WHITE PAPER

MARCH 2017

EFFICIENCY TECHNOLOGY AND COST ASSESSMENT FOR U.S. 2025–2030 LIGHT-DUTY VEHICLES

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ACKNOWLEDGMENTS

The authors are grateful for contributions from various automotive suppliers that provided input in the efficiency technology series published by the International Council on Clean Transportation. Francisco Posada provided advice and support on fleet technology modeling. Fanta Kamakaté, Anup Bandivadekar, Francisco Posada, Therese Langer, and Dave Cooke provided critical reviews on an earlier version of the report. Their reviews do not imply endorsement, and any errors are the authors' own.

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EXECUTIVE SUMMARY

Understanding advanced vehicle efficiency technologies and their potential to reduce oil use and emissions is critical, as governments around the world continue to seek ways to accelerate their deployment through regulatory efficiency standards. The three largest automotive markets, the U.S., Europe, and China, are in various stages of development toward meeting 2025 efficiency standards. Key questions include how much efficiency technology is available to improve internal combustion vehicles, how much the fleet will need to transition to electric vehicles to meet efficiency and carbon dioxide (CO_2) targets, and what the associated costs are.

This report analyzes emerging vehicle efficiency technologies, their ability to achieve lower emission levels, and their costs in the 2025–2030 time frame. The analysis is focused on providing an update to the U.S. midterm evaluation regulatory analysis for new 2025 vehicles, as well as estimating the potential and cost of continued improvements through 2030. The analysis builds on the extensive U.S. government agency technology inputs, state-of-the-art modeling, and underlying peer-reviewed reports. We make updates for the latest research on emerging technologies, including cylinder deactivation, hybridization, lightweighting, and electric vehicles, based on the research literature, simulation modeling, and auto industry developments.

Figure ES-1 shows the reduction of new light-duty vehicle regulatory CO_2 emission levels analyzed in this assessment, along with the associated increase in vehicle prices attributable to the efficiency technology. We assess increased consumer label fuel economy from 26 mpg in 2016, to 35 mpg in 2025, to 42–46 mpg by 2030. These fuel economy levels are achieved based on sustained 4%–6% annual reduction of fuel use per mile with incremental technology additions that do not compromise vehicle size or utility at an incremental cost of $800–$1,300 from 2025 to 2030. The resulting trajectory would reduce CO_2 emissions by half and increase fuel economy by more than 60% from 2016 through 2030. Based on a detailed analysis of the efficiency technologies used to achieve these lower CO_2 emission levels, vehicle prices would increase by about 5% by 2030.

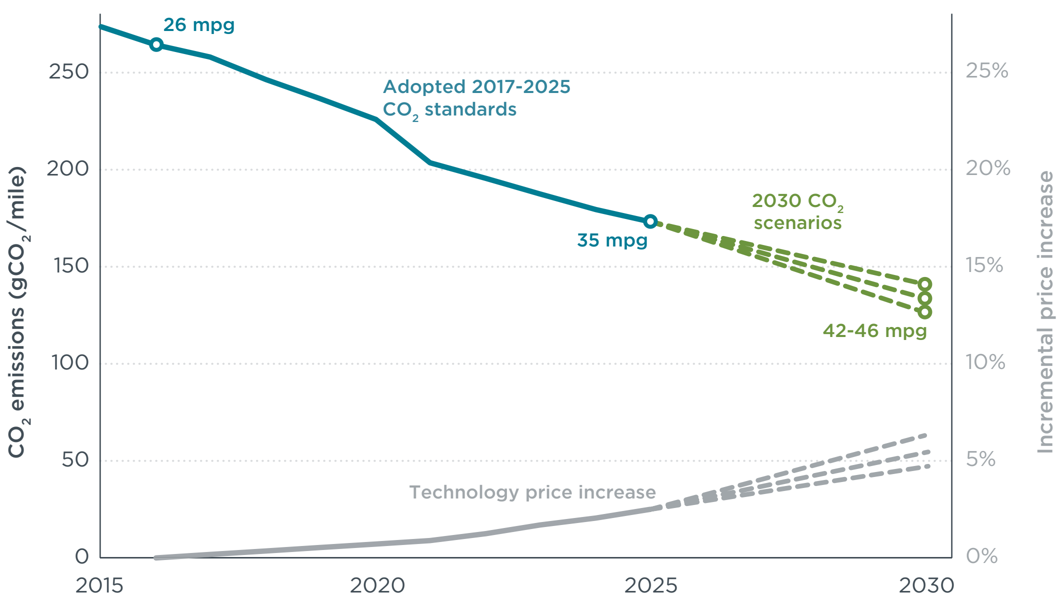

Figure ES-1. Vehicle price increases from using increased vehicle efficiency technology to achieve lower CO_2 emission levels.

This analysis explores the deeper technology implications of the shift to increased efficiency and lower CO_2 emissions in the 2025–2030 time frame. We highlight the following three findings:

> ***Conventional vehicles could dominate in the near term.*** Emerging technologies are expanding the internal combustion vehicle efficiency frontier. Our analysis indicates 8%–10% greater efficiency improvement is available and cost effective for vehicles by 2025, compared to the latest U.S. regulatory analysis. Continually improving technologies such as cylinder deactivation, high compression Atkinson cycle engines, lightweighting, and mild hybridization will allow internal combustion to dominate automakers' strategies to comply with adopted 2025 standards.

> ***Previous costs of compliance have been greatly overestimated.*** Technology costs continue to decrease, proving that previous estimates, including those made by the federal regulatory agencies, have been too conservative. State-of-the-art engineering studies and emerging supplier technology developments indicate that costs for lightweighting, direct injection, and cooled exhaust gas recirculation will be reduced by hundreds of dollars, and electric vehicle costs will drop by thousands of dollars per vehicle by 2025. Including these latest efficiency developments, compliance costs for the adopted 2025 standards will be 34%–40% lower than projected in the latest U.S. midterm evaluation regulatory analysis.

> ***Progress can continue at the same rate out to 2030.*** Standards that get progressively more stringent, at 4%–6% lower fuel use per mile annually from 2025 to 2030, can be achieved cost-effectively. Such standards would result in modest, gradual vehicle price increases through 2030, and with two to three times greater consumer fuel savings than costs. Such 2030 standards could be achieved mostly with advanced combustion technology, while also initiating the wider launch of plug-in electric vehicles to 13%–23% of the new vehicle fleet. Such standards would shift the new vehicle fleet from 26 miles per gallon in 2016 up to 42–46 miles per gallon by 2030.

We note several additional implications of the results. This technology assessment indicates that the average payback period will become even more advantageous to first vehicle owners than the regulatory agencies indicated. Further consumer analysis ideally would investigate any such payback implications, as well as possible increases in vehicle sales and positive effects on jobs. We also suggest further investigation into how best to integrate and credit electric vehicles in the regulation, considering their 2020–2030 inflection point. A broader investigation of the effects of this work internationally also would be warranted. Many regulatory agencies around the world are researching potential 2025–2030 standards that extend their currently adopted regulations. The expanding opportunities for advanced combustion, hybridization, and plug-in electric vehicle technologies affect all these markets. Adoption of progressive, harmonized, long-lead-time standards around the world would ensure that technology is widely deployed and would further reduce technology costs. This, in turn, would allow for greater and more cost-effective emission-reduction and oil-saving benefits.

I. INTRODUCTION

Governments around the world are promoting clean vehicle technology to help achieve their climate, clean air, oil dependence, renewable energy, and industrial development goals. Among the more prominent strategies to reduce transport emissions and oil use are regulatory performance standards that require vehicles to reduce emissions over time through continued development and application of efficiency technologies. Exactly which technologies are deployed, and how quickly, depends on many complex factors related to companies' technology decisions, supporting policy, and consumer demand.

The automobile industry is global, with major automakers producing and selling many of the same models and technologies across multiple continents. Governments around the world are increasingly recognizing this global technology development with regulations that promote similar technologies on similar timescales to achieve their energy and environmental goals. This global context has given rise to similar regulatory standards, adopted with 5–10 years lead time, that typically require new vehicles to achieve 3%–5% lower energy use per mile each year (International Council on Clean Transportation [ICCT], 2016). Regulatory efficiency and carbon dioxide (CO_2) standards now encompass about 80% of the world automobile market (Miller & Façanha, 2014). Such standards primarily promote more efficient engines, transmissions, accessories, lightweighting, aerodynamics, and tires. From 2025 on, electric vehicles could play a more widespread role in automakers' longer-term technology plans.

