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SERIES: U.S. PASSENGER VEHICLE TECHNOLOGY TRENDS

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# Diesel Technology Developments

Although diesel engines developed a black eye with American motorists after bad experiences with them in the early 1980s, the technology offers significantly greater efficiency than gasoline engines and higher low engine speed torque. That has encouraged automakers and suppliers to continue investing in improved diesels for passenger vehicles. Recent advances suggest that these engines can deliver better fuel economy at lower cost than regulators estimated in the 2012 rulemaking for 2017-2025 standards while overcoming emission-control challenges.

Diesels' limited U.S. consumer appeal reflects their reputation for being hard to start, noisy, smelly, and underpowered relative to gasoline engines. General Motors reinforced all of that and then some in the late 1970s by rushing out an extremely unreliable product in response to the 1973 and 1979 fuel crises. Additionally, diesel fuel in the US has cost more than gasoline for the last 12 years, eroding the efficiency advantage.

In recent years, technology improvements such as direct fuel injection, higher fuel line pressure, cooled exhaust gas recirculation, and turbocharging have almost fully addressed the performance and reliability issues. These gains, together with fuel-tax policies encouraging diesel use in Europe and India have enabled these engines to capture large passenger-vehicle penetration in these regions, demonstrating the technology's market potential.

The remaining challenges are primarily cost and emissions control. Diesel engines are more expensive 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 costly and more difficult to control diesels' particulate and nitrogen oxide ($NO_x$) emissions.

As engineers continue to address those issues, future diesels will most likely cost at least $200 less, and new developments, such as 48V e-boost/hybrid systems, will provide greater benefits than projected by government rulemakers a half-decade ago. Consequently, diesel-powered vehicles can deliver greater reductions in fuel consumption than predicted and will be another feasible technology approach that manufacturers can use to comply with the standards.[1]

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[1] This technical brief is based on Aaron Isenstadt and John German (ICCT), *Diesel engines* (ICCT: Washington, DC, 2017). http://theicct.org/diesel-engines

**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.

## TECHNOLOGY DESCRIPTION

Diesel engines' efficiency advantages over gasoline grow out of important differences in how the engines operate. Diesels do not use a throttle to control airflow into the engine or a spark plug to start ignition as gasoline engines do. Instead, load is controlled by the amount of fuel injected. Timing of fuel injection determines 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 combustion process of a diesel also allows much leaner air/fuel ratios than with pre-mixed gasoline combustion. These lean air/fuel ratios reduce average in-cylinder temperatures and improve thermal efficiency by reducing heat losses to the cooling system and exhaust.

An additional, indirect advantage is that the higher density of diesel fuel results in about 14% more energy per gallon than gasoline, meaning a diesel vehicle can go 14% farther on the same amount of fuel. On the other hand, diesel fuel also contains 14% more carbon per gallon, resulting in higher $CO_2$ emissions.

In gasoline engines, vaporized fuel is mixed with air before a spark sends a flame through the mixture. The fuel is completely burned except for quench layers at the chamber walls and in crevices. In diesel engines, the fuel 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. This leaves behind an unburned carbon core. As the gas cools during passage through the exhaust, uncombusted and partially combusted products adhere to the carbon particles, resulting in diesels' signature, particulate-laced black smoke exhaust. Modern particulate traps effectively reduce the release of particulate emissions, but the systems are not cheap.

A common misconception is that diesel engines produce a lot of $NO_x$. $NO_x$ formation is proportional to combustion temperature and diesels have much lower average combustion temperatures than gasoline engines, although there are localized hot spots with higher temperatures at the point of combustion. Thus, under some conditions, engine-out $NO_x$ emissions from diesel engines can be lower than from gasoline engines. 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. As diesels run unthrottled, there is always excess oxygen in the exhaust, and three-way catalysts do not work. The solution for diesel engines is some combination of engine-out $NO_x$ control through exhaust gas recirculation (EGR) and injection timing retard; plus $NO_x$ aftertreatment using lean-$NO_x$ traps (LNT) or selective catalytic reduction (SCR) using urea injection. However, these $NO_x$ aftertreatment systems are expensive, lean-$NO_x$ traps and engine-out controls increase fuel consumption, and SCR systems require periodic refills of the urea storage tank.

