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SERIES: U.S. PASSENGER VEHICLE TECHNOLOGY TRENDS

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Downsized, Boosted Gasoline Engines

In the U.S. market, automakers are leveraging advances in technology to dramatically shrink engines without compromising performance. This will help the industry reduce carbon emissions and improve fuel economy in response to market and regulatory demands since smaller, more efficient engines consume less fuel.

Capitalizing on these technological developments means automotive engineers can reduce the number of cylinders in an engine to three from four or to four from six, potentially cutting fuel consumption by more than 30% in each case with much of the cost of necessary new technology offset because fewer cylinders and valve-train components are needed. Downsizing the power plant also reduces the weight of one of the heaviest components of a vehicle, decreasing the work necessary to move it. And, because less structure is required to support and house the engine, auto bodies can be lightened, compounding the benefits.

The technologies making this possible aren't all new. They include refinements on turbochargers, which have been around almost as long as internal combustion engines, and application of the more efficient Miller cycle with variable valve timing, patented almost 60 years ago. But some are new, such as direct gasoline injection, cooled exhaust gas recirculation, and improvements in materials and electronic controls. Another significant trend has been an explosion in development of 48-volt e-boosting systems, or electric supercharging. These devices increase the ability to run smaller engines at lower speeds, burning less fuel, and pave the way to low-cost 48V hybrid systems.

Even though it has been less than five years since the technology assessments conducted by the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) to inform the 2017–2025 CAFE and greenhouse gas vehicle emissions standards, major improvements that were not anticipated in those assessments are already in production. In still more cases, automakers have already announced production plans for vehicles that incorporate technology whose efficiency benefits the EPA and NHTSA did not take into account for the rulemaking. Figure 1 illustrates these improvements by comparing the turbocharger-related cost and benefit estimates from the rulemaking to updated cost assessments and one possible pathway for new technologies that the agencies did not anticipate: Miller cycle, variable-geometry

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

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

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

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turbochargers (VGTs), e-boost, and 48V systems. Variable compression ratio is not included in the figure, but that is yet another pathway that Nissan will soon put into production. In summary, advances in downsized engines give every indication that they will exceed the best technology projections available at the time the 2022–2025 fuel economy and CO_2 emission standards were finalized, and enable significant additional reductions in fuel consumption and carbon emissions.[1]

TURBOCHARGERS AND EFFICIENCY

The key to engine downsizing without significant loss of performance is increasing the intake air pressure above atmospheric with boosting technology. This is usually accomplished with a turbocharger, a turbine-driven device that forces extra air into an engine's cylinders. Internal combustion engines produce power in proportion to the amount of air that flows through them. Turbochargers increase engine power by raising the intake air density, increasing the mass flow of air and fuel to the engine.

Smaller engines equipped with turbochargers can deliver maximum power at lower engine speeds than naturally aspirated engines, which rely solely on ambient air pressure within and around the engine to provide the oxygen necessary for fuel combustion. The boost in power is larger at low engine speeds than at higher engine speeds, which means that for the same maximum power, turbocharged engines will accelerate faster and climb steeper hills without having to downshift, and provide more towing capability.

