WORKING PAPER 2017-08

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

Diesel Engines

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Date: 10 July 2017
Keywords: Passenger vehicles, diesel, advanced technologies, fuel-efficiency, technology innovation

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 fuel economy 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 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.[2] 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 about five years ago.[3] 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 (costs, benefits, market penetration) compares with projections in the rule;
- Recent technology developments that were not considered in the rule and how they impact costs and benefits;
- Customer-acceptance issues, such as real-world fuel economy, performance, drivability, reliability, and safety.

This paper provides an analysis of advanced diesel engine technology developments and trends. It is a collaboration between ICCT and automotive parts suppliers. The paper relies on data from publicly available sources, as well as data and information from the participating automotive suppliers.

Background

DIESEL ENGINE TECHNOLOGY AND EFFICIENCY

Diesel engines possess a number of efficiency advantages over gasoline engines. These grow out of significant differences in how diesels operate. The diesel engine does not use a throttle to control airflow into the engine or a spark plug to start ignition of the fuel as do gasoline engines. Instead, load is controlled by the amount of fuel injected. The timing of fuel injection controls combustion timing, as the fuel ignites almost immediately after being injected into the hot compressed gas within the cylinder.

As a result, diesels eliminate the significant pumping losses that come from forcing air past the throttle in gasoline engines. The heterogeneous combustion process of a diesel also allows much leaner air/fuel ratios than with pre-mixed gasoline combustion. These lean air/fuel ratios reduce

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[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] The air conditioning credits are roughly 20.6 g/mi in 2025. There are also off-cycle credits, estimated at roughly 8.1 g/mile in 2025, that would slightly reduce the required tailpipe CO_2 and fuel consumption reductions.

[3] 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

Acknowledgements: Thanks to Dave Lancaster of BorgWarner, Pierre-Jean Cançalon of Honeywell, and Sean Osborne of The ITB Group for their input and reviews.

average in-cylinder temperatures and improve thermal efficiency by reducing heat losses to the cooling system and exhaust. In addition, the diesel engine is not subject to the knock constraints of a homogeneous-charge engine and can operate with much higher compression ratios for increased efficiency.

An indirect advantage of diesel engines is that the higher density of diesel fuel results in about 14% more energy per gallon than gasoline. This means that diesel vehicles will go 14% farther on a gallon simply because of the higher energy content. On the other hand, diesel fuel also has 14% more carbon per gallon, so this advantage does not apply to CO_2 emissions.

For all that, diesel engines historically have had limited consumer appeal for passenger vehicles in the United States. Diesels used to be hard to start, noisy, and smelly, and they did not provide as much horsepower. General Motors also damaged the reputation of diesels in the late 1970s by rushing out an extremely unreliable product in response to the fuel crises in the 1970s. GM converted a gasoline V8 to a pre-chamber naturally-aspirated diesel—a marketing disaster.

Technology improvements such as direct fuel injection, higher fuel line pressure, and turbocharging have since almost fully addressed the performance and reliability issues, though diesels can still chatter a bit after startup and at idle. These advances, together with fuel-tax policies encouraging diesel use, have enabled such engines to capture large passenger vehicle market shares in Europe and India.

The remaining challenges for diesels are primarily cost and emissions control. Diesel engines inherently cost more to manufacture than gasoline engines because of the need for increased structure to contain higher combustion pressures and because of their more sophisticated and higher-pressure fuel injection systems. It is also more expensive and more difficult to control particulate and nitrogen oxide (NO_x) emissions from diesel engines, because of their lean, heterogeneous combustion process.

In gasoline engines, vaporized fuel is mixed with air before a spark sends a flame through the mixture. As a result, the fuel is completely burned except for quench layers at the chamber walls and in crevices. The fuel in diesel engines ignites shortly after being injected, and droplets of fuel do not have time to fully evaporate and mix with air before combustion. As a result, diesel combustion is characterized by diffusion burning in which oxygen cannot fully penetrate the burning flame front surrounding the fuel droplets, resulting in an unburned carbon core. As the gas cools during passage through the exhaust, carbon particles adsorb uncombusted and partially combusted products, forming particulates. Modern particulate traps are effective in controlling the release of particulate emissions, but they are not cheap.

A common misconception is that diesel engines produce a lot of NO_x. Engine-out NO_x emissions from diesel engines are lower than from gasoline engines under some conditions, as NO_x formation is proportional to combustion temperature. Diesels have much lower bulk combustion temperatures than gasoline engines, although temperatures around the fuel droplets are higher. The problem is that reducing NO_x emissions requires splitting NO_x into nitrogen and oxygen. This process will not proceed if there is excess oxygen in the exhaust. Gasoline engines run at stoichiometric with extremely precise air/fuel control that allows three-way catalysts to reduce NO_x at greater than 99% efficiency. However, as diesels run unthrottled, there is always excess oxygen in the exhaust, and the three-way catalyst does not work. The solution for diesel engines is some combination of engine-out NO_x control through exhaust gas recirculation (EGR) and injection retard, plus exhaust after-treatment using lean-NO_x traps (LNT) or selective catalytic reduction (SCR) using urea injection. However, these systems are expensive; engine-out NO_x control and LNT systems increase fuel consumption; and SCR systems require periodic refilling of a urea tank.

MARKET PENETRATION TRENDS

According to the EPA's fuel economy trends report[4], diesel accounts for a very small portion of the U.S. passenger vehicle market. As shown in Table 1, diesel penetration of cars and light-duty trucks (large SUVs,

Table 1: U.S. diesel market penetration trends (passenger vehicles, including light trucks)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Diesel Share	0.1%	0.3%	0.4%	0.1%	0.1%	0.5%	0.7%	0.8%	0.9%	0.9%	1.0%	0.9%

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[4] 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

vans and minivans, pickups) increased 10-fold from 2004 to 2014, but still accounts for just 1% of the market. The share of diesel engines among cars and trucks does not vary greatly from the combined values.

In Europe, diesel engines have captured about half of the passenger car market and the large majority of the light commercial market. This is primarily because much higher fuel taxes overall and relatively lower taxes on diesel fuel in Europe encourage consumers to choose more diesel vehicles.

