benefits of VCR may be becoming less relevant due to the introduction of variable valve timing and cam profile switching systems, which offer a greatly expanded range of authority. These technologies have led to the implementation of Atkinson cycle and Miller cycle with increased geometric compression ratio and increased expansion, while avoiding knock at high load by use of either early or late intake valve closure. When starting with a much higher compression ratio from the application of Miller cycle (12.0:1 for the FEV study and 13.0:1 for the Ricardo concept), the incremental benefits of adding VCR will likely be reduced. While VCR allows for slightly higher compression ratio than Miller cycle, it does not offer the efficiency benefits from increased expansion.

VCR does have one significant benefit over Miller cycle – it allows performance to be completely maintained at lower engine speeds, whereas Miller cycle must give up some performance and/or employ a very efficient (and costly) intercooler to get close to (but not quite) the same low-end torque. Thus, VCR may be a competitor to Miller cycle concepts in the long run, offering manufacturers more options to improve efficiency while maintaining performance.

That said, Nissan/Infiniti is implementing the first variable compression ratio application in a production turbocharged engine (dubbed “VC-T”) in MY2017, well ahead of predictions by FEV and others. In development for nearly 20 years,[84] compression ratio varies continuously between 8.0:1 and 14.0:1 using several linkages connecting the piston to the crankshaft to a control rod.[85] The system is shown schematically in Figure 13.

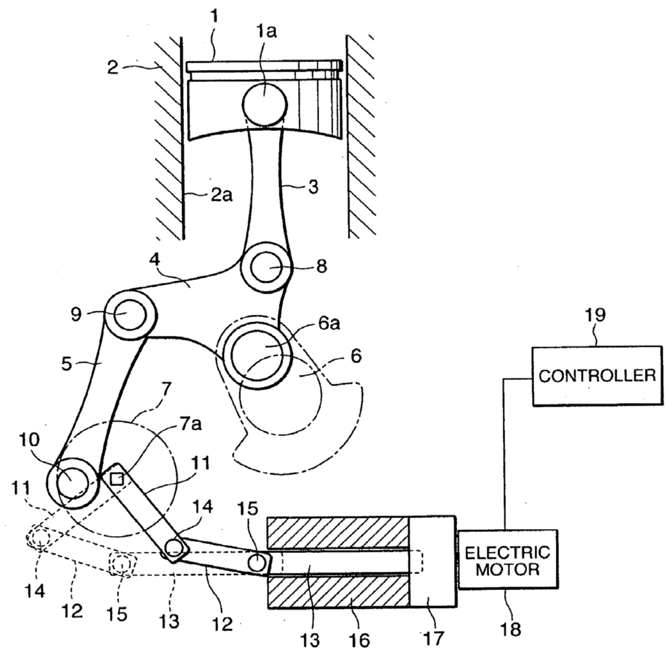

Figure 13 Nissan multi-link system for variable compression ratio[86]

The VC-T linkages reduce engine friction by generating rotational torque on the crankshaft even when the piston is at top dead center, when most piston connecting rods push directly down onto the crankshaft. However, the additional bearings for all the linkages will increase friction, thus Nissan’s historical success in friction reduction may prove most important for the VC-T engine. Testing revealed that fuel economy and power output improve at low load with higher CR and EGR, and at high load with lower CR and greater boost pressure.[87]

The inline-4 downsized VC-T engine is expected to use VCR as well as Miller cycle and both port and direct injection to achieve the highest efficiency it can at any load. All of this contributes to a 21% in fuel consumption compared to the

83 Ferrey, P., Miehe, Y., Constensou, C., and Collee, V., “Potential of a Variable Compression Ratio Gasoline SI Engine with Very High Expansion Ratio and Variable Valve Actuation,” SAE Int. J. Engines 7(1):468-487, 2014, doi:10.4271/2014-01-1201. Constensou, C., Collee, V., “VCR-VVA-high expansion ratio, a very effective way to Miller-Atkinson cycle,” SAE Int. J. Engines. Published: 2016-04-05. Others have also noted the increased benefits of VVT (VVA, too) combined with VCR: Bruce Morey, “Learning how to optimize engine efficiency,” Automotive Engineering, September 25, 2015, http://articles.sae.org/12485/