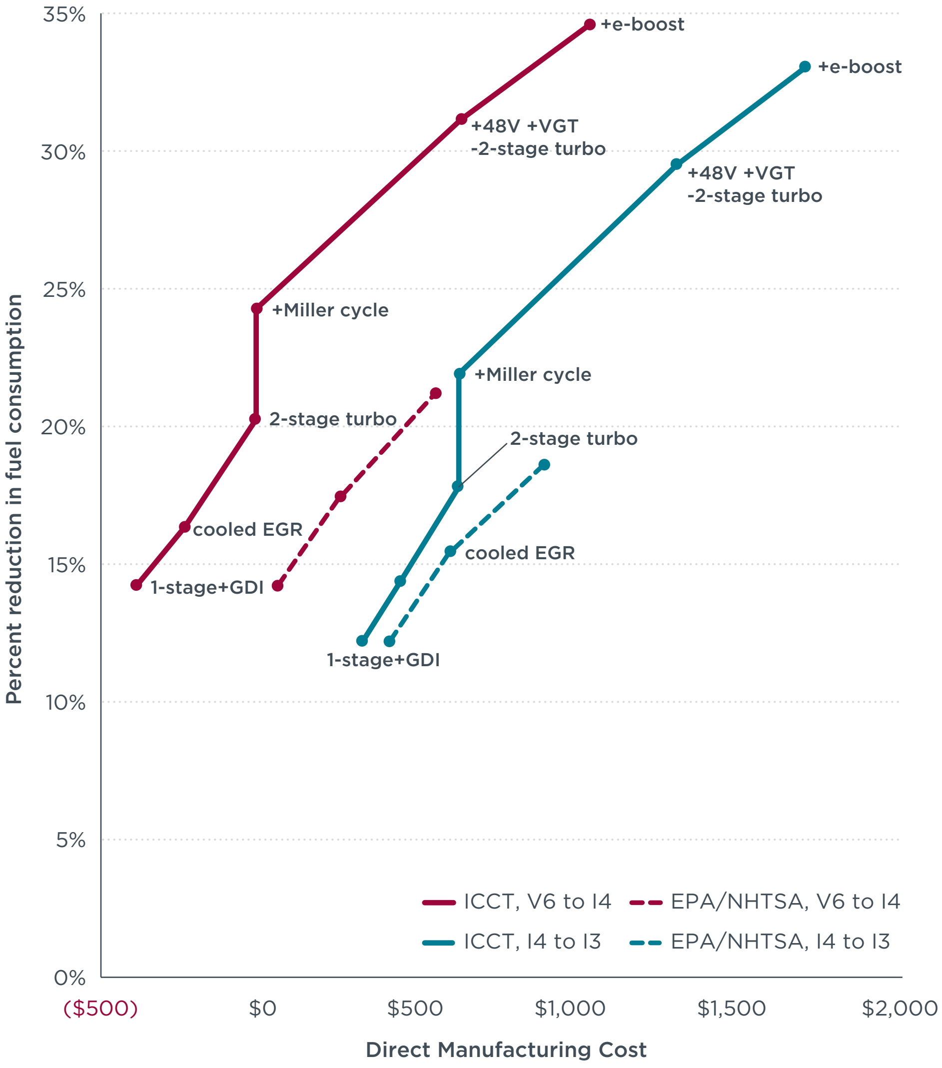

Figure 1. Comparison of ICCT/supplier and EPA/NHTSA 2012 costs and benefits of turbocharging and downsizing technologies.

Until recently, turbochargers were primarily used to elevate the performance of sporty vehicles, due to efficiency compromises caused by side effects of the older systems, knock and early detonation. But improvements in materials used in turbochargers, electronic controls, and the introduction of gasoline direct injection (GDI) have transformed the use of this technology.

Previous fueling systems combined the air and fuel before the mixture entered the combustion chamber. Gasoline direct injection (GDI) systems inject 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, as a result, knock and early detonation. This also allows valve timings that promote clearing exhaust gases from the cylinder during high-load operation, further reducing charge temperatures while increasing the amount of air compressed in the cylinder. With GDI, the compression ratio in the turbocharged engine can be higher, improving engine efficiency.

Turbochargers are driven by exhaust gas pressure. This recovers some exhaust-gas energy that would otherwise be

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[1] This technical brief is based on Aaron Isenstadt, John German, Mihai Dorobantu, David Boggs, Tom Watson, Downsized, boosted gasoline engines (ICCT: Washington, DC, October 28, 2016). http://www.theicct.org/downsized-boosted-gasoline-engines

lost out the tailpipe. But there is a delay between opening of the throttle and building up of boost pressure, a result of the inertia of the turbo. This "turbo lag" is especially noticeable at low engine speeds and is generally mitigated by running the engine at higher speeds and with automatic transmissions that allow engine revolutions and flow rate to rise rapidly.

Use of low-weight materials for turbine or compressor wheels and lower friction bearing systems, such as ball bearings, can decrease the lag in turbo response. Two-stage boosting systems can also reduce response lag, by combining a small turbine with fast response and a larger turbine for higher power, although these systems are higher cost.

The benefits of engine downsizing are already appearing in the U.S. market. Turbocharged vehicles jumped to 22% of sales in 2016 from 3.3% in 2010 (Figure 2). Most automakers in the U.S. market offer downsized gasoline engines, and all of the world's ten largest auto companies produce engines capitalizing on these technologies. Based on product planning estimates, the market share for downsized, boosted engines will continue to increase.