HISTORICAL ESTIMATES OF COSTS AND BENEFITS

The National Academy of Sciences determined in a 2002 report[5] that it would be a challenge to create emission control systems for NO_x and particulate matter that could be certifiable for a 120,000-mile vehicle lifetime. At the same time, the academy estimated that a diesel engine with direct injection, a high-pressure common rail, and a variable geometry turbocharger could achieve a 30-40% reduction in fuel consumption compared with a two-valve per cylinder gasoline engine.

In its 2008-2011 rulemaking,[6] NHTSA estimated that combustion improvements (high-pressure injectors and EGR) along with improved aftertreatment (LNTs, injectable urea) would result in a 15-30% reduction in fuel consumption compared with a conventional gasoline engine, at a cost of $1,000-$5,000. The lower amount of fuel consumption improvement is due to comparing the diesel against a more efficient gasoline engine baseline.

The EPA and NHTSA make two main assumptions on why manufacturers might hesitate to increase production of diesel vehicles. The first is that, although expanded diesel penetration could help them meet fuel economy standards, manufacturers are likely to determine that other technologies are more cost-effective for reducing greenhouse gas emissions. Secondly, manufacturers may find it difficult to comply with NO_x emissions limits without reducing the fuel economy benefits of diesels or dramatically increasing vehicle cost.

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

As shown in Table 2, the agencies predict close to 0% market penetration of diesel by 2021 and continuing into 2025, although this varies by manufacturer. For example, Mercedes is predicted to have 2% diesel market penetration in 2025. To generate these projections, the agencies assumed that manufacturers would initially concentrate on improving gasoline engines. Once all the more cost-effective technologies were implemented, manufacturers would turn to alternative fuel/powertrains, including diesel, the agencies assumed.

However, the agencies recognized that a number of manufacturers offer diesel vehicles, indicating that these manufacturers envision diesel as a viable option for meeting tighter standards. In the absence of standards, the agencies' baseline projections include a 2% market share for diesel engines in 2025. Furthermore, several diesel technology developments were examined in the 2017-2025 rulemaking. These include improved fuel injection systems (higher pressure, better fuel atomization, and multiple injection events), advanced controls/sensors for combustion and emissions optimization, advanced turbocharging, and expanded use of cooled EGR, which helps control NO_x with less impact on fuel consumption.

For emissions control, the agencies assumed that all diesel vehicles would require a catalyzed diesel particulate filter, sometimes paired with a diesel oxidation catalyst and a selective catalytic reduction system (SCR)—usually a base-metal zeolite urea-SCR. It is unlikely that lean NO_x traps

Table 2: EPA/NHTSA rulemaking estimated future diesel market penetration, incremental direct manufacturing cost (DMC), and fuel consumption reduction

	2021 Market Penetration	2025 Market Penetration	2025 aftertreatment incremental DMC	2025 engine incremental DMC*	Fuel consumption reduction**
Small car	0%	0%	$1,134	$618	19.7%
Standard car	0%	0%	$1,311	$441	21.5%
Large car	0%	0%	$1,321	$824	22.3%
Small MPV^	0%	0%	$1,315	$441	19.3%
Large MPV	0%	0%	$1,331	$441	21.7%
Large Truck	0%	0%	$1,577	$878	20.7%

** 2025 engine incremental DMC is derived from engine incremental DMC in 2012-16 rulemaking and 2017-25 rulemaking total DMC incremental to a comparable gasoline engine; costs in 2010 dollars.*
*** Compared with baseline gasoline vehicle with equivalent performance.*
^ MPV: multi-purpose vehicle

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[5] 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.

[6] U.S. NHTSA, "Light Truck Fuel Economy Standard Rulemaking, MY 2008–2011" (2006). http://www.nhtsa.gov/fuel-economy

(LNTs) alone can achieve the required emissions reductions without a significant fuel consumption penalty, as fuel is used to regenerate the catalyst, and LNTs are not as durable as SCR systems. LNTs may be paired with SCRs or eliminated entirely in favor of SCRs, as assumed in the rulemaking. It is the incremental cost of these emission control systems, particularly for smaller car segments, that the agencies perceive as a hindrance to wider adoption of passenger diesels.

Table 2 shows the aftertreatment (SCR + diesel particulate filter + diesel oxidation catalyst) and engine-related direct manufacturing cost (DMC). The agencies sought to determine diesel costs by comparing gasoline and diesel vehicles of equivalent performance. The agencies assumed that

- a 2.4L I4 gasoline engine would be replaced by a 2.0L I4 diesel,
- a 3.2L V6 gasoline engine would be replaced by a 2.8L I4 diesel,
- a 4.5L V8 gasoline engine would be replaced by a 3.0L V6 diesel, and
- a 5.6L V8 gasoline engine would be replaced by a 4.0L V6 diesel.

All classes used SCR systems. The cost of diesel conversion included the cost of the engine and the associated incremental costs for aftertreatment.

It was also assumed that manufacturers would meet Tier 2, Bin 2 pollutant emissions level criteria on average in anticipation of more-stringent future regulations. To meet this standard, the agencies estimated a 20% increase in catalyst volume over Tier 2, Bin 5 emissions level, a slightly increased price of platinum group metals (PGM), and an additional blanket $50 of DMC to account for upgraded urea and fuel controls.

Because the 2017-2025 joint technical support document (TSD)[7] did not separate aftertreatment and engine-related costs, the separated costs given in the MY2012-2016 joint TSD[8] formed the basis for deriving the two separate 2025 DMCs shown in the two DMC columns in Table 2.[9]

For all but two vehicle classes, the total DMC for switching to diesel falls below $2,000 as early as MY2019 and is well under $2,000 in 2025.[10] PGM costs represent 16-23% of the combined diesel DMC. However, the February 2011 prices used in the TSD were some of the highest historically: $1,829/troy ounce for platinum and $2,476/troy ounce for rhodium. By comparison, in December 2016, platinum averaged around $930/troy ounce and rhodium, $785/troy ounce.[11] Although the specific catalyst formulations and amounts assumed by the agencies are not known, these PGM price reductions could result in an 8-15% reduction in emission control system cost, or $150 to $400. Future aftertreatment systems will reduce the effects of PGM price volatility on system cost, as we will show.