84 Nissan Global. (2016). Infiniti VC-T: The world’s first production-ready variable compression ratio engine. August 14, 2016, https://newsroom.nissan-global.com/releases/infiniti-vc-t-the-worlds-first-production-ready-variable-compression-ratio-engine

85 Moteki et al. “Variable compression ratio mechanism of reciprocating internal combustion engine.” US Pat. No. 6505582 B2. January 14, 2003. Frank Markus, “Infiniti preparing world’s first variable-compression engine for 2018,” *Motor Trend*, August 14, 2016, http://www.motortrend.com/news/infiniti-prepares-worlds-first-variable-compression-engine-for-2018/

86 Hiyoshi et al. “Variable compression ratio device for internal combustion engine.” US Pub. No. 20090038588 A1. February 12, 2009.

87 “Infiniti introducing production-ready variable compression ratio engine at Paris Motor Show,” Green Car Congress, August 15, 2016, http://www.greencarcongress.com/2016/08/20160814-vct.html

3.5-L V6 predecessor.[88] If, after the MY2017 introduction, Nissan (and others) incorporate VCR systems on other I4 engines, it would be a clear indication of the technology's cost effectiveness for meeting the standards.

ENGINE IMPROVEMENTS BEYOND 2025

Researchers at Toyota have shown that gasoline internal combustion engines can achieve thermal efficiency above 45% using lean burn (gasoline), cooled EGR, and boosting (with a motor-driven supercharger and turbocharger).[89] They found that air/fuel ratio between 20-22, EGR rates around 20%, and supercharger boost pressure between 7-8MPa led to a peak thermal efficiency of 45.6% with regular 91RON fuel. However, backpressure and inefficiencies of the turbocharger may limit the efficiency of this engine and lean burn engines require additional aftertreatment, beyond three way catalytic converters. Incorporating an electric supercharger, which is not motor-driven, could solve the backpressure and inefficiency problems and make this otherwise conventional engine achieve unprecedented efficiencies.

Researchers at Hyundai, Delphi, and the University of Wisconsin have been developing a gasoline direct injection engine that uses compression ignition (GDCI).[90] Rather than homogeneous charge, as tested by Toyota, partially premixed charge (PPCI) is used. The GDCI engine operates full time under PPCI. With a 14.8:1 CR and supercharger & VGT, the GDCI engine routinely achieves diesel-like efficiency or better. Coupled with a 48V electrical system and e-booster, the GDCI concept could improve transient and overall fuel efficiency 25% greater than a comparable gasoline engine, but at cost lower than a diesel with similar efficiency.

Neither of these engine concepts is likely to be fully developed and produced in significant numbers before 2025 and is not included in any summary analyses in this paper. They are discussed here to illustrate that boosted engine developments are still ongoing and significant improvements are possible post-2025.

CONSUMER IMPACTS

Downsized, turbocharged engines are usually sized to maintain constant power at high engine speed. However, turbocharged engines can deliver their maximum power at lower engine speeds than naturally aspirated engines. This means that turbocharged engines have more power at low engine speeds and, thus, will accelerate faster, climb steeper hills without having to downshift the transmission, and provide more towing ability.

This effect was dramatically illustrated with a recent high-volume turbocharger application, the Ford 3.5L EcoBoost engine offered on their F150 pickup truck. The 3.5L V6 turbocharged engine was an optional engine on the F150. In the first model year, Ford charged an extra $1750 over the standard 3.7L V6 engine, or $595 over the 5.0L V8 standard in higher trim levels. Ford originally expected that 20% of customers would pay the additional $595 for the smaller engine. The reality was that 45% of F150 customers paid $595 for the 3.5L EcoBoost and sales were higher than the standard 5.0L V8 (the F150 offered two other engines that combined for about 15% of sales, with 40% for the 5.0L V8). Certainly the better efficiency of the smaller engine was desirable, but what most customers wanted was the higher low rpm torque and greater towing capacity of the 3.5L EcoBoost.

The upside is that the performance benefits make consumers more accepting of downsized-boosted engines, avoiding any tradeoffs that might make consumers balk at the technology. The downside is that if customers routinely use the additional power from the turbocharger, real world efficiency might not be quite as good as expected.