## HISTORICAL ESTIMATES OF COSTS AND BENEFITS

The National Academy of Sciences determined in 2002 that it would be a challenge to create diesel emission control systems for $NO_x$ and particulate matter that could be certified to last 120,000 vehicle miles. 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, the National Highway Traffic Safety Administration (NHTSA) estimated that combustion improvements including high-pressure injectors and EGR, along with improved aftertreatment such as LNTs, 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 fuel consumption benefits are due primarily to improvements in the baseline gasoline engine used for the comparison.

The Environmental Protection Agency (EPA) and NHTSA made two main assumptions on why manufacturers might hesitate to increase diesel production. The first is that manufacturers might determine that other technologies are more cost-effective for reducing greenhouse gas emissions. Secondly, manufacturers might find it difficult to comply with $NO_x$ emissions limits without reducing the fuel economy of diesels or dramatically increasing vehicle cost.

Moreover, the EPA's fuel economy trends reports show that diesel accounts for a very small share of the U.S. passenger vehicle market, limiting the technology's historical fleet-wide benefits. As shown in Table 1, even

**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% | 1.0% |

after a 10-fold increase in penetration from 2004-2014, diesel vehicles amounted to just 1% of light-duty sales.

## EPA/NHTSA 2017-2025 PROJECTIONS

The government agencies projected almost no increase in diesel market penetration by 2021 or even 2025, although individual brands such as Mercedes may have a higher penetration. The regulators assumed that manufacturers would initially concentrate on improving gasoline engines. Once all the cost-effective technologies are implemented, manufacturers would turn to alternative fuel/powertrains, including diesel.

However, the agencies did acknowledge that some manufacturers see diesel as a viable option for meeting tighter standards. Several diesel technology developments were examined in the 2017-2025 rulemaking, which was written in 2012. These include improved fuel injection systems, advanced controls/sensors for combustion and emissions optimization, advanced turbocharging, and expanded use of cooled EGR, which helps control $NO_x$ while minimizing the fuel consumption tradeoff.

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). The agencies identified the incremental cost of these systems, particularly for smaller cars, as a barrier to wider adoption of passenger diesels.

For all but two vehicle classes in the agency projections, the total direct manufacturing cost (DMC) for switching to diesel declines to below $2,000 in MY2019, and declines to about $1,750 in 2025.

## CURRENT PRODUCTION AND FUTURE DEVELOPMENTS VERSUS AGENCY PROJECTIONS

Many developments in diesel engines are similar to those being incorporated into gasoline engines. Examples include advanced friction reduction, higher turbocharger pressures, improved variable geometry turbochargers, downsizing and downspeeding, better thermal management, 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 pollution reductions, diesel engines may be best suited for larger vehicle types. In the bigger classes, diesels' fuel economy benefits per incremental cost are comparable to, or better than, those of strong hybrids.

Diesel production in the larger segments is increasing along with rising demand. Sales of EcoDiesel engines on Fiat Chrysler Automobiles' Ram 1500 pickup and Jeep Grand Cherokee SUV have surged over the past few years. As a result, FCA is expanding production of those engines.[2] These vehicles are fuel economy leaders in their classes, earning FCA compliance credits for the future. The company plans for the next generation 2018 four-door Wrangler diesel to nearly meet 2022 fuel economy standards. Diesels in these segments also benefit from increased towing capacity and better low-speed performance.