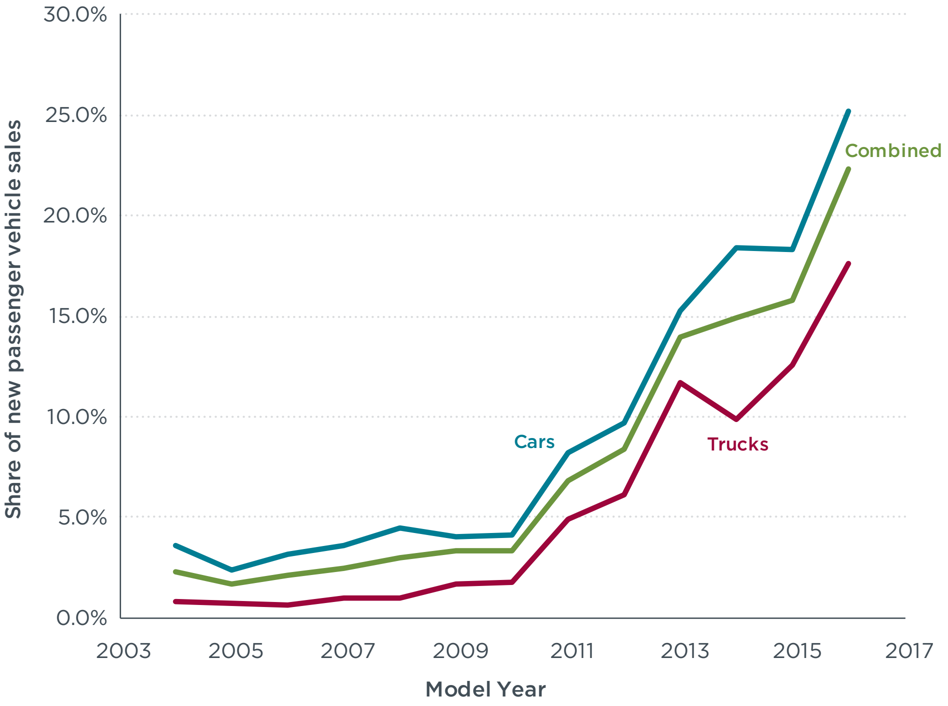

Figure 2. Market share of turbocharged light-duty vehicles. (Source: U.S. EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016" 2016). https://www.epa.gov/sites/production/files/2016-11/documents/420r16010.pdf

NEW DEVELOPMENTS

In writing fleet fuel-economy rules for 2017–2025, federal regulators took some of these developments into account, such as cooled exhaust-gas recirculation. However, they did not anticipate three significant advances: Miller cycle, e-boost, and variable compression ratio. These technologies are being enabled, in part, by in-cylinder flow improvements for knock limitation, variable valve timing, and higher injection pressure.

MILLER CYCLE

The Miller cycle is a special variant of the Otto thermodynamic cycle used on gasoline spark-ignition engines. By timing intake-valve closing so that it occurs early or is delayed, the Miller cycle decouples expansion and compression. This creates a higher expansion ratio relative to the compression ratio, which has several efficiency benefits. The higher expansion ratio increases the work extracted from combustion. It also reduces the risk of knock, allowing a higher compression ratio for increased engine efficiency. This is because some of the compression work takes place outside the cylinder in the turbocharger, where the incoming air goes through an intercooler and enters the cylinder at a lower temperature.

The tradeoff is that the Miller cycle can decrease specific engine power and torque, which must be offset with higher boost pressures and effective intercooling. Miller-cycle engines achieve the greatest benefits when they rely on significant amounts of intake manifold pressure from the boost system, compensating for the shorter compression stroke.

All turbocharger manufacturers are developing Miller-cycle engines. The German engineering consultancy FEV GmbH estimates that the Miller cycle improves geometric compression ratio from 10.0:1 to 12.0:1 and reduces fuel consumption by 3.9%–5.7% compared with a downsized, turbocharged engine with variable valve lift and timing. For its EA211 TSI evo engine family, scheduled to go into production in Europe late in 2016, Volkswagen used the Miller cycle along with a variable-geometry turbocharger and other in-cylinder improvements, and claims that it will see an efficiency improvement of 10%. Audi will also offer vehicles with Miller-cycle engines, starting with the A4 in the 2017 model year. Mazda now offers a 2.5L turbocharged version of its I4 SKYACTIV-G, designed to replace V6 engines in SUVs and other larger vehicle classes. As shown in Figure 3, this engine achieves a 23% reduction in fuel consumption over the naturally aspirated V6 engine Mazda used previously.

Further refinements in advanced valve controls are likely to result in additional improvements in the efficiency and performance of Miller-cycle engines. Because of gains in knock resistance and efficiency provided by the Miller cycle, automakers will probably increase production of downsized, turbocharged, high-compression-ratio engines like VW's and Mazda's.