The impact of turbocharging on real-world efficiency was recently addressed in a report from the University of Tennessee, which compared the in-use fuel economy results reported by consumers on fueleconomy.gov to the fuel economy label for their vehicles.[91] On average, gasoline

88 Norihiko Shirouzu, "Nissan revolution: could new petrol engine make diesel obsolete?" Reuters, August 15, 2016, http://www.reuters.com/article/us-autos-japan-nissan-engine-idUSKCN10P0IK. Michael Austin, "Infiniti's new VC-T changes the rules of small turbocharged engines," Auto Blog, August 14, 2016, http://www.autoblog. com/2016/08/14/infiniti-vc-t-engine-variable-compression-official/

89 Nakata, K., Nogawa, S., Takahashi, D., Yoshihara, Y. et al., "Engine Technologies for Achieving 45% Thermal Efficiency of S.I. Engine," SAE Int. J. Engines 9(1):2016, doi:10.4271/2015-01-1896.

90 Sellnau, M., Foster, M., Moore, W., Sinnamon, J. et al., "Second Generation GDCI Multi-Cylinder Engine for High Fuel Efficiency and US Tier 3 Emissions," SAE Int. J. Engines 9(2):2016, doi:10.4271/2016-01-0760. Sellnau, M., Foster, M., Hoyer, K., Moore, W. et al., "Development of a Gasoline Direct Injection Compression Ignition (GDCI) Engine," SAE Int. J. Engines 7(2):2014, doi:10.4271/2014-01- 1300. Richard Truett, "Hyundai works on gasoline engine that mimics diesel," Auto News, November 15, 2013, http://www.autonews.com/ article/20131115/OEM05/131119918/hyundai-works-on-gasoline-engine-that-mimics-diesel Lindsay Brooke, "Delphi and Hyundai GDCI program aims to top diesel efficiency," Automotive Engineering, February 17, 2014, http://articles.sae.org/12823/. For further discussion of partially premixed compression ignition (PPCI) for heavy-duty vehicles in particular, see: Ryan Gehm, "Lund University runs truck diesel engines on gasoline to boost efficiency, reduce emissions," Automotive Engineering, March 18, 2014, http://articles.sae.org/12892/

91 David Greene et al, "How Do Motorists' Own Fuel Economy Estimates Compare with Official Government Ratings? A Statistical Analysis," University of Tennessee Baker Center for Public Policy, October 1, 2015.

Table 6 Comparison of estimated efficiency from rulemaking and suppliers

Technology	Baseline	Rulemaking Estimate	FEV Estimate (average)	Supplier Estimates
Cooled EGR	Turbo, VVL, VVT	3.6%	2.5%	--
2-stage turbo	Turbo, VVL, VVT, cooled EGR	4-4.7%	--	--
Miller Cycle	Turbo, VVL, VVT	--	4.4%	~ 5%
Axial flow turbine	Turbo, VVL, VVT	--	--	~ 2%
Diesel VGT	Turbo, VVL, VVT, Miller cycle	--	--	~ 1%
2-step VCR	Turbo, VVL, VVT, cooled EGR	--	4.2%	--
E-boost	1-stage turbo	--	--	2% - 5%**
48V hybrid	Conventional vehicle	Uncertain	6.2%*	10% - 15%
E-boost + 48V hybrid	1-stage turbo	--	--	15% - 20%

* Did not include engine downsizing to maintain constant performance and baseline included advanced start-stop system with sailing.

** Does not include benefits from helping to enable Miller cycle

turbocharged engines had a 1.7% higher on-road shortfall compared to the fuel economy reported for naturally aspirated engines. Interestingly, this was primarily due to turbocharged pickup trucks, which had a 6% larger shortfall than naturally aspirated pickups, although it should be noted there were only 67 pickups in the entire dataset. The 542 turbocharged SUVs in the dataset did not show an increased shortfall compared to naturally aspirated SUVs. Unfortunately, the number of vehicles in the study was relatively small, making it difficult to derive valid statistical results. Still, the results suggest that while turbocharged engines may have higher real world fuel consumption shortfall than naturally aspirated engines, the effect may not be large.

DISCUSSION: COMPARISON OF CURRENT PRODUCTION COSTS, NEW DEVELOPMENTS, AND AGENCY PROJECTIONS

Honeywell and BorgWarner projected that turbocharging market share would reach about 40% by 2020, which is consistent with the annual increase in turbocharging market share from 2010 to 2015. However, this is short of the rulemaking projection of 64% turbocharger share in 2021. Part of this shortfall may be due to improvements in naturally aspirated engines that were not anticipated in the 2017-25 rulemaking, as discussed in the technology working paper on naturally aspirated engines.[92] Toyota, Hyundai, Mazda, and Subaru, in particular, appear to be committed to improved naturally aspirated engines for a substantial portion of their fleet, at least in the near term.