Status of current production and future developments versus agency projections

Many of the developments in diesel engines are similar to those being incorporated into gasoline engines.[12]

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[7] 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

[8] U.S. EPA & NHTSA, "Joint Technical Support Document: Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards" (2010). https://nepis.epa.gov/Exe/ZyPDF.cgi/P1006W9S.PDF?Dockey=P1006W9S.PDF. Pp. 3-37 through 3-45.

[9] First, the total MY2012 DMC was estimated from that of MY2017 given in the 2017-2025 joint TSD, based on a flat learning curve assumed by the agencies (3% per year reduction in DMC for the first five years). This back-calculated MY2012 total DMC includes the increased cost of PGM, reflecting volume increases and PGM prices from Feb 2011, as the agencies assumed. The engine-related costs, applying no additional assumptions, were extracted directly from the 2012-2016 joint TSD. Presented in 2007 dollars, these costs were $813 for small cars, $1,085 for large cars, $580 for medium/large MPV, $580 for small trucks, and $1,156 for large trucks. After adjusting to 2010 dollars, these engine costs were subtracted from the calculated 2012 DMC to reveal the aftertreatment costs in MY2012, as modified by the agency assumptions. Finally, aftertreatment and engine DMC in 2025 were calculated from their corresponding 2012 values using flat manufacturer learning as assumed by the agencies (3% in the first 5 years, 2% afterwards). This assumes no major changes in PGM prices through 2025.

[10] It is unlikely that the VW diesel emission scandal will significantly affect these costs. As shown in Table 1, diesel vehicles represent a very small fraction of new vehicle sales of in the U.S. Diesel engine and aftertreatment development is primarily driven by the 7 million-plus diesels sold every year in Europe. Diesel sales in Europe may decline in the future because of the scandal and revisions in fuel taxes, but they will still most likely be well above 5 million per year. Thus, the 2025 estimated DMC probably would not change. For a more detailed analysis of the effect of the VW scandal on German diesel sales in particular, see: Uwe Tietge, "Diesels dip, electric vehicles rise in Germany," ICCT, December 9, 2016, http://www.theicct.org/blogs/staff/diesels-dip-electric-vehicles-rise-in-germany

[11] Johnson Matthey. (2016). *Price Charts* [PGM historical price data]. Retrieved from http://www.platinum.matthey.com/prices/price-charts

[12] 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

Examples include advanced friction reduction, higher turbocharger pressures, improved variable geometry turbochargers, downsizing and downspeeding, better thermal management,[13] greater use of high- and low-pressure EGR, higher-pressure injection systems capable of multiple injections, and e-boosting with 48-volt mild hybridization.

CURRENT PRODUCTION COSTS AND BENEFITS

Because of the cost and complexity of currently available aftertreatment systems and future requirements for pollutant reductions, diesel engines may be best suited for larger vehicle types. In the bigger vehicle classes, the costs and fuel economy benefits of diesels over conventional gasoline power plants are comparable to or better than those of strong hybrids.[14] For example, the MY2016 pickups and the five non-hybrid 4wd SUVs with the highest fuel economy were all diesels.[15]

Demand and production of diesels in the larger vehicle segments is increasing. For example, sales of EcoDiesel engines on Fiat Chrysler Automobiles' Ram 1500 pickup and Jeep Grand Cherokee SUV have surged over the past few years.[16] As a result, FCA is expanding production of those engines.[17] These vehicles are fuel economy leaders in their respective classes, earning compliance credits for the future, and the manufacturer plans for the next generation four-door Wrangler diesel to nearly meet 2022 fuel economy standards.[18] Diesels in these segments benefit not just from better fuel economy over gasoline engines but also increased towing capacity and better low-speed performance.[19]

While diesels are not as cost-competitive in small vehicles, buyers of smaller autos are generally more concerned about fuel economy.[20] This is reflected in Chevrolet's efforts to boost sales of the Cruze by offering an optional diesel engine in 2017.[21] Mazda, too, plans to offer its SKYACTIV-D engine on the new CX-5 in the second half of 2017.[22] (As of this writing, fuel economy data for the SKYACTIV-D engine is not yet available.) Mazda reduced the cost of the aftertreatment system by designing the engine to operate with a much lower compression ratio than most diesels.[23] The reduced pressures lower the operating temperature. Combustion takes longer, which improves air-fuel mixing. The lower temperatures and better mixing reduce the formation of NO_x. The weight of many parts of the engine was reduced, which also led to reduced friction, on a par with some gasoline engines. As with many modern, light-duty diesel engines, the SKYACTIV-D uses piezoelectric injectors to more precisely control timing and location of fuel injection than traditional electromagnetic injectors. Unlike some OEMs, Mazda uses a two-stage turbocharger. The better injectors, two-stage turbo, and improved variable valve lift enable the low-compression ratio diesel engine to operate cleanly even upon cold start.

Whatever the vehicle class, diesel engines must contend with NO_x and particulate matter aftertreatment. In interviews with suppliers, the Martec Group found that PGM price reductions and technology improvements have led to significantly reduced costs for today's aftertreatment systems.[24] For instance, in 2008 the cost of a 2015 emission control system for a 4-cylinder engine was estimated at

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[13] Sean Osborne, Dr. Joel Kopinsky, Sarah Norton, Andy Sutherland, David Lancaster, Erika Nielsen, Aaron Isenstadt, John German, *Automotive Thermal Management Technology* (ICCT: Washington DC, 2016). http://www.theicct.org/automotive-thermal-management-technology

[14] As noted previously, diesel fuel has 14.5% higher density per gallon than gasoline. For CO_2 emissions, where diesels do not gain this benefit, hybrids generally have lower CO_2 emissions than diesels.

[15] EPA. (2016). *Download Fuel Economy Data* [datasets for individual model years]. Retrieved from http://fueleconomy.gov/feg/download.shtml

[16] In January 2017, the EPA issued a notice of violation to FCA for failing to disclose eight software algorithms that revise emission control calibrations on MY2014-2016 Dodge Ram 1500 3.0L diesel and Jeep Grand Cherokee 3.0L diesel (see https://www.epa.gov/fca). The results of the investigation may affect future sales.