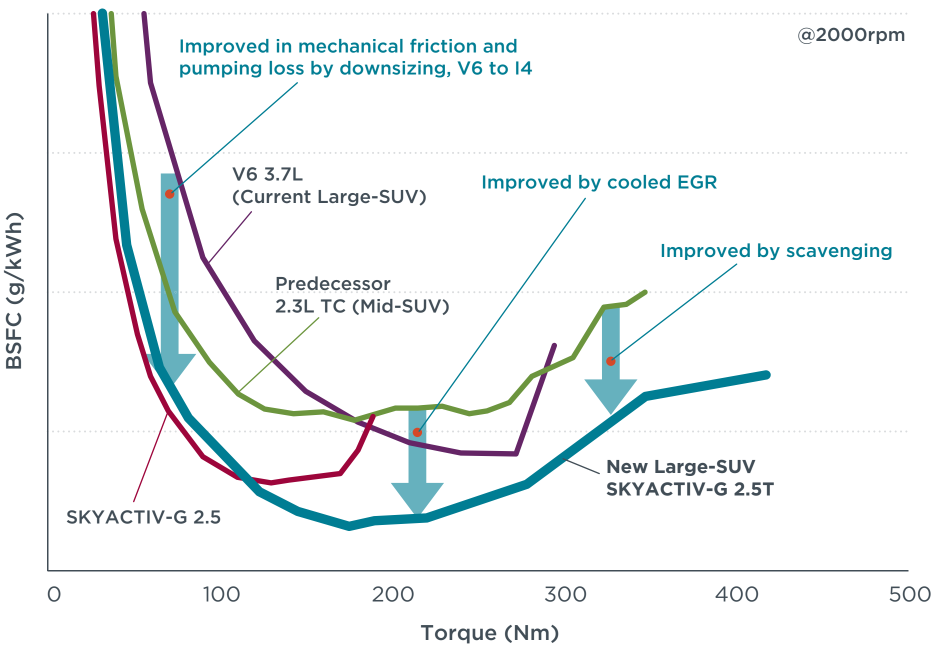

Figure 3. Reduction in fuel consumption of SKYACTIV-G 2.5T. (Source: Ichiro Hirose (2016). *Mazda 2.5L SKYACTIV-G Engine with New Boosting Technology*. Presented at the 37th International Vienna Motor Symposium, 28-29 April 2016.)

E-BOOSTING AND 48-VOLT HYBRID SYSTEMS

Perhaps the most significant development in downsized, turbocharged engines is an explosion in development of 48V e-boosting—i.e., electric supercharging—systems. These systems increase the electrical system voltage to 48 volts from 12, providing power for a small electric compressor motor within or external to the turbocharger. These either directly boost the engine or spin up the turbocharger faster to greatly reduce turbo lag, without losing the benefit of waste-heat recovery. This increases the ability to downsize the engine and also allows the engine to run at lower speeds (down-speeding). E-boost also enables the use of larger turbines with lower backpressure and higher efficiency.

A larger battery delivers the power needed for the e-booster. As with conventional hybrid vehicles, the availability of the additional electrical power from the battery allows automotive engineers to replace mechanical pumps and accessories with more efficient electrical systems, reducing engine losses. By simply adding a small motor/generator, these systems can also capture regenerative braking energy. And the 48V-hybrid design enables more robust start-stop systems, in which the engine is shut off at higher speeds and the 48V-system maintains power to all electronics and electrical devices. Enhanced starter-generators make restarting the engine quick and seamless.

The major turbocharger manufacturers, including BorgWarner, Hitachi, Valeo, and Honeywell, all have e-boost prototypes under consumer evaluation. The first e-boost system is in production on the Audi V8 diesel SQ7. This engine integrates a compressor driven by a 48V electric motor with a more conventional turbocharger system, eliminating the need for a two-stage turbocharger system. Audi has said this V8 will consume about the same amount of fuel in operation as a V6 diesel.

The 48V e-boost systems typically realize at least 60% of the efficiency of deeper hybridization/electrification at only about 40% of the cost. Examples include Ricardo's prototype 1.0L HyBoost engine, which demonstrated dramatically increased torque compared with a baseline 2009 Ford Focus 2.0L, 4-cylinder engine while eliminating turbo lag. Efficiency jumped to 59 mpg from 39 mpg with a 40g–50g reduction in CO_2 on the New European Driving Cycle, which is less stringent than the U.S. certification test cycles. Valeo is working on all types of microhybrid 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% when used with regenerative braking. IDTechEx estimated that mild-hybrid systems could reduce CO_2 emissions by 15%–20%, or half to three-quarters as much as full hybrids; the company projects that volume sales will begin in 2017, and anticipates that manufacturers will sell more than 300 million such vehicles by 2030. AVL estimates that nearly 300,000 mild hybrids will be produced annually in North America in 2020.