Based on efficiency standards adopted in 2012, the U.S. automobile market has had long-term regulatory certainty to guide automakers' efficiency technology investments through 2025. Adopted after extensive technical analysis and automaker input, these regulations apply to new vehicles sold in the U.S. through model year 2025. These standards were co-developed by three government authorities: the U.S. Department of Transportation, the U.S. Environmental Protection Agency (U.S. EPA), and the California Air Resources Board (CARB). The adopted 2025 standards received commitments by 15 major automobile manufacturers (BMW, Fiat-Chrysler, Ford, General Motors, Honda, Hyundai, Kia, Jaguar Land Rover, Mazda, Mitsubishi, Nissan, Subaru, Tesla, Toyota, Volvo) (U.S. EPA, 2011). These companies represent approximately 90% of the U.S. automobile market.

Figure 1 illustrates new U.S. vehicle fuel economy from 1985 through 2016, with projections through 2025 based on the adopted standards. The figure shows the regulatory test cycle fuel economy and the consumer label fuel economy. In both the figure and the analysis below, we assume that real-world consumer label fuel economy will remain 23% lower than the regulatory test cycle fuel economy, due to factors like greater real-world acceleration and operating in hot and cold temperatures (see U.S. EPA, 2016c). As shown, with the adopted standards, average new vehicle fuel economy as seen on consumer labels has increased from 19 miles per gallon (mpg) in 2004, the year California adopted standards though 2016, to 26 mpg in 2016, representing a 2.4% annual increase.

The standards are indexed to vehicle footprint, and therefore are designed to accommodate shifts in the market while still requiring more efficiency technology across all vehicle types. For the broader market context, over the 2011–2016 period, automobile fuel economy has increased by 14%, auto sales have increased by more than 40%, and vehicle footprint and power have remained approximately the same (U.S. EPA, 2016a). For each of the first four years of the U.S. EPA CO_2 standards, the industry has outperformed the standard and has carried a major credit balance into future years (U.S. EPA, 2016b).

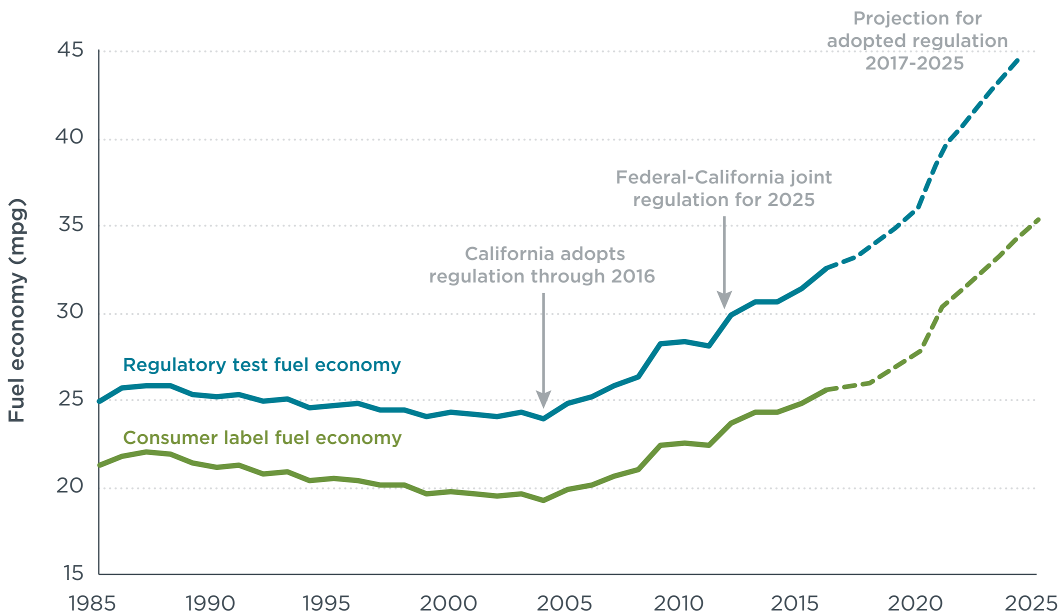

Figure 1. Historical and adopted regulatory test cycle and consumer label fuel economy for new vehicles for model years 1985 through 2025.

The future fuel economy levels shown in Figure 1 assume that all manufacturers comply with the adopted standards and do so with full use of air-conditioning credits. The 2025 projection also assumes a split of 53% passenger cars and 47% light trucks, based on a moderate increase in the light truck mix, up from 43% in 2015. This car-truck split includes the regulatory distinction where most smaller two-wheel-drive sport utilities are classified as cars within the regulation. As shown, with the adopted standards, average new vehicle fuel economy as shown on consumer labels would increase from 26 mpg in 2016 to 35 mpg in 2025, representing a fuel economy increase of 38%, or 3.6% annual improvement on average. We assume, as the regulatory agencies do, that automakers will fully utilize the alternative refrigerant and efficiency air-conditioning system credits from 2021 on. Excluding the air-conditioning credits, the associated CO_2 emission reduction on new vehicles from 2016 to 2025 would be 29%, or 3.7% annually.

Yet there are many questions going forward about how the 2025–2030 efficiency might evolve beyond the adopted 2025 standards. Following the United States' best-practice precedent for providing extended lead time to invest in the next generation of efficiency technologies, regulators would have to adopt 2030 standards by 2018 (Lutsey, 2012). U.S. EPA has finalized its 2025 standards, and the National Highway Traffic Safety Administration (NHTSA) is working on its midterm evaluation toward implementing 2022–2025 standards (U.S. EPA, 2016c; U.S. EPA, 2017a; NHTSA, 2017). In addition, how California could move toward new standards that apply to 2026 through 2030 new vehicles while federal agencies continue to review 2025 standards further increases this uncertainty (CARB, 2016). Among the most prominent technical questions are which technologies are available and which technologies will be most cost-effective in meeting more stringent standards over time.

This report assesses the technology potential and associated costs of meeting the adopted 2025 efficiency standards and further post-2025 efficiency improvements. We start from the most comprehensive and detailed assessments of 2025 technologies, including the vehicle simulation and engineering teardown analysis that were part of the U.S. midterm evaluation regulatory analysis. We then update that analysis to incorporate the impact that the latest emerging technology developments are likely to have on technology potential and cost in the 2025 to 2030 time frame.

This analysis includes two main elements. The first element, in section II, develops technology-cost curves, evaluating the incremental cost of increasing vehicle efficiency technology in the model year 2025 time frame. As part of this, we also assess the potential for further technical improvements to achieve lower fuel consumption and CO_2 levels in the model year 2030 time frame. These incorporate information from the U.S. EPA's latest final determination and supplier input received through the ICCT's technical briefing series with automotive suppliers. The second element, summarized in section III, entails using the ICCT-updated vehicle technology costs on a fleet level. This element uses the Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) framework (U.S. EPA, 2017d) to estimate the cost of complying with potential 2025–2030 standards across the diverse vehicle fleet.

II. EFFICIENCY TECHNOLOGY AND COST

This section assesses available technology for passenger cars and light trucks to comply with the adopted federal efficiency standards. In the first subsection, we summarize key technology inputs from the most recent federal regulatory analysis, U.S. EPA's analyses in December 2016 for its proposed determination (U.S. EPA, 2016c), including analysis of a typical technology progression for increasing efficiency technology and its associated cost to achieve more stringent efficiency requirements through model year 2025. This is followed by our updated estimate of technology availability and costs that includes longer-term technologies, including those that are likely to be available for wider scale adoption in the 2025–2030 time frame. All costs below are in 2015 dollars.

FEDERAL ANALYSIS OF U.S. EFFICIENCY TECHNOLOGY

This section summarizes available technology directly from the federal U.S. midterm evaluation regulatory analysis for typical passenger cars and light trucks to comply with the adopted federal efficiency standards. The latest analysis from the U.S. EPA applies many dozens of efficiency technologies across 29 different vehicle types that have differing engine technology, power, and weight characteristics. These vehicle types represent various vehicle categories including subcompact cars, midsize cars, crossovers, sport utilities, and pickups as well as variants within these categories, such as luxury or sport models, with different performance characteristics. This allows U.S. EPA to simulate applicable efficiency technologies across the entire U.S. light-duty vehicle fleet, including manufacturers' unique baseline fleet technology characteristics.