[17] Larry P. Vellequette, "Chrysler seeks more diesels," *Automotive News*, July 7, 2014, http://www.autonews.com/article/20140707/OEM01/307079960/chrysler-seeks-more-diesels

[18] Fiat Chrysler Automobiles. (2016). *Business Plan Update 2014-2018*. Retrieved from https://www.fcagroup.com/en-US/investor_relations/events_presentations/quarterly_results_presentations/FCA_2014_18__Business_Plan_Update.pdf

[19] The Martec Group. (2016). *Diesel Engine Technology: An Analysis of Compliance Costs and Benefits* [White Paper]. Retrieved from http://www.martecgroup.com/diesel-engine-technology-an-analysis-of-compliance-costs-and-benefits-white-paper/

[20] John German, *Vehicle Technology and Consumers*. Presented at Focus on the Future Automotive Research Conferences, slide 13, November 10, 2008

[21] Mike Colias, "Chasing Jetta, Chevy equips Cruze with a new turbodiesel," *Automotive News*, June 29, 2015, http://www.autonews.com/article/20150629/OEM04/306299984/chasing-jetta-chevy-equips-cruze-with-a-new-turbodiesel

[22] Hans Greimel, "Mazda solves its diesel dilemma," *Automotive News*, November 21, 2016, http://www.autonews.com/article/20161121/OEM06/311219928/mazda-solves-its-diesel-dilemma

[23] Mazda. "SKYACTIV-D". *SKYACTIV Technology*. 2017. http://www.mazda.com/en/innovation/technology/skyactiv/skyactiv-d/

[24] The Martec Group. (2016). *Diesel Engine Technology: An Analysis of Compliance Costs and Benefits* [White Paper]. Retrieved from http://www.martecgroup.com/diesel-engine-technology-an-analysis-of-compliance-costs-and-benefits-white-paper/

$980. In 2016, the system actually cost just $550 and was projected to rise to only $620 in 2025 while complying with stricter emissions standards.

Martec calculated in 2015 that a 2025-compliant 4-cylinder diesel would cost an additional $1,828 compared with a port-fuel injected gasoline V6. In their 2017-2025 Joint TSD, the government agencies found that the same advanced diesel would cost $2,059 more (or $1,752 more in 2025, as shown in Table 2). Similarly, a 2025-compliant V6 diesel would cost $2,246 more than its V8 gasoline counterpart according to Martec. That would be $276 less than the agencies' estimate.

In a report commissioned for the ICCT, FEV estimated that improved EGR systems for smaller vehicle segments would cost between $40 and $50.[25] In larger segments, adding EGR cooling across all pressure ranges would cost $109-$122. These costs cover upgrading the EGR system to include cooling at both high and low pressures, which enhances NO_x emissions control by lowering in-cylinder temperatures and reduces the fuel consumption tradeoff.

FEV also estimated that downsizing the engine would create savings for all vehicle segments. However, as expected, diesel engines with reduced displacement but not reduced number of cylinders realized savings of only $17-$24. Reducing the number of cylinders leads to savings of $149-$274.

Significantly, FEV found that a baseline diesel engine with a 2025-compliant aftertreatment system would cost $1,000 to $1,900 more than a comparable gasoline engine. This takes into account the downsizing and cylinder-count reduction of the diesel engine and other modifications.

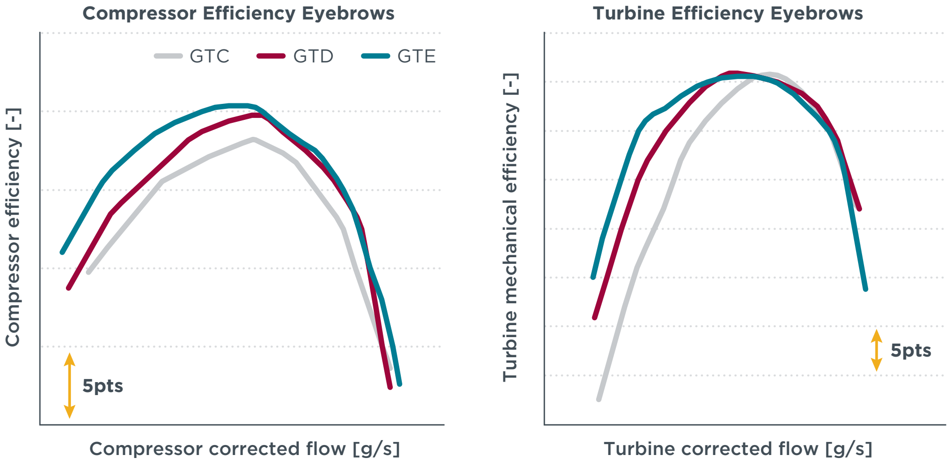

Figure 1: Evolution of VNT efficiency. Note that the higher the curve, the greater the efficiency. At greater flow speeds—the right side of each graph—newer turbochargers show efficiency similar to older generations. The biggest improvements appear at lower speeds—the left half each graph. Here, the eyebrows of newer turbochargers are significantly higher than prior generations, indicating improved efficiency. (Source: Honeywell correspondence, Feb 16, 2016)

Most diesels in North America use variable nozzle turbines (VNTs), or variable geometry turbochargers.[26] As shown in Figure 1, the development of VNTs by Honeywell shows continuously increased efficiency of the turbocharger.[27] Successive generations show improved efficiency on both the compressor side of the turbocharger, as well as on the turbine side. This improvement is particularly noticeable at lower speeds, where Figure 1 shows the blue eyebrows at higher efficiency than both the red and gray eyebrows of earlier generations.

For every sequential generation of improved VNT (from GTC to GTD to GTE), the range of operation grows. The result is increased low-end torque or an increase in rated power at reduced low-end speed. Improved performance makes room for engine downspeeding and downsizing, which improves fuel efficiency. As an example, the turbo improvements shown in Figure 2 going from Honeywell's GTC VNT to its successor GTD result in as much as a 6% reduction in brake-specific fuel consumption at low rpm.[28]

Newer VNT generations show additional reductions in fuel consumption with maximum declines of 2%, plus a torque increase of 20Nm

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[25] FEV. (2015). *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. September 2015. Report commissioned by ICCT. Retrieved from http://www.theicct.org/2025-passenger-car-and-light-commercial-vehicle-powertrain-technology-analysis

[26] Correspondence with Honeywell, February 16, 2016.