Three significant developments for turbocharged gasoline engines are already being implemented into the fleet. These advancements were not anticipated or considered in the rulemaking: Miller cycle, 48V e-boost systems, and variable compression ratio. Table 6 summarizes the potential efficiency improvements of these technologies, as well as for enabling technologies such as cooled EGR and variable geometry turbochargers (VGT). As discussed above, the benefits of Miller cycle and variable compression ratio may be largely redundant, with the primary benefit of variable compression ratio being more power without the need for 2-stage boosting systems.

There were many estimates for e-boost, 48V hybrid, and e-boost + 48V hybrid systems from different suppliers. For e-boost + 48V hybrid systems, Ricardo found almost a 50% increase in efficiency against a naturally aspirated engine on the NEDC, Continental/Schaeffler found a 17% reduction in fuel consumption against a 1.0-L EcoBoost engine on the NEDC, Valeo found efficiency improvements up to 20% against a baseline turbocharged engine, Eaton found a 14% reduction in fuel consumption against a baseline turbocharged engine, ITB found a 15% fuel consumption

92 Aaron Isenstadt, John German, Mihai Dorobantu, *Naturally aspirated gasoline engines and cylinder deactivation* (ICCT: Washington DC, 2016). http://www.theicct.org/naturally-aspirated-gas-engines-201606

Table 7 Comparison of estimated costs from rulemaking and suppliers

Technology	Baseline	Rulemaking Cost Estimate	FEV Cost Estimate	Other Cost Estimates
Turbo + GDI	I4 → I4	\$409 - \$554	\$454	--
	I4 → I3	\$326 - \$471	\$297 - \$333	--
	V6 → I4	\$54 - \$209	(\$391)	--
VGT	1-stage turbo, I3/I4	--	\$67	--
2-stage turbo	1-stage turbo, I3/I4	\$310	\$184 - \$226	--
Cooled EGR	Turbo	\$180	\$116 - \$149	--
Miller cycle	1-stage turbo, I3/I4	--	\$0 - \$226*	\$67 (VGT)
2-step VCR	1-stage turbo, I3/I4	--	\$124-\$170	--
E-boost	48v hybrid	--	--	\$400
48V hybrid	Base stop/start	\$1,087**	\$784	\$600 - \$1,000
E-boost + 48V hybrid	1-stage turbo	--	--	\$800 - \$1,400

* Miller cycle is zero cost, but in some cases can create need for VGT or 2-stage turbo to maintain performance

** 110V BAS

Source: FEV 2015 report.

reduction, and Delphi estimated CO_2 reductions would be 60-70% of that from higher voltage hybrid vehicles. For 48V hybrid systems alone, Valeo found more than 15% efficiency improvement, ITB found 9-12% fuel consumption reduction, and IDTechEx estimated CO_2 emission reductions of 15-20%. FEV estimated 48V hybrid fuel consumption reductions of only 6.2%, but this was against a vehicle with advanced stop-start systems and whose engine was not downsized to maintain constant performance. For e-boosting alone, BorgWarner found a direct reduction of 4-8 gCO_2/km plus an additional benefit (unquantified) of enabling Miller cycle, and Valeo found efficiency improvements of roughly 5%. There is some discrepancy between the e-boost + 48V hybrid benefits and those for 48V hybrid systems alone, while e-boost appears to offer about a 5% efficiency improvement. There may also be some overlap between the benefit of e-boost systems and Miller cycle.

Unfortunately, the agencies did not consider a 48V hybrid system in their analyses. They did consider a 110V BAS mild hybrid, but even here the agencies' hybrid efficiency estimates were not conducted independently from other technologies and we were not able to determine an independent estimate of the benefits just from the hybrid system itself. Also, note that FEV only provided 48V hybrid estimates against an advanced stop-start system that includes engine stop-start during deceleration (sailing) and some regenerative braking energy, plus FEV did not downsize the engine to maintain constant performance when adding the hybrid system. These assumptions reduce the incremental efficiency benefits of the 48V hybrid system.