U.S. EPA has updated its technology assessment in many ways since its original 2012 analysis for the 2017–2025 rulemaking. Among the more significant changes were the addition of new highly efficient naturally aspirated engines (i.e., high compression Atkinson cycle engines, such as Mazda's SkyActiv), a more cost-effective 48-volt mild hybrid system, Miller-cycle turbocharging, variable geometry turbocharging, updated mass reduction costs, increased effectiveness of future 8-speed transmissions, updated battery cost modeling, and improved on-cycle stop-start effectiveness modeling. These improvements reflect automaker and supplier innovations that are occurring and entering production through 2025. The work is based on rigorous peer-reviewed studies using physics-based, system-level vehicle simulation and engineering "tear-down" cost studies for improved accuracy and transparency (e.g., see reports at U.S. EPA, 2017b, 2017c; NHTSA, 2017; CARB, 2017). This amounts to the most comprehensive, rigorous, and detailed regulatory assessment in the world.

As U.S. EPA did in its late 2016 proposed determination assessment, we analyze the technology progression of increasing CO_2-reduction technology and cost for 29 vehicle types. For the vehicle-level analysis below, we summarize the results for two representative vehicles that are among the highest in sales and are nearest to the passenger car and light truck fleet averages. Our fleet analysis below, like U.S. EPA's, uses all 29 types; the two technology progressions are summarized here simply to illustrate and describe several details related to the technology inputs involved in the analysis. The technology inputs and costs are all described in detail in U.S. EPA's proposed determination and its accompanying technical support document (U.S. EPA, 2016c). This report summarizes only the key technical details to provide the background and context for ICCT updated analysis. We provide additional technical details in the Appendix.

Passenger cars and crossovers

The technology cost progression we highlight for passenger cars and crossovers is that of EPA's vehicle type #6. It is based on an inline 4-cylinder engine and has a relatively low power-to-weight ratio and relatively high road load characteristics (i.e., higher than average aerodynamic and tire rolling resistance). The average curb weight for this vehicle type is approximately 3,500 pounds. The vehicle type represents 1.6 million vehicles, about 10% of all the U.S. light-duty vehicle sales in 2015. The vehicle type includes fractions of the vehicle sales of models such as the Subaru Forester, Honda CR-V, Toyota RAV4, Ford Fusion, and Honda Accord. Based on U.S. EPA's reference 2015 fleet, the 2015 harmonic average fuel economy of this class is 36 mpg (test cycle) and 29 mpg (real-world). The 2015 passenger car fleet already incorporated efficiency technologies that have reduced CO_2 emissions by about 23% since 2008, when the emerging efficiency technologies had yet to bring much benefit to the fleet.

Figure 2 illustrates the technology progression for a representative passenger car or crossover for increased efficiency in the 2025 time frame, based on U.S. EPA's proposed determination analysis. The chart shows the implementation of increasing efficiency technology to reduce fuel consumption and CO_2 emissions on the horizontal axis, by percent, along with the associated vehicle technology cost on the vertical axis. The data points in the figure represent technology packages with subsequent addition of technology as analyzed in U.S. EPA's technology modeling framework. Starting from a 2008 baseline, without the named technologies, the chart shows the lowest-cost progression to increase vehicle efficiency and reduce CO_2 emissions. As shown by the increasing slope, the progression moves from the least costly near-term technologies to more advanced long-term technologies. For context, the average 2015 passenger car fleet is at approximately a 23% CO_2 reduction on the chart, while the 2025 standards would require about a 47% reduction in CO_2 emissions. The particular baselines and technology paths of various automakers vary significantly.

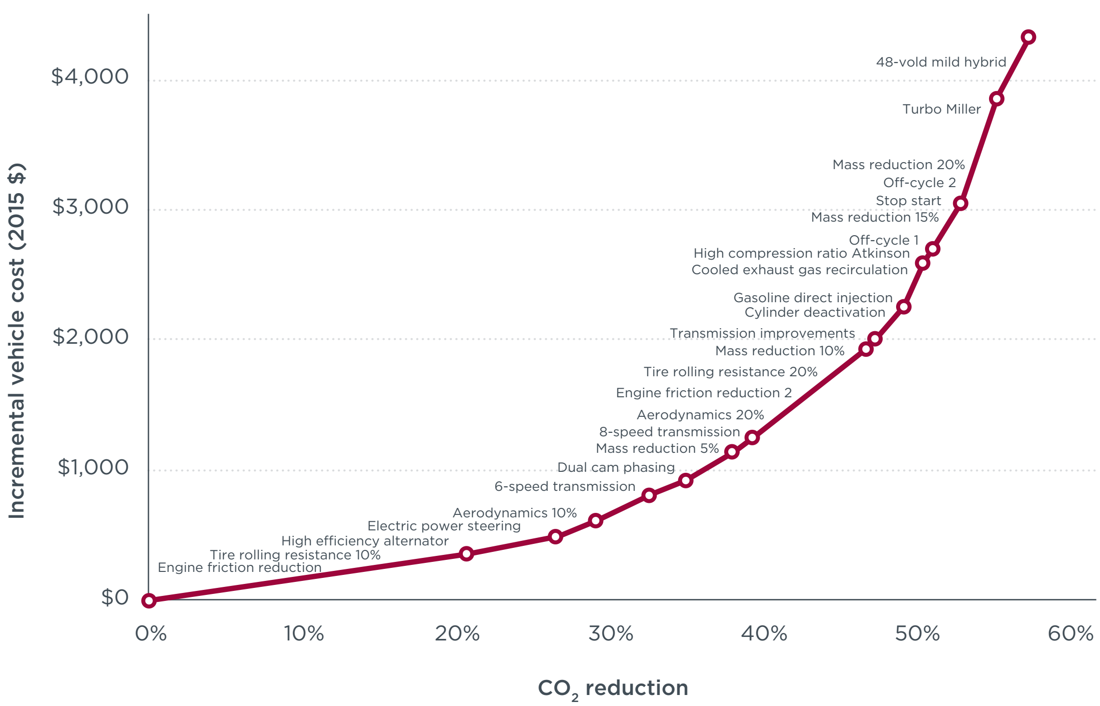

Figure 2. Lowest cost efficiency technology progression for CO_2 reduction in passenger cars and crossover vehicles (Based on U.S. EPA, 2016c).

Based on the U.S. EPA analysis shown in Figure 2, the first CO_2-reduction technology steps achieve approximately a 20% CO_2 reduction at less than $500 from engine friction reduction, tire rolling resistance reduction of 10%, high efficiency alternator, electric power steering, aerodynamic drag reduction of 10%, low drag brakes, dual cam phasing, weight reduction of 5%, and an improved transmission (e.g., 6-speed). The 2015 fleet has, on average, adopted technologies that achieve approximately this CO_2 emission level. However, we show this full technology progression to illustrate the full EPA technology and cost logic and because different automakers are at different points in their technology adoption process. Although not shown anywhere in the technology progression, automakers by 2025 are assumed in the U.S. EPA analysis to fully utilize air-conditioning technology credits for system efficiency and an alternative low global warming potential refrigerant that are worth 18.8 grams CO_2 per mile per car. All the 2025 technology costs shown incorporate volume- and time-based learning, which typically reduces the technologies' costs by about 2% per year in the near term and 1% per year in the long term.

The subsequent steps in Figure 2 include the progression to a more efficient transmission (e.g., wider gear ratio, 8-speed or continuously variable), further aerodynamic improvement to a drag reduction of 20%, further engine friction reduction, tire rolling resistance reduction of 20%, and weight reduction of 10%. These steps take the vehicle technology package to 34% CO_2 reduction for an incremental vehicle technology cost of under $1,000. The next technology steps include cylinder deactivation, gasoline direct injection, cooled exhaust gas recirculation, and an Atkinson cycle engine with higher compression ratio, achieving a 45% CO_2 reduction at a total technology package cost $1,900 in 2025. After this, additionally available technologies include off-cycle technologies worth 1.5 and 3.0 grams of CO_2 per mile, weight reduction of 15% and 20%, stop-start technology, a turbocharged Miller cycle engine, and finally a 48-volt mild hybrid, with packages costing $3,000–$4,300 for 49%–56% CO_2 reduction.

Light trucks

The technology cost progression that we highlight for light trucks is U.S. EPA's vehicle type #21, which is based on a 6-cylinder engine, has an average power-to-weight ratio, and has relatively high aerodynamic and rolling resistance load characteristics. The average curb weight for this type is approximately 4,600 pounds. This vehicle type represents 1.8 million vehicles, about 11% of all the U.S. light-duty vehicle sales. Example vehicles of this type include some of the Chevrolet Traverse, Ford Explorer, Jeep Grand Cherokee, and Lexus RX350 models. The 2015 harmonic average fuel economy of this class is 25 mpg (test cycle) and 20 mpg (real-world). The 2015 light truck fleet has added efficiency technologies that have reduced CO_2 emissions by about 21% since 2008, when the emerging efficiency technologies had yet to bring much improvement to the fleet.