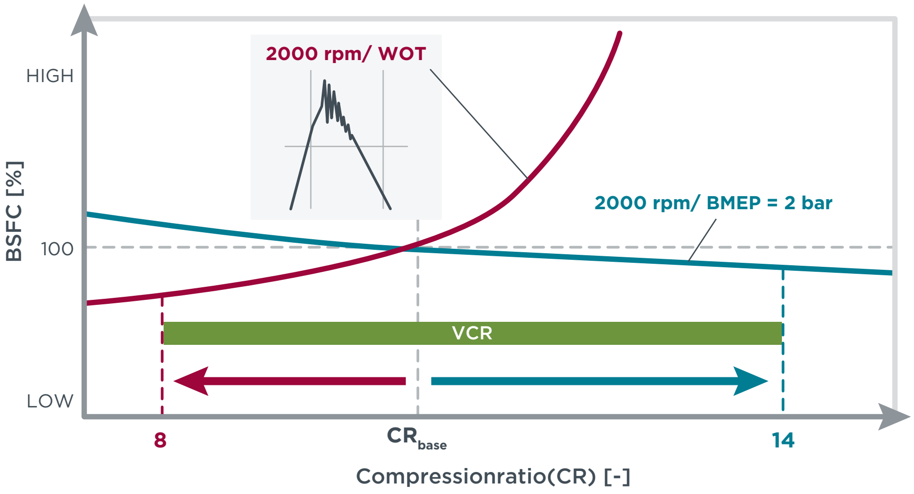

Figure 4. Fuel-consumption dependence on compression ratio under part and full-load operation conditions. (Source: Kleeberg et al. *Two-Stage Variable Compression Ratio (VCR) System to Increase Efficiency in Gasoline Powertrains.* Presented at Automotive World Megatrends USA 2014, 18 March 2014.)

VARIABLE COMPRESSION RATIO

Higher compression ratios improve efficiency, but at high engine loads they increase detonation, which is especially a problem for boosted engines. Variable compression ratio (VCR) allows for a high compression ratio to be used at light loads, when detonation is not a problem, and a low ratio at heavy loads for increased power.

Engineering research into VCR engines dates to the early 1970s, with no production applications. However, yearly patent filings related to VCR technology increased rapidly after 2000, from fewer than 25 filings annually before that year to more than 100 in 2013, signaling an upsurge in VCR research and investment.

The 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 or changing the crankshaft radius, recent innovations have focused on raising/lowering the piston position at top-dead-center (TDC) within a fixed cylinder bore.

FEV is developing a two-step VCR system, which uses an eccentric bearing on the connecting rod. The system uses gas and mass forces to change the compression ratio and hydraulically fix the position of the connecting-rod length-adjusting mechanism. FEV estimates that the cost of a two-step VCR system will be significantly lower than for a fully variable system while still delivering more than 80% of the potential reduction in fuel consumption. The consultancy also estimated that two-step VCR with a low-pressure EGR system would reduce fuel consumption by 4.2% to 6.2% on the U.S. combined cycles. This is mostly due to optimizing compression ratio during part and full loads, as shown in Figure 4.

Nissan/Infiniti plans to introduce the first VCR application in a production turbocharged engine, the I4 VC-T for the 2017 model year—well ahead of the moment when FEV and others had anticipated that technology to go into production. Nissan's engine has been in development for nearly 20 years. Its compression ratio varies continuously between 8.0:1 and 14.0:1 using a crankshaft-mounted linkage that smoothly raises or lowers the piston head via a control rod. Nissan's 2.0L VC-T engine is expected to use VCR as well as Miller cycle to achieve the highest efficiency at any load. The engine achieves a 21% reduction in fuel consumption compared with its 3.5L V6 predecessor.

The benefits of incorporating the use of Miller cycle and VCR into engine designs will likely overlap, as both increase geometric compression ratio. While VCR allows for higher compression ratios than the Miller cycle, it does not offer the efficiency benefits of 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 add boost to maintain low-end torque. VCR may thus be a competitor to Miller cycle concepts in the long run, offering manufacturers more options for improving efficiency while maintaining performance.