[27] P. Davies, D. Jeckel, G. Agnew, G. Figura, P. Barthelet. (2015). *25 Years of VNT™ Technology – Past, Present & Future*. Presented by Honeywell at 20th ATK, Dresden, Germany, September 2015.

[28] P. Barthelet, N. Morand, B. Chammas, L. Toussaint, L. Sausse, C. Rivière, E. Bouvier. (2013). *The New Family of VNT™ Turbocharger Developed by Honeywell Turbo Technologies for Eu6 and Beyond.* Presented at the Dresden Supercharging Conference 2013, 12 September 2013. Retrieved from https://turbo.honeywell.com/whats-new-in-turbo/story/honeywell-at-dresden-supercharging-conference-2013/

M. Pannwitz, T. Tietze, J. Kabitzke, P. Barthelet, D. Jeckel. (2011). *Upgrading Diesel TurbochargingSystem to Fulfill CO_2 and Euro 6 Requirements*. Presented by IAV GmbH and Honeywell at IQPC in Wiesbaden, March 11, 2011.

and nearly a 1-second decrease in time-to-torque at 1,000 rpm.

The newest turbochargers designed for 3- and 4-cylinder diesel engines are optimized to handle the higher loads generated by these smaller engines. Because of present and future fuel consumption and greenhouse gas standards, turbocharger improvements are necessary for compliance using downsized engines. Downsized diesels have the benefit of already being more fuel efficient than gasoline engines.

Suppliers including Honeywell and BorgWarner are reducing the friction of the bearings within turbochargers by replacing hydrodynamic bearings with ball bearings.[29] Ball bearings generate as much as a 20% improvement in torque, a 5% increase in power, 50% better transient response, and significantly better cold-start performance as a result of lower oil friction.[30]

IMPROVEMENTS IN DEVELOPMENT

Aftertreatment and emissions control

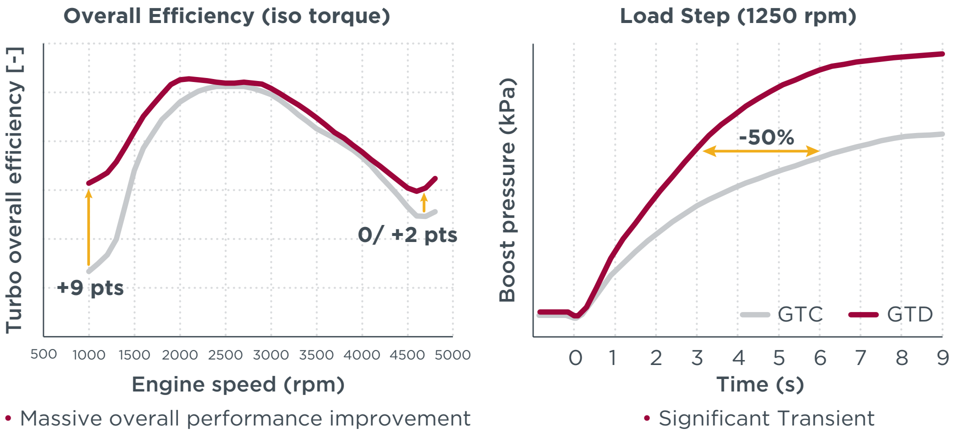

Figure 2: Improvement of Honeywell VNT from generation GTC to GTD (Source: Barthelet et al. (2013). *The New Family of VNT™ Turbocharger Developed by Honeywell Turbo Technologies for Eu6 and Beyond*. Presented at the Dresden Supercharging Conference 2013, 12 September 2013.)

Future aftertreatment systems for compliance with Tier 3 emissions standards are expected to cost less than $100 compared with today's Tier 2 systems, albeit requiring a higher-pressure injection system.[31] Because NO_x emissions are highest at cold start and SCR catalysts need time to warm up, suppliers are developing methods of warming up the catalyst faster and catalyzing or storing NO_x at cold start to hasten NO_x conversion and limit NO_x emissions.[32] Many systems are capable of NO_x conversion over a wide temperature range at rates close to those of three-way catalytic converters on gasoline vehicles. Examples of aftertreatment devices that can be configured to reduce cold-start and operating diesel emissions include NO_x storage catalysts, SCR-on-filter catalysts, and ammonia slip catalysts. Suppliers and manufacturers are experimenting with combinations to create durable aftertreatment systems that are cheaper and more compact.

Cummins developed a demonstration diesel engine for the 2010 Nissan half-ton 2wd Titan pickup that meets MY2015 CAFE targets and Tier 2, Bin 2 emissions requirements. Designers applied engine and aftertreatment improvements.[33] Compared with the gasoline version, the diesel truck achieved 29.8 mpg, a 37% reduction in fuel consumption with a 28% drop in CO_2 emissions. The engine used emission controls without a noticeable fuel economy penalty. High- and low-pressure EGR loops reduced engine-out NO_x and assisted the NO_x storage and SCR systems to dramatically reduce tailpipe-out NO_x to regulatory levels. Although the engine-vehicle integration increased cost somewhat, the biggest cost contributor was the emission control system, at nearly four times the cost of the baseline system.

At low loads, cylinder deactivation increases the load on the active cylinders, thereby increasing the exhaust temperature more than if all cylinders were used at low loads. This increased temperature can be used on diesel engines to help warm up the aftertreatment system to the

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[29] Marsal, D., Davies, P., Jeckel, D., Tietze, T., Lautrich, G., Sommer, A. (2008). *A new Turbocharger Bearing System as a further step to improve the overall TC Efficiency*. Presented at Aufladetechnische Konferenz 2008, October 2008. Retrieved from https://turbo.honeywell.com/whats-new-in-turbo/technical-papers/page/2/

[30] Peter Davies, Damien Marsal, Regis Michel, Paul de Montfalcon. (2013). *Ball Bearing goes Mainstream*. Presented at IQPC, Wiesbaden, Germany, March 18, 2013.