Figure 3 illustrates the technology progression for a representative light truck for increased efficiency in the 2025 time frame, based on EPA's final determination analysis. The chart shows the implementation of increasing efficiency technology to reduce fuel consumption and CO_2 emissions on the horizontal axis, by percent, along with the associated vehicle technology cost on the vertical axis. As above, the origin is the 2008 baseline, without the named technologies, and the chart shows the lowest-cost progression to increase vehicle efficiency based on U.S. EPA's analysis. For context, the average 2015 light truck fleet is at approximately a 21% CO_2 reduction on the chart, and the 2025 standards would require about a 47% reduction in CO_2 emissions. As with the passenger car previously considered, the particular baselines and technology paths of various automakers' light truck fleets vary significantly.

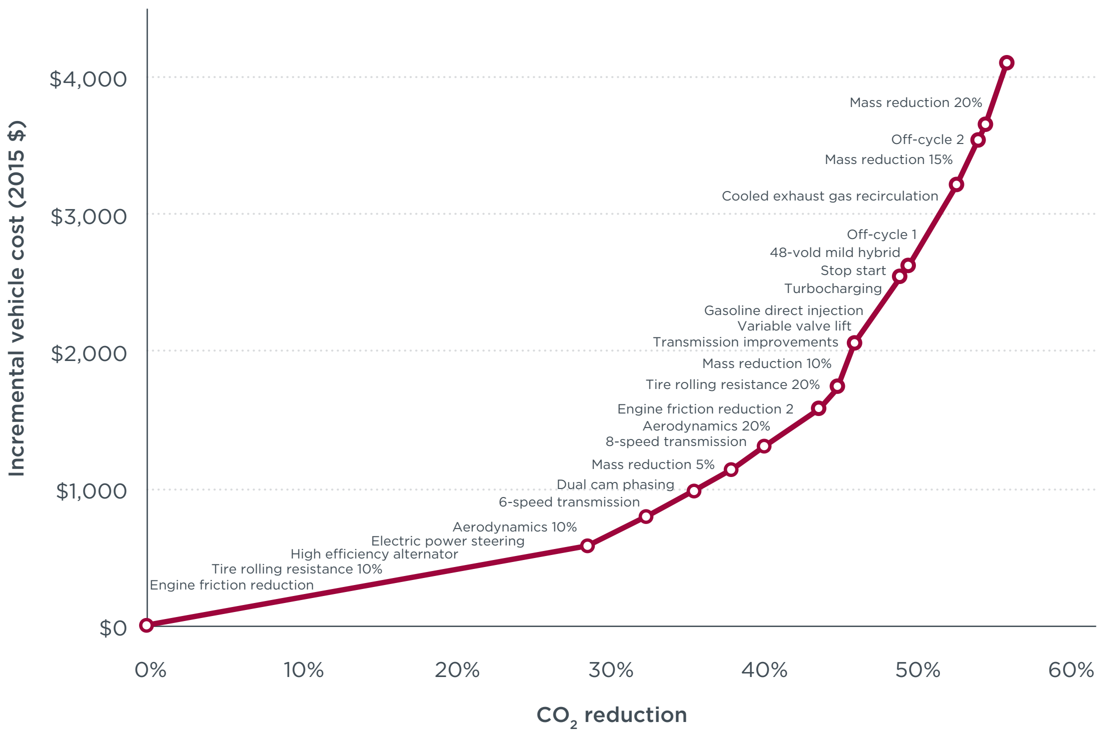

Figure 3. Lowest cost efficiency technology progression for CO_2 reduction in light trucks (Based on U.S. EPA, 2016c).

Based on U.S. EPA's analysis shown in Figure 3, the first CO_2-reduction technology steps achieve approximately a 28% CO_2 reduction at less than $600 from engine friction reduction, tire rolling resistance reduction of 10%, high efficiency alternator, electric power steering, aerodynamic drag reduction of 10%, low drag brakes, dual cam phasing, weight reduction of 5%, and a more efficient transmission (e.g., 6-speed). The 2015 fleet, on average, already has adopted approximately this first level of CO_2-reduction technology, but again it is shown here to illustrate U.S. EPA's full technology progression and to recognize that some automakers are at different stages. Although not shown anywhere in the technology steps in the figure, by 2025 automakers are assumed in the U.S. EPA analysis to be fully utilizing air-conditioning technology credits that are worth 24.4 grams CO_2 per mile per light truck.

The subsequent steps in Figure 3 include the progression to a more advanced transmission (e.g., wider gear ratio, 8-speed or continuously variable), further aerodynamic improvement to drag reduction of 20%, further engine friction reduction, tire rolling resistance reduction of 20%, and weight reduction of 10%. These technology steps take the vehicle technology package to 40% CO_2 reduction for an incremental vehicle technology cost of less than $1,300. Note that, from this point, where the above passenger car technology path takes a high compression ratio engine path, this light truck progression relies on turbocharging and mild hybridization. This is due to the large cost reductions enabled by downsizing from a V6 engine to an inline 4-cylinder engine with turbocharging. The next technology steps include variable valve lift, gasoline direct injection, turbocharging, stop-start, and then mild hybrid technology, achieving a 48% CO_2 reduction at a total technology package cost of $2,500 in 2025. After this, additionally available technologies include off-cycle technologies worth 1.5 and 3.0 grams of CO_2 per mile, cooled exhaust gas recirculation, and weight reductions of 15% and 20%, with packages that cost $3,200–$4,100 for a 52%–55% CO_2 reduction.

Electric vehicles

U.S. EPA incorporated plug-in hybrid electric vehicles (PHEVs) and battery electric vehicle (BEVs) of various electric ranges into its compliance analysis. Electric vehicles were excluded from the vehicle types that have substantial towing requirements. The electric vehicle technology packages fall beyond the technology progressions shown in Figures 2 and 3 due to their higher cost and higher benefits. Battery packs constitute the most predominant cost component associated with electric vehicle technology, followed by components like the electric motor-generator, power electronics, and charging equipment. Both BEV and PHEV technology packages also include complementary vehicle technologies, such as 20% reductions in aerodynamic drag, tire rolling resistance, and vehicle weight. The BEV technology packages also include credit for the subtraction of the internal combustion engine and the conventional multiple-speed baseline transmission. Electric vehicle costs typically range from $9,000 to $13,000 above the no-technology 2008 baseline in U.S. EPA's analysis, depending on the vehicle type and electric range. The CO_2 reduction from these vehicles is analyzed based on their upstream emissions from the future average U.S. electric grid, delivering a 71%–82% reduction for BEVs and 65%–75% reduction for PHEVs, depending on their range and electric efficiency. We analyze these electric vehicle technologies in more detail below.

UPDATED EFFICIENCY TECHNOLOGY ANALYSIS

In the following section, we highlight our technology changes from the preceding federal agency analysis. For this analysis of 2025–2030 technologies, we include updates from a variety of recent research studies and industry developments on new vehicle efficiency technologies. We describe the modifications to the U.S. EPA technology assumptions and the rationale for each change. We apply updates for this analysis based on our focus on 2025–2030 technologies and to reflect market developments that are applicable in this time frame.

The updates reflect the latest developments affecting both CO_2-reduction effectiveness and associated technology costs. The referenced work evaluates new developments in engines, transmissions, lightweighting, and electric vehicle technology. The conventional technology updates are based primarily on the ICCT's collaboration with automotive suppliers that include Eaton, Ricardo, Johnson Controls, Honeywell, ITB, BorgWarner, Dana, FEV, Aluminum Association, Detroit Materials, and SABIC, and on a series of working papers. Electric vehicle updates are based on two recent ICCT papers, Wolfram and Lutsey (2016) and Slowik, Pavlenko, and Lutsey (2016). Based on the technology updates in these analyses, we assess how the technology improvements and additions affect the overall CO_2-reduction technology cost curves, comparing the changes to the U.S. EPA analysis above. In this section, we assess technologies in terms of their direct manufacturing costs, excluding the various indirect and overhead costs, because this is the most common way those costs are cited and discussed in the literature. We emphasize, however, that the costs in Figures 2 through 5 include both direct and indirect costs, including the associated overhead, marketing, distribution, warranty, and profit, following U.S. EPA's methodology.