While diesels are not as cost-competitive in small vehicles, customers in those segments are generally more concerned about fuel economy. Chevrolet's effort to boost sales of the Cruze by offering an optional diesel engine starting in 2017 reflects this. Mazda plans to offer its SKYACTIV-D diesel engine on the new CX-5 in the second half of 2017. Mazda reduced the cost of the aftertreatment system by designing the engine to operate with a much lower compression ratio than most diesels. 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 $NO_x$.

Whatever the vehicle class, diesel engines must contend with $NO_x$ and particulate matter aftertreatment. In interviews with suppliers, the Martec Group found that platinum group metal (PGM) price reductions and technology improvements have led to significantly reduced costs for today's aftertreatment systems. In 2008, the cost of a 2015 emission control system for a 4-cylinder engine was estimated at $980. But in 2016, the system actually cost just $550, which was projected to rise only to $620 in 2025 while complying with stricter standards. In support, PGM costs represent 16-23% of the combined diesel DMC. However, the February 2011 prices used in the government's technical analyses for 2017-2025 are historically some of the highest: $1,829/troy ounce for platinum and $2,476/troy ounce for rhodium. By December 2016, platinum declined

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[2] A US Department of Justice lawsuit against FCA filed on May 23, 2017 will likely impact the company's plans for their diesel vehicles, although the extent of this impact is unknown. The complaint can be found here: https://www.justice.gov/opa/pr/united-states-files-complaint-against-fiat-chrysler-automobiles-alleged-clean-air-act

by almost half to an average of $930/troy ounce, and rhodium by two-thirds to $785/troy ounce. These PGM price drops could result in an 8-15% reduction in emission control system cost, or $150 to $400. Future aftertreatment systems requiring lower amounts of PGMs will reduce the effects of PGM price volatility on system cost.

Martec calculated the current (2015) costs of 2025-compliant diesel vehicles compared to their gasoline counterparts. As shown in Table 2, below, when these costs are adjusted for manufacturer learning during the ten years from 2015 to 2025, suppliers' estimated costs over their gasoline equivalents fall to $1,463-$1,798. Over the same time frame, EPA costs, which also fall due to learning, remain $289-$348 higher than suppliers' estimates as compiled by the Martec Group.

In a report commissioned for the ICCT, FEV estimated the costs for upgraded EGR systems with cooled high and low pressure loops, which help reduce $NO_x$. FEV also estimated that downsizing the engine would create savings for all vehicle segments. Overall, 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.

## IMPROVEMENTS UNDER DEVELOPMENT

### AFTERTREATMENT AND EMISSIONS CONTROL

Future aftertreatment systems are expected to cost less than an additional $100 over today's systems, albeit requiring a higher-pressure injection system. Because $NO_x$ emissions are highest at cold start and SCR catalysts need time to warm up, suppliers are developing technical solutions. 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. Suppliers and manufacturers are experimenting with combinations to create durable aftertreatment systems that are cheaper and more compact.

At low loads, cylinder deactivation increases the load on the active cylinders, thereby increasing the exhaust temperature more than if all cylinders were in use. This increased temperature can be used on diesel engines to quickly warm up the aftertreatment system to the point at which it is most efficient. Deactivation also has fuel savings of as much as 25%, although this is only under low-load operation.

Higher-pressure direct injection is being implemented to improve diesel and gasoline efficiency, but this can result in the generation of ultrafine particulate matter, which is especially harmful to health. Consequently, 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, ideally generating carbon dioxide. 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 aftertreatment further away.

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.

### 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. E-boost systems, comprising an electric supercharger or a turbocharger with an integrated electric motor, use the 48V electrical system to directly boost the engine, or to spin up the turbocharger and greatly reduce turbo lag. E-boosting systems can use larger turbines with lower backpressure. Better boosting and reduced lag permit further engine downsizing and downspeeding.

The 48V electrical system with a larger battery has further benefits. 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.