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[33] Michael J. Ruth, Cummins, Inc. (2015). *ATP-LD; Cummins Next Generation Tier 2 Bin 2 Diesel Engine* [Project ID: ACE061]. Presented at the 2015 DOE Annual Merit Review, Washington, DC, 12 June 2015. Retrieved from https://energy.gov/eere/vehicles/vehicle-technologies-office-annual-merit-review-presentations

point at which it is most efficient.[34] Deactivation also has fuel savings of as much as 25%, but this is only under low-load operation.

As previously discussed, the late injection of fuel in a diesel engine causes high particulate emissions. To meet stringent particulate standards, diesel particulate filters have been universally installed. As these filters slowly fill up, they must be regenerated at high temperatures to burn off the carbon residue, which results in some CO_2 emissions. This process can take as long as 20 minutes and can lead to greater fuel consumption and elevated NO_x emissions. The high temperatures require heat-resistant SCR systems or increased packaging to move the after-treatment further away. Just as NO_x conversion catalysts are improving, so too are diesel particulate filters. One potential alternative is non-thermal filter regeneration. This method uses backpressure—flowing gases backward through the filter. This form of regeneration does not require high temperatures, eliminating the need for temperature-resistant catalysts and extended packaging. This process also takes seconds rather than minutes, which could lead to fuel savings. However, collection of the blown-back soot requires some additional space for a container to store the captured soot.[35]

E-boost and 48V hybrid systems

As with gasoline downsized and turbocharged engines, downsized diesel engines will soon benefit from e-boosting and 48V mild hybridization.[36] E-boost systems, comprising an electric supercharger or an electric motor integrated into a turbocharger, use the 48V electrical system to directly boost the engine, or to spin up the turbocharger and greatly reduce turbo lag. E-boosting systems also enable the use of larger turbines with lower backpressure. Better boosting and reduced lag permit further engine downsizing and downspeeding. Taken with reduced backpressure, these engine modifications reduce brake-specific fuel consumption.[37]

The 48V electrical system has further benefits if a larger battery is added. It captures regenerative braking energy that can be used to power the e-booster or for propulsion, permits accessory operation with the engine off, enables more-robust start-stop systems, and can shift the burden of powering certain accessories to the electrical system, reducing engine accessory losses. Cooling fans, HVAC blowers, electric heaters, and other accessories will most likely be among the first to be powered by the 48V system. Electric pumps may be introduced later because they cost more than mechanical pumps.

Automakers and suppliers have reported these developments:

- Bosch's electric boosting system helps break the traditional trade-off between NO_x and CO_2 emissions, according to an early 2015 announcement.[38] The "boost recuperation system" reduces CO_2 emissions by 7% (on the New European Drive Cycle, or NEDC) and engine-out NO_x by 10-20% on diesel engines. The 48V electrical system would also help increase efficiency and decrease parasitic losses of the selective catalytic reduction systems. More recent reports from Bosch indicate that the system will be ready for production in 2017 and will decrease fuel consumption even more, by as much as 15%.[39]
- Ricardo's "ADEPT" concept for diesel vehicles parallels the developments of its gasoline HyBoost concept.[40] It uses a higher-power 12.5kW belt-drive starter-generator from SpeedStart, with further energy recovery from the exhaust using Controlled Power Technologies' 48V turbine integrated exhaust gas energy recovery system, known as TIGERS. An advanced lead-carbon battery is used to store recovered energy from braking regeneration and exhaust. The battery is easily recyclable and costs significantly less than a Li-ion battery, albeit at lower energy density. The system was fitted to a Ford Focus with the 1.5TDCi ECOnetic diesel and achieved CO_2 emission levels as low as 80g/km on the NEDC, a greater than 10% reduction in fuel consumption over the baseline vehicle. Ricardo states that the

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[34] Dr. James McCarthy, Jr. (2016). *Driving Automotive Innovation—Cylinder Deactivation*. Presented at the ICCT conference, "Driving Automotive Innovation," September 13, 2016. Retrieved from http://www.theicct.org/events/driving-automotive-innovation

[35] Bailey, B., "Non-Thermal Active Particulate Filter Regeneration for Global Particulate Matter Reduction while Enabling High Sulfur Tolerant Low Temperature Urban Effective SCR Solutions," SAE Technical Paper 2015-01-0990, 2015, doi:10.4271/2015- 01-0990.

[36] 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

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

[38] Jack Peckham, "Novel Electric Boost Can Slash Diesel NO_x, Cut CO_2: Bosch," Downstream Business, May 13, 2015, http://www.downstreambusiness.com/novel-electric-boost-can-slash-diesel-nox-cut-co2-bosch-559016

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[40] "ADEPT," Ricardo, 2016, accessed June 2016, http://www.ricardo.com/en-GB/What-we-do/Technical-Consulting/Research--Technology/adept/ Ricardo. (2016). Advanced ADEPT 48V affordable hybrid on path to meet future ultra-low vehicle emissions, 29 June 2016, retrieved from http://www.ricardo.com/en-GB/News--Media/Press-releases/News-releases1/2016/Advanced-ADEPT-48V-affordable-hybrid-on-path-to-meet-future-ultra-low-vehicle-emission/

"cost-effective focus on the combination of near-market, available technologies" gives it the potential for an "extremely high level of mass-market appeal, providing arguably a greater overall fuel and carbon emissions saving in the near to medium term."

- Powertrain engineers at VW-Audi and suppliers have been developing e-boosters with 48V hybrid systems for years. When combined with regenerative braking, the systems may result in fuel consumption reductions of 7-15%. The higher boost pressure at low loads also reduces particulate emissions.[41] And using 48V Li-ion batteries enables electrification of ancillary mechanical pumps, further reducing engine load.
- FEV estimated that a 48V hybrid system applied to diesel engines would cost $708 to $712 more than a 12V stop-start system.[42] That is in line with estimates from suppliers that 48V systems cost between a third and half as much as full hybridization while reducing fuel consumption by one-third to two-thirds as much.[43]

CONSUMER IMPACTS

Diesels have a mixture of many undesirable and highly desirable features. On the plus side, diesel engines have high low-end torque and good acceleration from a stop. These two attributes are highly desirable for many consumers. For large vehicles, especially for pickups, this low-end torque is especially attractive for increasing cargo and towing capacity. For all vehicle types, the fuel savings of diesel engines can be quite high. This feature may be particularly important for larger vehicles, which usually have lower fuel economy.