Advanced engines

A number of engine technology developments allow for greater efficiency benefits and lower costs than indicated in U.S EPA's proposed determination analysis for 2025. In particular, we make several updates related to direct injection, cooled exhaust gas recirculation, cylinder deactivation, high compression ratio Atkinson cycle, and turbocharged engines as outlined below.

Direct injection is a critical underlying technology for most high-efficiency vehicle paths in the 2025 time frame, including those based on turbocharging and cylinder deactivation technology. U.S. EPA estimated direct manufacturing costs for direct injection technology at $196–$356 per vehicle, ranging from inline 3-cylinder to V8 engines. Based on updated engineering teardown analysis by FEV, we reduced these costs to $91–$185 (FEV, 2015). Cooled exhaust gas recirculation is another component typically combined with several other technologies, such as turbocharging and high compression ratio naturally aspirated engines in advanced 2025 engine packages. U.S. EPA estimated the associated costs as approximately $216 per vehicle. Based on updated engineering teardown analysis by FEV, we reduce the costs to $95 for inline engines and $114 for V configuration engines (FEV, 2015).

Cylinder deactivation technology offers greater potential CO_2 reduction benefits in the 2025–2030 time frame than estimated in the U.S. EPA analysis. The agency analysis indicated cylinder deactivation CO_2 benefits of 3.5%–5.8% across vehicle types, at a cost of $75–$149 for various engine sizes. In the 2025 and beyond time frame, dynamic cylinder deactivation, a technology not considered in the U.S. EPA analysis, will be deployable with greater ability to control each cylinder with variable valve lift, allowing a 6.5%–8.3% benefit at a $54–$107 increase in cost over the agency cost estimate. These estimates reflect the combined benefits and costs of dynamic cylinder deactivation and enabling variable valve lift technology (Isenstadt, German, & Dorobantu, 2016).

High compression ratio Atkinson cycle engines are opening up a low-cost option to achieve higher efficiency without turbocharging. The original 2012 U.S. EPA rulemaking assessment found naturally aspirated engines would have difficulty competing with turbocharged engines by 2025. Since then, however, Mazda has been deploying a 13:1 compression ratio engine on most of its vehicles, and Toyota is using variable valve timing and other techniques to expand its use of Atkinson cycle engines to nonhybrid vehicles. The 2016 U.S. EPA analysis indicated this technology would have a 3%-8% (6% across class average) CO_2 reduction benefit when including an Atkinson cycle, high compression ratio, and cooled exhaust gas recirculation engine, whereas recent analysis suggests the benefit is likely to be 10%-15% (Isenstadt, German, & Dorobantu, 2016). Thus, we apply a 10%–14% (12.5% across class average) CO_2 reduction benefit to this technology. For the cost of this engine technology, we retain U.S. EPA costs without change, but do include technology package cost reductions for direct injection and cooled exhaust recirculation, as discussed above.

For turbocharged Atkinson cycle engines (i.e., Miller cycle engines), we retain U.S. EPA benefits as properly representative, but reduce costs for Atkinson-enabling technology to zero. Costs associated with enabling Atkinson cycle operation primarily target improved cylinder scavenging as required to maintain performance and expand the region of operating efficiency. Technology packages that include variable geometry turbocharging already provide such functionality, enabling Atkinson cycle operation at no additional cost.

U.S. EPA's analysis did not fully incorporate the potential of advanced turbocharging technology. Electrically boosted turbocharging, or *e-boost*, is estimated to increase turbocharging benefits by 5% at an additional cost of $338 (Isenstadt, German, Dorobantu, Boggs, & Watson, 2016). Thus, this turbocharging enhancement was included in our analysis of 2025 technology packages. The federal agency analysis appears to also miss the potential for variable compression ratio turbocharged engines, which offer an approximate 4% efficiency increase (Isenstadt, German, Dorobantu, Boggs, & Watson, 2016; Nissan, 2016); however, we elect not to include this technology in our analysis because of its uncertain potential costs. Technology advances also are underestimated in the federal analysis in the diesel technology area. U.S. EPA diesel technology costs, including engine plus aftertreatment, are approximately $2,100–$3,000. We estimate these costs will be $600–$850 lower due to aftertreatment cost reductions and improvements from a solenoid fuel injection and air handling systems (see Martec, 2016).

The U.S. EPA estimates the CO_2 reduction benefits of mild hybrid vehicles range from about 7.0%–9.5%. Our analysis, based on supplier information, indicates average CO_2 reductions to be 12.5% for passenger cars and sport utility vehicles (Isenstadt, German, Dorobantu, Boggs, & Watson, 2016). We thus adjust the U.S. EPA estimates by the ratio between a 12.5% average reduction and their average passenger car and SUV reduction of 9.1% to derive estimated CO_2 reduction benefits of 10.5%–12.9%. We retain U.S. EPA cost estimates for this technology without change.

Lightweighting

U.S. government agencies tend to underestimate the extent to which lightweighting technology is available and could penetrate the fleet. From the 2012 rulemaking analysis to the latest U.S. EPA analysis, the fleetwide mass reduction in new 2025 vehicles has moved from 8% up to 9%. This modest amount of lightweighting does not reflect all the recent relevant developments that indicate there is the potential to cost-effectively reduce mass by 15% in 2025, and by 20% in 2030, by using advanced materials and optimized design. Automaker redesigns are showing substantial lightweighting technology deployment is already underway, with a range of car, crossover, sport utility vehicle, and pickup models demonstrating 5%–15% weight reduction in 2014–2016 redesigns (Isenstadt, German, Bubna, et al., 2016).

Rigorous analysis of a number of different vehicle types is similarly indicating high potential for lightweighting. EPA's latest peer-reviewed analyses indicate that mass reduction of 19% for crossovers and 9% for pickups can effectively be achieved at no additional direct cost with optimized crashworthy designs (Caffrey, Bolon, Harris, & Kolwich, 2013; Caffrey, Bolon, Kolwich, Johnston, & Shaw, 2015). These analyses are further supported by earlier peer-reviewed mass-reduction studies from Lotus, EDAG, and FEV that similarly show that lightweight vehicle designs are opening up more very low-cost lightweighting opportunities (ICCT, 2017). Recent synthesis study of lightweighting assessments indicates that up to 15% mass reduction can be achieved at about one-third of the cost that U.S. EPA estimated (Isenstadt, German, Bubna, et al., 2016). For this study, to better reflect the latest engineering studies, we modified the U.S. EPA total lightweighting cost assumptions downward. To do so, we retained U.S.

EPA's direct technology manufacturing costs and reduced its indirect costs such that long-term indirect costs do not exceed 50% of direct costs for technology applications in 2025 and beyond.

The U.S. EPA's mass reduction benefit estimates improved substantially between its 2016 Draft Technical Assessment Report, which showed 0.51%-0.52% CO_2 reduction per percent mass reduction, and its 2016 Proposed Determination analysis, which reflected a 0.55%-0.68% CO_2 reduction per percent mass reduction. Based on a detailed analysis of the effect of such improvements across a range of vehicle types, we revised the benefit estimates slightly upward to 0.57%-0.68% CO_2 reduction per percent mass reduction (Meszler, German, Mock, & Bandivadekar, 2016; National Research Council, 2013).

Electric vehicles

We use U.S. EPA's electric vehicle cost structure but reduce several component costs to bring them in line with updated state-of-the-art analyses for the 2025–2030 timeframe. The largest cost component for such vehicles is the battery pack. The applicable U.S. EPA electric vehicle battery pack numbers, for small to mid-size vehicles, are from $180 to $200 per kilowatt hour (kWh). Leading analysis is now indicating that $140 per kWh is a realistic value due to battery innovation and volume by the 2025 time frame (Wolfram & Lutsey, 2016; Slowik et al., 2016; Anderman 2016a, 2016b; Nelson, Ahmed, Gallagher, & Dees, 2015). We use $140/kWh for the battery cost for BEVs and $200/kWh for 40-mile-range PHEVs for 2025. Our incorporation of a vehicle efficiency improvement of 2% per year in kilowatt-hour per mile over 10 years, for 18% more efficient electric vehicles for our 2025–2030 analysis, reduces electric vehicle costs further. This is based on the improvements underway from aerodynamics, tires, power electronics, transmission, and charging efficiency, and it reduces the battery pack sizes. We also upgrade the BEV electric ranges to 100, 125, and 200 miles (whereas U.S. EPA has chosen to model 75-, 100-, and 200-mile ranges). This increases battery size, and thus costs, but it is warranted based on the trending market balance between lower cost and higher electric range electric vehicles.