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. The "boost recuperation system" reduces diesel engines' $CO_2$ emissions by 7% and engine-out $NO_x$ by 10-20%. More recent reports from Bosch indicate the system will be ready for production in 2017 and will decrease fuel consumption by as much as 15%.

- Ricardo's "ADEPT" concept for diesel vehicles uses a high-power 12.5kW belt-drive starter-generator with further energy recovery from the exhaust using a 48V turbine-integrated exhaust gas energy recovery system. An advanced lead-carbon battery is used to store recovered energy from braking regeneration and exhaust. On a Ford Focus with the 1.5TDCi ECOnetic diesel, the system achieved $CO_2$ emission levels as low as 80g/km with a reduction in fuel consumption of more than 10%.
- 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 reductions of 7-15% in fuel consumption, they estimate. The higher boost pressure at low loads adds the benefit of lower particulate emissions.
- FEV estimated that a 48V hybrid system applied to diesel engines would cost $708 to $712 more than a 12V stop-start system.

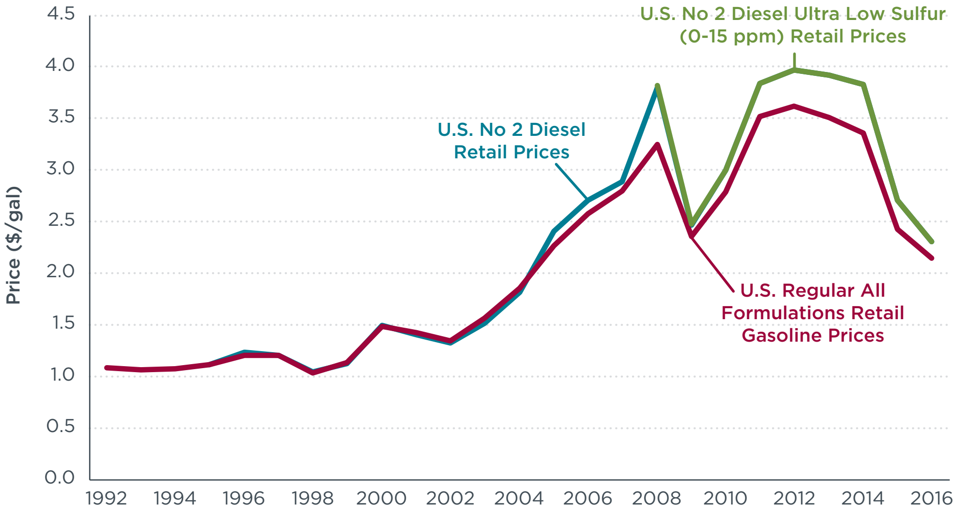

**Figure 1:** U.S. on-road gasoline and diesel fuel prices 1992-2016 (Source: U.S. EIA)

## CONSUMER IMPACTS

Diesels offer a mix of desirable and undesirable features. On the plus side, they deliver high low-end torque and good acceleration from a stop. For large vehicles, especially pickups, this low-end torque is attractive for increasing cargo and towing capacity. For all vehicle types, the fuel savings of diesel engines can be quite high.

On the other hand, many consumers have outdated perceptions of diesel engines. These include poor starting at colder temperatures, noise, smell, and slow acceleration. 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 diesel and gasoline at almost the same rates.

Also putting upward pressure on diesel prices is a worldwide shortage. Diesel demand has been rising rapidly in the past decade or two, and refiners have not shifted production from gasoline to diesel fast enough to keep up. 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 1 shows the trends in fuel prices over the past 23 years in the U.S. Historically, diesel fuel was the same price as gasoline, if not slightly cheaper, but the trend crossed over in 2004, and for the past 12 years diesel fuel has been consistently more expensive than gasoline.

## IMPLICATIONS FOR MIDTERM EVALUATION

Diesels have two major advantages over gasoline engines: They will always deliver 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.

In the government's 2012 rulemaking, diesel-powered autos were estimated to reduce fuel consumption by around 20% compared with baseline gasoline vehicles. 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.