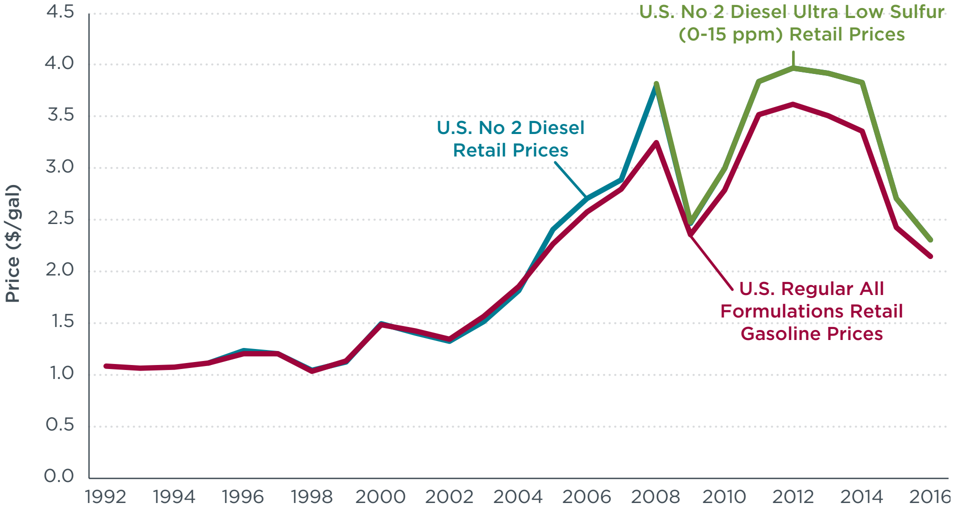

Figure 3: U.S. on-road gasoline and diesel fuel prices 1992-2016 (Source: U.S. EIA)

Many consumers have outdated perceptions of diesel engines. These include poor starting at colder temperatures, noise, smell, and slow acceleration. On the other hand, consumers also believe that diesels are more durable than gasoline engines, which is also outdated. A recently introduced perception problem is the VW emissions testing scandal. As with past such cases, the negative impacts will probably blow over in time, but there may be short-term damage.

The larger challenges for diesels are higher vehicle cost, higher fuel cost in the U.S. compared with gasoline, and rapid improvements to gasoline engines. Unlike Europe, where most countries levy substantially lower taxes on diesel fuel than on gasoline, the U.S. taxes the two fuels at almost the same rates.

Diesel use has been rising rapidly worldwide in the past decade or two, and refiners have not been able to shift production from gasoline to diesel fast enough to keep up. As a result, there is a worldwide shortage of diesel fuel, putting prices at a premium compared with gasoline. Part of this reflects the rapid expansion of diesel sales in Europe, but a much larger factor is the explosion of freight movement in developing countries, almost all of which uses diesel fuel.

Figure 3 shows the trends in fuel prices over the past 23 years in the U.S.[44] Historically, diesel fuel was the same price as gasoline, if not slightly cheaper, but the trend crossed over in 2004, and for the last 12 years diesel fuel has been consistently more expensive than gasoline.

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

Government projections for the costs of advanced diesel engines are higher

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[41] E-boosting for VW-Audi's 2015 V6 diesel. (November 4, 2014). *Automotive Engineering*. Retrieved from http://magazine.sae.org/14autp11/ Stuart Birch, "Testing Audi's new e-booster reveals turbocharging's future," *Automotive Engineering*, August 4, 2014, http://articles.sae.org/13421/

[42] FEV. (2015). *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. September 2015. Report commissioned by ICCT. Retrieved from http://www.theicct.org/2025-passenger-car-and-light-commercial-vehicle-powertrain-technology-analysis

[43] 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

[44] Graph downloaded on January 17, 2017 from https://www.eia.gov/dnav/pet/PET_PRI_GND_DCUS_NUS_W.htm

than estimates from suppliers.[45] Current prices of PGMs have dramatically reduced diesel package costs. Although monthly PGM prices have been relatively stable or trending downward for several years, they can change direction quickly. As a result, suppliers continue to create emission control systems with lower levels of PGMs. Component makers have been developing new designs and methods for particulate filters, NO_X storage/adsorbers, and NO_X reducers. There are numerous strategies and configurations for engines of different sizes tailored for specific loads and temperatures. These developments are likely to decrease the costs associated with aftertreatment systems.

Several engine improvements are poised to assist in reaching peak aftertreatment temperatures faster while reducing engine-out NO_X and boosting efficiency. These include cooled low- and high-pressure EGR loops and cylinder deactivation, for example.

Significant research continues on diesel turbochargers, some of whose components are appearing in downsized gasoline engines. Each generation improves performance and permits greater engine downspeeding and downsizing. Major suppliers already have turbochargers ready for the growth of 3- and 4-cylinder engines. These sharply downsized engines promise increased fuel economy.

Table 3 shows the estimated 2025 direct manufacturing cost for engines and emission control from the EPA rulemaking and from suppliers. The values represent the difference in cost between a naturally aspirated gasoline engine and its corresponding downsized diesel engine.

Table 3: Comparison of EPA, FEV, and Martec Group estimates of 2025 incremental direct manufacturing cost

	EPA	FEV	MARTEC
Engine	$441-$824	$530-$1,288	$869-$1,123
Aftertreatment	$1,311-$1,321	$428-$532	$595-$675
Total	**$1,752-$2,146**	**$996-$1,893**	**$1,463-$1,798**

Note: Martec Group estimates for 2025-compliant diesels were derived by applying the same manufacturer learning curves EPA used to Martec Group's 2015 estimated incremental costs. FEV incremental costs were determined by comparing baseline segments C and D diesel and gasoline engines.