We also make several changes in nonbattery pack assumptions. The U.S. EPA (2016c) analysis includes home level 2 charging equipment, and based on numerous online accounts of at-home installations and continued support from utilities, we reduce the applicable cost from approximately $1,300 to $500. We also include cost reductions for BEVs for their lack of aftertreatment systems. We subtract aftertreatment system costs of $500 for small cars and $700 for crossovers based on Posada, Bandivadekar, and German (2012) and U.S. EPA (2014). We also modify the indirect costs by changing BEV cost complexity from “high” to “low.” This is appropriate because BEVs are inherently less complex than conventional vehicles, which reduces or eliminates the need for engineering calibrations of the engine, transmission, and mechanical auxiliary parts and reduces tooling costs.

Summary of technology updates

Table 1 summarizes the key modifications and additions this 2025–2030 analysis makes to the U.S. EPA's 2022–2025 analysis. Ranges are shown because the percent CO_2 emission reduction improvements and associated technology costs tend to differ by vehicle type and engine size. The lower part of each range applies to smaller engines and vehicles. As shown, our technology assumptions result in several percentage points in additional technology improvement in advanced combustion vehicles and mild hybrid technology. The cost differences indicate that some of the advanced combustion technology costs will be reduced by about $100 for direct injection and cooled exhaust gas recirculation. The largest cost difference is in the case of electric vehicles, where our costs are approximately $1,600–$2,700 less than those of the U.S. EPA. We note that the costs in the table are direct manufacturing costs and exclude indirect costs for factors like warranty, overhead, and retooling. Indirect costs typically add 20%–50% in the long term for these technologies. Both the U.S. EPA and this analysis include such costs for all the technologies in the subsequent cost curves and fleet modeling.

Table 1. Summary of technology fuel consumption reduction and direct manufacturing cost input differences between U.S. EPA final determination and this analysis for 2025

	Fuel consumption and CO_2 reduction benefits[a]		Direct manufacturing cost (2015 $)[b]	
	U.S. EPA	ICCT	U.S. EPA	ICCT
Cylinder deactivation	3.5%-5.8%	No change	$75-$149	No change
Dynamic cylinder deactivation[c]	Not included	6.5%-8.3%	Not included	$138-$256
Direct injection[d]	1.5%	No change	$196-$356	$91-$185
Cooled exhaust gas recirculation	1.7%-5.3%	No change	$216	$95-$114
Advanced diesel	20.0%-25.2%	No change	$2,104-$2,950	$1,491-$2,096
E-boost	Not included	5.0%	Not included	$338
Mild hybrid (48-volt)	7.0%-9.5%	10.5%-12.9%	$580	No change
High compression ratio[e]	3.4%-7.7%	10.1%-14.1%	Varies	Varies
Miller cycle[f]	12.4%-20.3%	No change	Varies	$93-$222 lower
Plug-in hybrid electric vehicle[g]	65%-75%	No change	$5,534-$10,371	$3,564-$7,805
Battery electric vehicle[g]	71%-82%	No change	$5,131-$10,663	$2,410-$9,098
Mass reduction (20%)	11.2%-13.7%	11.6%-13.7%	$0.17-$1.15 per pound	No change

[a] Shown as per mile reduction; benefits vary by vehicle type and engine size; improvements are shown for individual technology; effects are handled as applied with multiple technologies simultaneously in lumped parameter model
[b] Costs in 2015 dollars, ranges as shown because they vary by vehicle type and engine size
[c] Includes variable valve lift technology
[d] Direct injection technology without synergistic technologies such as cooled exhaust gas recirculation and turbocharging
[e] Includes Atkinson cycle, direct injection, and cooled exhaust gas recirculation
[f] Includes Atkinson cycle, 24 bar turbocharging, cooled exhaust gas recirculation, and engine downsizing; costs vary not only by vehicle type #1 through #6, but also with the base engine and camshaft configuration subject to downsizing
[g] Range shown for vehicle type #1 through #6, including low and high electric range and in-home charger; CO_2 emission reductions are based on U.S. EPA estimation of 2025 average U.S. grid emissions

Passenger cars and crossovers

As for the U.S. EPA analysis above, here we show the ICCT-updated technology cost progression for vehicle type #6, which has a baseline inline 4-cylinder engine and an average vehicle curb weight of 3,500 pounds. Figure 4 illustrates the passenger car and crossover efficiency technology progression for the 2025 time frame, including our technology updates as discussed above, compared to the U.S. EPA analysis, which was previously depicted in Figure 2. The chart shows the implementation of increasing efficiency technology to reduce CO_2 emissions on the horizontal axis, along with the associated vehicle technology cost on the vertical axis. Starting from an approximate 2008 no-technology baseline, the chart shows the lowest-cost progression to increase vehicle efficiency. As shown by the increasing slope, the progression moves from the most cost-effective nearer term technologies to more advanced longer-term technologies. For context, the average 2015 passenger car fleet is at approximately a 23% CO_2 reduction on the chart, and the 2025 standards would require about a 47% reduction in CO_2 emissions.

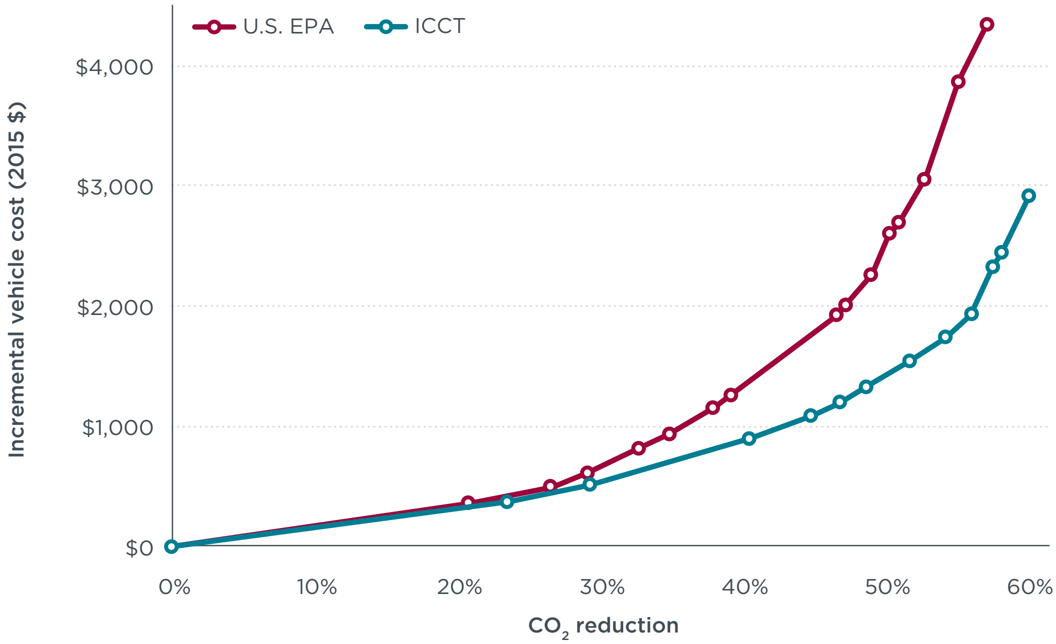

Figure 4. Lowest cost efficiency technology progression for CO_2 reduction in model year 2025 for passenger cars and crossover vehicles.

Comparing the ICCT and U.S. EPA results reveals several notable differences. The incrementally higher CO_2 benefit and lower cost of several technologies from our updated analysis makes for a lower overall cost curve throughout the progression. For example, at the 47% CO_2 reduction point, which is about the average required CO_2 level for compliance with the 2025 standards, the ICCT's updated cost curve shows approximately $1,300, about 40% lower than the U.S EPA's $2,100 cost for equivalent results.

There also are changes in the sequence of technologies that are adopted moving up the curve. In particular, cylinder deactivation and high compression ratio (direct injection, Atkinson, cooled exhaust gas recirculation) moved up in the progression compared to U.S. EPA's analysis. Dynamic cylinder deactivation expands the efficiency potential after the 44% CO_2 reduction point in the progression. In addition, lightweighting technology moves up within the progression due to its reduced cost, with 15% weight reduction at the approximated 2025 CO_2 standard level. The largest emission reduction shown in the ICCT analysis, a 59% CO_2 reduction at $2,900 additional cost above the 2008 no-technology baseline, is for a mild hybrid technology package. Comparing the two cost curves, the ICCT 2025–2030 technology updates expand the car efficiency frontier by approximately 8%–10% for a given technology package cost above $2,000.