Table 7 summarizes the cost estimates for the technologies in Table 6, and also compares FEV's cost estimates for basic and 2-stage turbocharging against the agencies' estimates in the rulemaking. FEV's cost estimates suggest that significant reductions in cost have occurred over the last 5 years.

The agencies did not estimate costs for Miller cycle, e-boost, or 2-step VCR, but their cost estimate for a 110 BAS mild hybrid system is included and compared against supplier estimates for 48V hybrid systems. Note that even though FEV only assessed efficiency benefits for 48V hybrid systems against a baseline vehicle with an advanced stop-start system, they provided cost estimates against both the advanced stop-start and a basic stop-start system, so the latter is used in this table. In addition, both IDTechEx and ITB estimated 48V hybrid cost is 25% of the cost of a full hybrid, Delphi estimated the cost is 30% of a full hybrid, and Valeo found a 48V hybrid should have a direct manufacturing cost of less than \$1,000. ITB further estimated

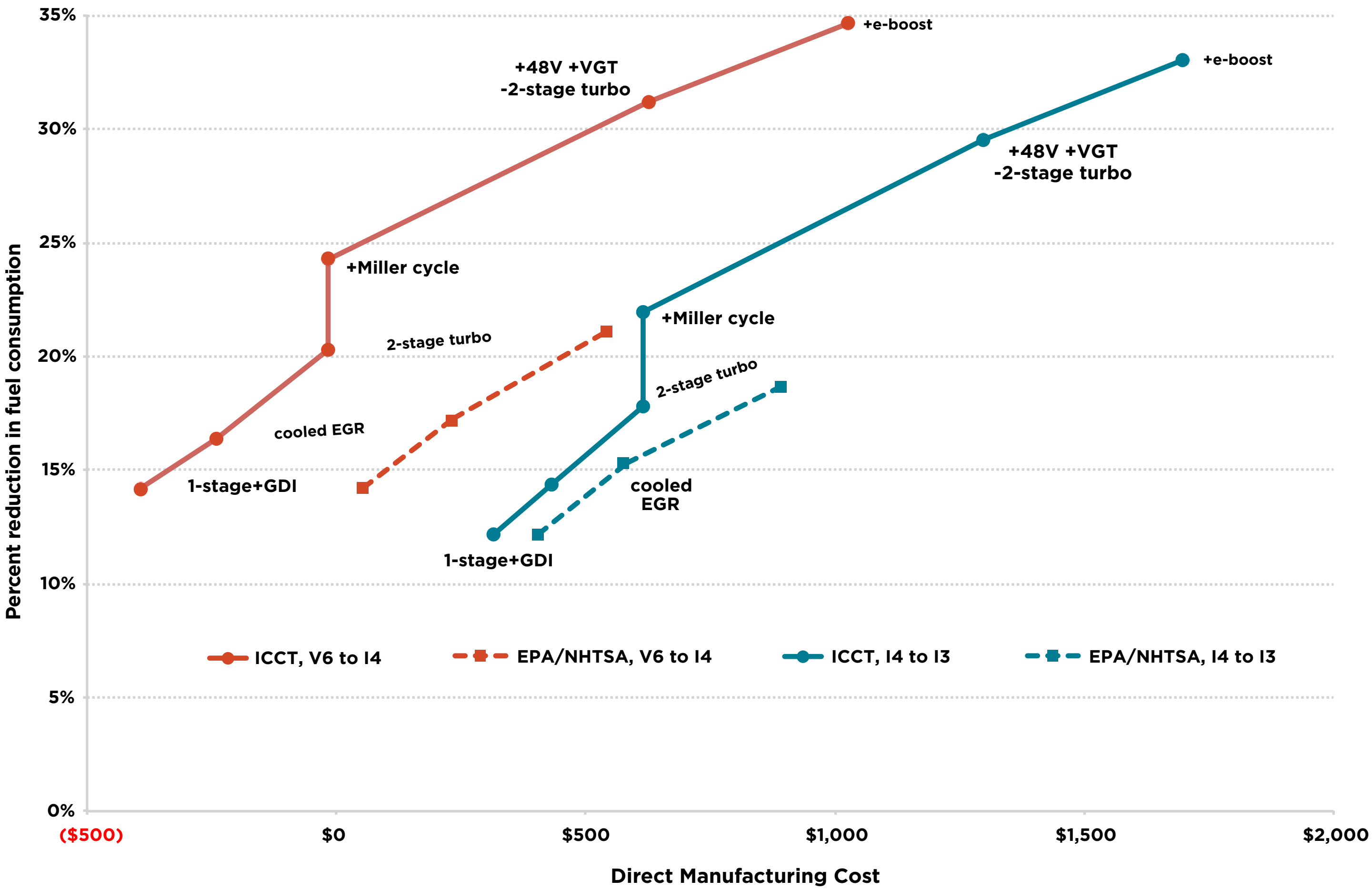

Figure 14 Comparison of ICCT/supplier and EPA/NHTSA costs and benefits of turbocharging and downsizing technologies.

that the cost of adding e-boost to a 48V hybrid system is $400.

Note that all of the supplier cost estimates for 48V hybrid systems are significantly lower than the estimate for a 110V mild hybrid in the rulemaking.

While FEV found the Miller cycle to be zero cost, they also determined that in some cases VGT or 2-stage turbocharging is needed to maintain performance. VW's Miller cycle engine added VGT – while VW did not provide the cost of VGT, the FEV cost estimate for VGT was used to estimate the cost of VW's Miller cycle engine.

Cost estimates for Miller cycle and 2-step VCR are generally under $200 each. Note that there are also cost synergies between Miller cycle and either E-boost or 48v hybrids, as adding either E-boost or a hybrid system will increase performance and eliminate the need for VGT or 2-stage turbos, making Miller cycle zero cost.

Conclusions

Figure 14 compares the turbocharger-related cost and benefit estimates from the rulemaking to one possible pathway for adding the new technologies that were not anticipated in the rulemaking (Miller, VGT, e-boost, 48v), based upon the data in Tables 6 and 7. For the technologies considered in the rulemaking, supplier estimates of costs are lower and benefits are higher. Note that there is no need for a 2-stage turbo with e-boost, so the cost of the 2-stage turbo has been subtracted when adding e-boost. Also of note is the Miller cycle cost effectiveness: 4-7% reduction in fuel consumption at virtually zero cost once enabling technologies (2-stage turbo or e-boost) have been implemented in the powertrain. Figure 14 presents a single pathway for illustrative purposes, but of course other pathways and combinations are also possible. Also note that variable compression ratio is not included in the figure, which is another possible pathway that Nissan is putting into production soon.