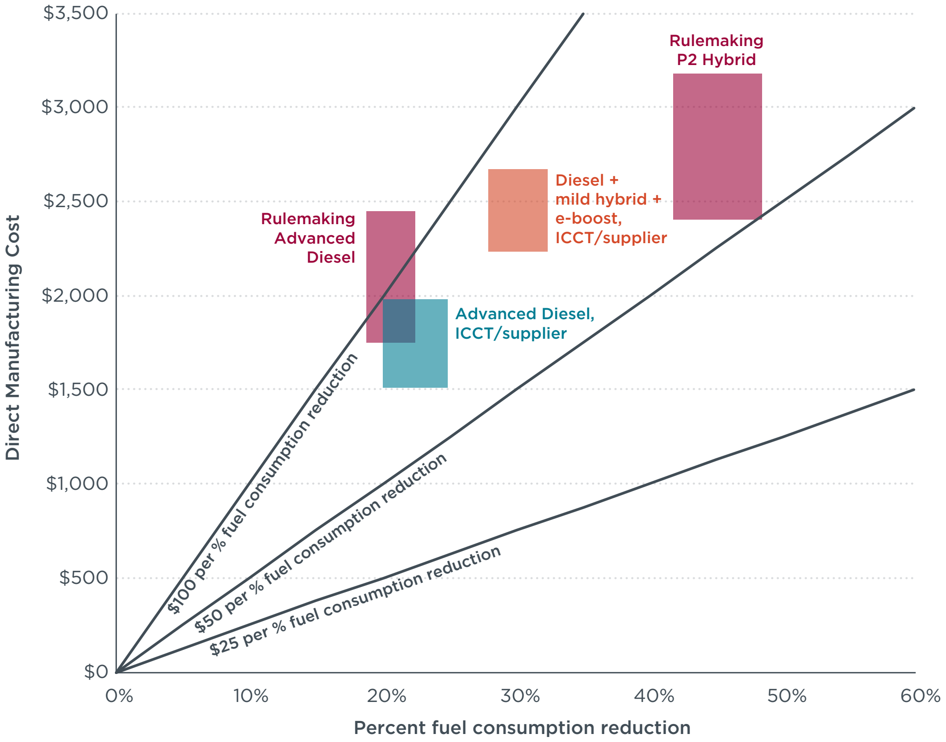

Figure 4: Comparison of rulemaking and ICCT/supplier estimates of direct manufacturing cost per percent fuel consumption reduction in 2025.

Aftertreatment costs are the incremental cost of diesel aftertreatment over gasoline aftertreatment. Improvements in emission control systems, turbocharging, and combustion/injection may increase costs but will certainly improve efficiency.

In the rulemaking, diesels were estimated to have around a 20% reduction in fuel consumption compared with baseline gasoline vehicles. Many of the developments discussed previously contribute to this benefit. However, a host of engine improvements and the near-production of 48V mild hybrid systems are likely to lead to diesels that reduce fuel consumption by more than 30%. The higher-voltage electrical system will take the load of powering ancillary systems off the engine, directly increasing efficiency. And the capacity for regenerative braking and e-boosting provides as much as two-thirds of the benefits of a strong hybrid drivetrain at half the cost or less.

Figure 4 compares the costs and benefits of advanced dieselization as estimated in the rulemaking (red

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[45] The Martec Group. (2016). *Diesel Engine Technology: An Analysis of Compliance Costs and Benefits* [White Paper]. Retrieved from http://www.martecgroup.com/diesel-engine-technology-an-analysis-of-compliance-costs-and-benefits-white-paper/

box) with more recent calculations by suppliers. The rulemaking cost-benefit analysis for full hybrid (P2) is also shown for reference. Future diesels are expected to cost less and have greater benefits than forecast in the rulemaking (blue box). The costs are lower because of less-expensive emission control systems and improved engine components. Adding the costs and benefits of a 48V mild hybrid system and electric supercharging (orange box) leads to slightly higher costs per each percent reduction in fuel consumption, but average total costs remain lower than for full hybrids.

For the increasingly popular larger vehicle classes, diesels provide a uniquely cost-effective alternative to hybrids for achieving deep reductions in fuel consumption. They have plenty of room for emission control systems and benefit from the low-engine-speed performance of diesels.

As a result of all these trends, it seems likely that diesels will have a larger market share in 2025 than predicted by the EPA and NHTSA, unless the diesel defeat device cases brought against VW and FCA cause some manufacturers to abandon diesels. Diesel share will expand further as incremental costs decline.

Conclusions

Diesel vehicles have had a rough time penetrating the U.S. light-duty vehicle market, reflecting outdated negative perceptions, higher fuel prices for diesel than for gasoline, the cost of complying with stringent U.S. emission standards, and rapidly improving gasoline engines. Then, just as light-duty diesels were finally gaining market share, the VW emissions testing scandal set diesels back once again.[46]

Still, improved aftertreatment systems are rapidly reducing the cost of complying with emissions standards, and further cost-reducing advances are expected. While the efficiency advantage of diesels over gasoline engines is narrowing,[47] diesel engine developments are also occurring and will further improve diesel efficiency. The VW scandal will eventually blow over.

Diesels have two significant advantages over gasoline engines: They will always have significantly higher fuel economy, and their ability to haul cargo and tow cannot be matched. Those things make diesels a strong option for customers who put a high priority on towing or fuel economy and manufacturers that want to market high fuel economy. This can be seen in the market with the successful use of diesels in GM's mid-size pickup trucks and coming diesel offerings for the Chevy Cruze, in the diesel Ram pickup truck, and in Mazda's diesel CX-5.

Diesels offer a promising pathway for compliance and another option in manufacturers' toolboxes. Their use is likely to vary significantly from manufacturer to manufacturer and model to model. This will depend on each automaker's assessment of diesel's cost-effectiveness compared with other technologies, such as hybrids, and customer desire for the advantages of diesels. Coming cost reductions will improve the diesel's competitiveness and likely increase its market share in the future.

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[46] The recent Notice of Violation from EPA against FCA's light-duty diesels is also of concern. However, it is not likely to have the same impact as the VW scandal, as unlike VW, FCA's software only deactivated the emission control system part of the time and FCA has cooperated with the U.S. agencies in their investigation.

[47] As described in other papers in this series, gasoline engines are reducing this fuel economy gap through higher compression ratios, Atkinson and Miller cycles, variable compression, and other improvements.