Light trucks

As we did for the U.S. EPA light truck analysis above, here we show the ICCT-updated technology cost progression for light trucks for vehicle type #21, which has a baseline 6-cylinder engine and an average vehicle curb weight of 4,600 pounds. Figure 5 illustrates the light truck efficiency technology progression for the 2025 time frame, including our updated technology inputs, and a comparison to the U.S. EPA analysis. The chart shows the implementation of increasing efficiency technology to reduce CO_2 emissions on the horizontal axis, along with the associated vehicle technology cost on the vertical axis. Starting from an approximate 2008 no-technology baseline, the chart shows the lowest-cost progression to increase vehicle efficiency. For context, the average 2015 light truck fleet is at approximately a 21% CO_2 reduction on the chart, and the 2025 standards would require about a 47% reduction in CO_2 emissions.

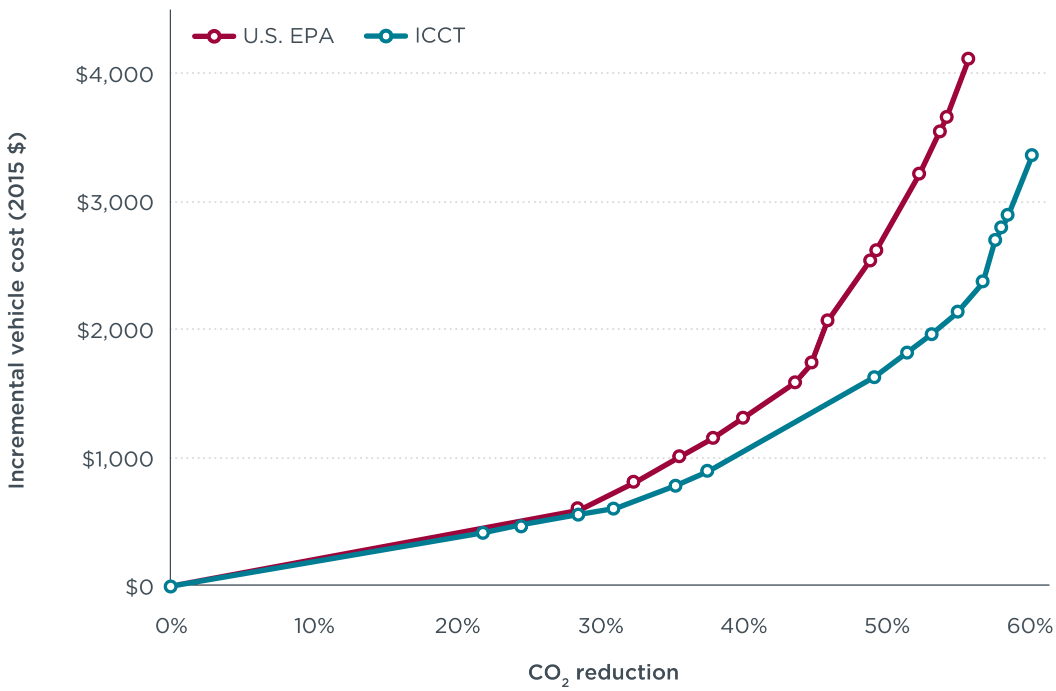

Figure 5. Lowest cost efficiency technology progression for CO_2 reduction in model year 2025 for light trucks.

Several differences are clearly apparent in comparing the U.S. EPA and ICCT data in Figure 5. The incrementally higher CO_2 benefit and lower cost of several technologies make for a lower overall cost curve throughout the progression. For example, at the 47% CO_2 reduction point, which is about the average CO_2 level required for compliance with the 2025 standards, the ICCT's updated cost curve shows approximately $1,500. This is about 34% lower than the U.S. EPA estimated cost of $2,300.

We also note several differences in the sequence of technology adoption while moving up the light truck cost-CO_2 curve. At the 48% CO_2 reduction level, the ICCT package includes dynamic cylinder deactivation and high compression ratio (direct injection, Atkinson, cooled exhaust gas recirculation) technology. This differs from the U.S. EPA light truck analysis, which has turbocharging and 48-volt mild hybrid technology at this CO_2 level. In addition, lightweighting technology moves up within the progression due to its reduced cost, with 15% weight reduction at the approximated 2025 CO_2 standard level. The largest emission reduction shown in the ICCT analysis, a 60% CO_2 reduction at $3,400 additional cost above the 2008 no-technology baseline, is for a mild hybrid. Comparing the two cost curves, the ICCT 2025–2030 technology updates expand the light truck efficiency frontier by approximately 8%–9% for a given technology package cost above $2,000.

Electric vehicles

Because electric vehicles fall outside the cost-CO_2 curves shown above, we provide some additional information on how the technology packages were updated for our 2025–2030 focused analysis. Figure 6 shows the components of the battery electric vehicle technology package costs for the U.S. EPA and ICCT analyses for model year 2025. The figure includes the direct and indirect costs for the low (75-mile for U.S. EPA, 100-mile for ICCT), mid (100-mile for U.S. EPA, 125-mile for ICCT0), and high (200-mile for U.S. EPA and ICCT) electric ranges for vehicle type #6. We illustrate vehicle type #6 to show representative passenger vehicles and crossovers as above, and due to the likelihood of higher electric vehicle penetration in these classes rather than light trucks. As indicated, ICCT's electric vehicle costs are $4,300–$5,300 lower than U.S. EPA's across the various ranges. The high electric range electric vehicle has technology costs of approximately $12,300, according to the U.S. EPA analysis, compared to $7,000 for our updated technology inputs. As indicated above, a major cost reduction in the ICCT's case is due to the battery pack cost being reduced to $140/kWh rated capacity; reduced home charger and indirect costs also contribute to the difference. Approximately similar cost dynamics are seen in the other vehicle classes, except for the towing truck classes that do not have electric vehicle packages.

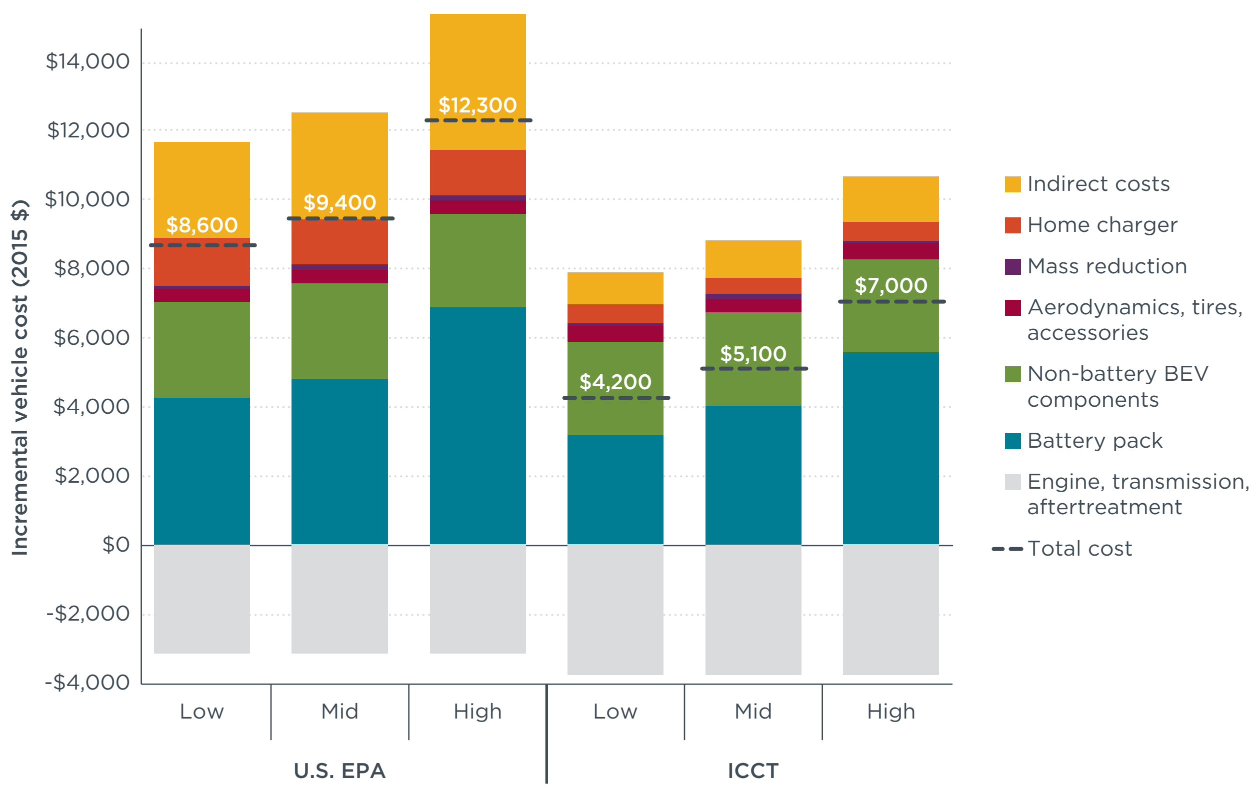

Figure 6. Battery electric vehicle cost in 2025 for low, mid, and high electric range vehicles based on U.S. EPA and ICCT data.