Table 2 shows the estimated 2025 direct manufacturing cost for engines and emissions control from the

EPA rulemaking and from suppliers. The suppliers' projections show substantially lower total costs than those of the EPA. The values represent the difference in cost between a naturally aspirated gasoline engine and a corresponding downsized diesel engine. Aftertreatment costs are the incremental expense for diesel engines compared with gasoline. Improvements in emission control systems, turbocharging, and combustion/injection may increase costs but will certainly improve efficiency.

The lower supplier cost projections partly reflect declines in prices of PGMs, which have dramatically reduced the package costs for diesels. Although monthly PGM prices have been stable or falling for several years, they can change direction quickly. As a result, suppliers continue to create emission control systems requiring lower levels of PGMs. Component makers have been developing new designs and methods for particulate filters and other emission controls. These developments are likely to further decrease the costs associated with aftertreatment systems.

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

**Table 2:** 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.

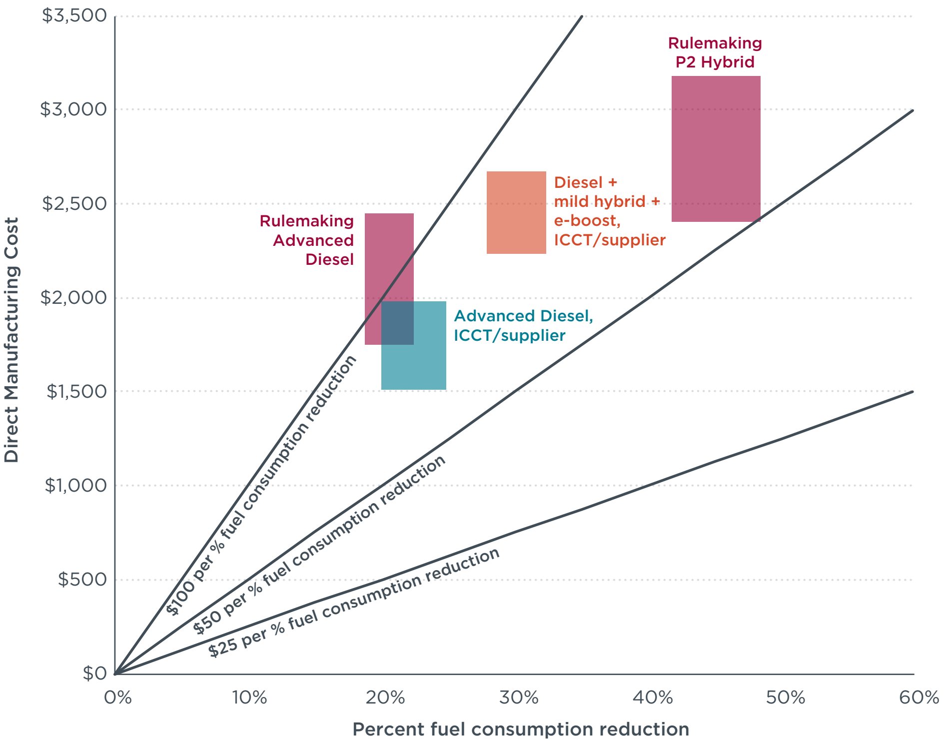

**Figure 2:** Comparison of rulemaking and ICCT/supplier estimates of direct manufacturing cost per percent fuel consumption reduction in 2025.

Figure 2 compares the costs and benefits of advanced dieselization as estimated in the rulemaking (red box) with more recent calculations by suppliers (blue box). The rulemaking's cost-benefit analysis for full hybrid is shown for reference. Future diesels are expected to cost less and have greater benefits than forecast. 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 percent reduction in fuel consumption, but average total costs remain lower than for full hybrids.

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 diesel engines. Coming cost reductions will improve diesels' competitiveness and may increase their market share in the future.