CONSUMER DEMAND

Turbocharged engines offer performance benefits that are highly valued by some drivers, in addition to the efficiency improvements. The Ford 3.5L EcoBoost engine offered on the F150 pickup truck dramatically illustrates consumer response to downsized, boosted power plants. In the first model year with the EcoBoost option (2011), Ford originally projected that 20% of customers would pay the additional $595 for the smaller 3.5L EcoBoost engine over the standard 5.0L V8. In reality, 45% of F150 customers did so, and sales of the optional EcoBoost V6 were higher than of the standard 5.0L V8.[2] Certainly consumers valued the greater fuel efficiency of the smaller engine, but what most buyers sought was the higher torque at low rpm and higher towing capacity.

The upside is that the performance benefits make consumers more accepting of the technology. The downside is that if customers routinely use the additional power from the turbocharger to accelerate faster, real-world efficiency gains might not be as great as if their driving habits were to remain unchanged.

Recent findings from researchers at the University of Tennessee suggest that in actual, everyday driving, gasoline turbocharged vehicles fall short of their fuel economy label values by only 1.7% more than naturally aspirated vehicles, or roughly 0.4 mpg for the average vehicle. The researchers compared in-use fuel economy reported by consumers on fueleconomy.gov with the fuel economy values on the vehicles' Monroney stickers, the window labels giving various vehicle specifications and ratings that all new vehicles are required to display. The slightly higher shortfalls reported for turbocharged vehicles were primarily attributable to turbocharged pickup trucks, whose drivers reported missing the mileage ratings by 6% more than owners of naturally aspirated pickups. That data subset was particularly small, only 67 vehicles. The 542 turbocharged SUVs did not fall short more than naturally aspirated SUVs. The total number of vehicles in the study was also relatively small, making it difficult to derive valid statistical results. Still, the findings suggest that while turbocharged engines may consume slightly more fuel in real-world driving than naturally aspirated engines, the effect is likely below half of a mile per gallon—too small for most customers to notice.

IMPLICATIONS FOR THE MIDTERM EVALUATION

Auto-industry component suppliers agree that engine downsizing is one of the most important pathways to improving the fuel efficiency of future vehicles. For example, BorgWarner estimates that, thanks to boosting, by 2019–2020 3-cylinder engines will sell at more than twice the rate of today; 4-cylinder engines will expand their market share by 13 percentage points; and 6-cylinder and 8-cylinder engines will lose share. Honeywell and BorgWarner both project that the market share for turbocharged engines will reach about 40% by 2020.

However, these projections fall short of the estimates in the government's 2017–2025 rulemaking, which projected that turbocharged engines would account for 64% of sales in 2021. In part, the differential likely reflects improvements in naturally aspirated engines that were not anticipated in the 2017–2025 rulemaking.[3] Toyota, Hyundai, Mazda, and Subaru appear committed to improved naturally aspirated engines for a substantial portion of their fleet, at least in the near term.

On the other hand, significant technical developments in turbocharged gasoline engines not evaluated for the rulemaking are already being implemented in the fleet, which will significantly improve efficiency over the agencies' projections. Most important of these are Miller-cycle engine designs, 48V e-boost systems, and variable compression ratio. In addition, for the technologies considered in the rulemaking, supplier estimates of costs are lower and their estimates of fuel-efficiency benefits are higher. See Figure 1, above, for a graphical comparison of turbocharger-related cost-benefit estimates by the EPA and NHTSA for the 2017–2025 ruling to only one of several possible new-vehicle-design pathways deploying new technologies—Miller cycle, variable-geometry turbochargers, e-boost, and 48V systems—that the agencies did not anticipate at all.

In short, although turbocharging is not penetrating the fleet as rapidly as predicted in the rulemaking, in the less than five years since the rulemaking technology assessments the U.S. vehicle market has already seen turbocharging and related technologies that were unanticipated in the rulemaking go into production, on top of significant cost reductions in efficiency improvements from technologies that were evaluated for the rule. Bottom line: Advances in boosted, downsized engines show every indication of exceeding projections and enabling significant reductions in fuel consumption and carbon emissions.

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[2] The 5.0L V8 engine had a sales rate of about 40%. A naturally aspirated 3.7L engine was standard on some base models (sold mostly to commercial fleets), and there was a 6.2L V8 option. These two engines account for the balance of F150 sales, or about 15%.

[3] For details on the agencies' pessimistic projections for naturally aspirated engines, contrasted with actual trends and technology developments indicating that those engines will be an important part of the fleet mix through 2025, see 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