Although turbocharging is not penetrating the fleet as rapidly as predicted by the rulemaking, there have been significant cost reductions in turbocharging and related components since the rulemaking. 48V hybrids are also significantly cheaper than the 110V BAS system assessed by the agencies in the rule. More importantly, even though it has been only 5 years since the rulemaking technology assessments, there are major efficiency developments already in production that were not anticipated or included in the rulemaking: Miller cycle, e-boost, and variable geometry turbochargers (for gasoline engines). Another major development will be in production by 2018: variable compression ratio.

Miller cycle is estimated to improve efficiency by at least 4% and the only cost is associated with the addition of VGT or 2-stage turbos to maintain performance. If Miller cycle is combined with e-boost or 48V hybrids, these technologies provide the needed performance boost and the cost of Miller cycle becomes zero. Further, the Miller cycle efficiency increase does not include the potential use of highly-efficient diesel VGTs or improvements in turbocharger design, such as axial flow turbines. Despite the Miller cycle being unforeseen in the rulemaking, it is already in production by at least two manufacturers, and is proliferating rapidly. Thus it is likely to be on nearly all turbocharged engines by 2025.

While the 2-step VCR system is much further from production and it's efficiency benefits overlap with those of Miller cycle, it is a possible option in the 2025-2030 timeframe due to its better performance. Indeed, one manufacturer will offer a continuous VCR system by MY2018, but its applicability in other engines has yet to be confirmed.

The costs of e-boost are higher than Miller cycle, but there are excellent synergies between e-boost and both Miller cycle and 48V hybrid systems. Overall, e-boost + 48V hybrid systems are expected to provide more than half of the benefits of a full hybrid system at less than half the cost, or a cost of \$800–\$1,400. They would also enable Miller cycle at no additional cost, resulting in roughly 20-25% reduction in fuel consumption at less than \$1,400 compared to the agencies' turbocharger estimates in the rulemaking, or roughly \$35-\$70 per percent fuel consumption reduction.