III. FLEET CO_2-REDUCTION SCENARIOS

We analyze the above vehicle technologies for new vehicle fleet impacts in model year 2025 and 2030. To model the fleet impacts, we use the Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) modeling framework (U.S. EPA, 2017d). This approach includes modeling the shift of the baseline model year 2015 vehicle fleet progressively into more advanced CO_2-reduction technology packages, as summarized above, until each automobile manufacturer is in compliance with the fleet CO_2 constraints. The vehicle technologies are modeled separately for the 29 different vehicle types with differing engines, power, road load, and towing characteristics. The individual technologies are combined and modeled as technology packages using the U.S. EPA Lumped Parameter Model, which has been refined through EPA's extensive computer simulation projects to assess system-level effects. The OMEGA model seeks cost-effective application of technologies to achieve compliance with the specified CO_2 target. Modeling in different future years accounts for time- and production-volume-based learning that reduces manufacturing costs of the technologies over time.

In this section, we analyze several 2025–2030 scenarios to investigate the implications of the updated CO_2 emission reduction technologies and their costs. We first model compliance in model year 2025 with the adopted greenhouse gas emission standards for that year, and compare our results to the U.S. EPA analysis. Following this, we simulate the fleet adopting higher levels of efficiency technology to achieve three progressively lower CO_2 emission levels, based on 4%, 5%, and 6% annually compounded CO_2 reductions for 2025 through 2030.

COMPLIANCE WITH ADOPTED MODEL YEAR 2025 STANDARDS

The modeling of fleet compliance with regulatory standards through 2025 is based on increasing the deployment of available efficiency technologies in the fleet and assessing their associated costs. The federal regulatory analysis incorporates many dozens of individual technologies and their costs, and estimates the minimal deployment of known technologies to cost-effectively comply with the standards. Our fleet analysis incorporates the individual technology modifications from section II, above, to estimate the technology penetration for compliance with the adopted 2025 standards and compares the results with those of the U.S. EPA proposed determination analysis. This fleet analysis takes U.S. EPA's methods for compiling, prioritizing, and selecting technology packages as a given. To further maintain integrity and consistency with U.S. EPA's methods, the OMEGA model and various associated constraints and inputs were also not modified, with one exception: We removed the percent technology penetration cap for 200-mile range battery electric vehicles to allow greater electric vehicle penetration in the more demanding low-CO_2 2030 scenarios, where otherwise several companies would not be in compliance.

Table 2 summarizes the fleetwide technology penetration and associated costs needed to comply with the adopted model year 2025 greenhouse gas standards. This analysis indicates that advances in combustion technologies are enabling substantially lower compliance costs to achieve model year 2025 standards. As shown in the table, the primary technology differences in the modeling are related to the lower penetration of hybrid technology in our updated analysis. This is largely due to the greater CO_2 reduction benefits at lower costs from advanced combustion technologies like high compression ratio Atkinson cycle engines and cylinder deactivation, as previously analyzed. Although the preceding analysis of individual technologies revealed lower cost diesel and mild hybrid technology, the OMEGA optimization prioritizes advanced combustion technologies due to their greater cost-effectiveness. The optimization routine selects only those technologies required to attain a specified CO_2 target, so additional cost-effective technologies may remain “on the table” that manufacturers could still choose to facilitate compliance with more stringent standards.

Table 2. Technology penetration to meet adopted 2025 standards

Area	Technology	U.S. EPA	ICCT
Advanced combustion (nonhybrid)		75%	93%
Hybrid	Mild hybrid	18%	0%
	Full hybrid	2%	2%
Electric	Plug-in hybrid electric	2%	2%
	Battery electric	3%	3%
Incremental technology cost from 2021 standards		$875	$551
Incremental technology cost from 2015		$1,378	$886

As shown in Table 2, our inclusion of lower electric vehicle costs did not have a significant impact on electric vehicle uptake in 2025. This indicates that additional electric vehicle deployment, beyond complying with the California Zero-Emission Vehicle regulation, is not part of a low-cost compliance scenario for 2025. However, we emphasize that many automakers may continue to choose to deploy more electric vehicle technology than these minimum compliance cost paths to stake out competitive leadership positions and be positioned for the longer term.

The fleet modeling cost results with ICCT’s updated technology assumptions are also shown side-by-side with U.S. EPA’s similar analysis from its final determination in Table 2. The U.S. EPA analysis indicates a total cost of $1,378 above reference 2015 costs to comply with the 2025 standards. Due to the combination of greater technology CO_2-reduction effectiveness and lower costs of technologies like direct injection and cooled exhaust gas recirculation, our analysis indicates the costs to comply with the 2025 standards will be substantially lower than the U.S. EPA projection. Our updated technology inputs reduce the 2025 fleet average technology cost to $886 per vehicle, 36% lower than the agency projection.

ANALYSIS OF SCENARIOS FOR POTENTIAL 2030 STANDARDS

We apply the same modeling approach and technology CO_2 emission-reduction benefits for our 2030 fleet analysis of incrementally lower CO_2 levels. We simulate the new vehicle fleet achieving three progressively lower CO_2 emission levels, based on footprint-indexed CO_2 standards that are reduced by 4%, 5%, and 6% annually for 2025 through 2030. The technology costs are reduced marginally between 2025 and 2030 through the standard learning assumptions that generally reduce technology costs at 1% per year from the cost curves shown above.

Table 3 summarizes the percent technology penetration in model year 2025 and in the three 2030 scenarios. This analysis indicates that several individual advanced combustion technologies continue to increase in penetration from 2025 to 2030 to achieve lower fleet CO_2 levels. High compression ratio Atkinson cycle and cylinder deactivation penetration increases to account for a majority of new engines in 2030. Lightweighting technology is deployed at greater levels in the 2030 scenarios, reaching 12%–13% fleet average mass reduction in 2030, up from 9% in 2025. The 2030 scenarios also see greater hybrid uptake, including mild and full hybrids, with 7%–14% of new vehicles in 2030. The analysis indicates that incrementally more stringent 2030 standards could still be achieved mostly with advanced combustion technology, while also initiating the launch of electric vehicles to 13%–23% of the new vehicle fleet.

Table 3. Technology penetration to meet adopted 2025 standards and achieve various levels of potential 2030 standards

Area	Technology	ICCT 2025	ICCT 2030 4%/year	ICCT 2030 5%/year	ICCT 2030 6%/YEAR
Advanced combustion (nonhybrid)		93%	80%	72%	63%
Hybrid	Mild hybrid	0%	5%	9%	12%
	Full hybrid	2%	2%	2%	2%
Electric	Plug-in hybrid electric	2%	2%	2%	2%
	Battery electric	3%	12%	16%	21%
Fuel economy, test cycle (mpg)		46	55	57	60
Fuel economy, real world (mpg)		35	42	44	46
CO_2 emissions test cycle (g/mile)		173	141	134	127
Incremental technology cost from 2025		—	$772	$1,038	$1,343

Percentages rounded to the nearest percent

As shown in Table 3, the scenarios that get progressively more stringent at 4%–6% lower CO_2 emissions and fuel use per mile annually from 2025 to 2030 can be achieved with an incremental cost increase between 2025 and 2030 of $772 to $1,343. This cost increase is associated with an increase in consumer new vehicle fuel economy from 35 mpg in 2025 to 42–46 mpg in 2030.

The above results are presented in terms of the fleet average impact, but manufacturers are at different levels of baseline deployment of technology and have different technology penetration rates and associated costs. The OMEGA modeling does analyze such differences. Most major manufacturer groups, including Ford, General Motors, Honda, Hyundai-Kia, Mitsubishi, Nissan, Subaru, Toyota, and Volvo, are near or below the industry average technology costs represented above. This is largely due to these companies having relatively good standing in their reference 2015 fleets' CO_2 emissions, compared to the 2015 and beyond standards. Other companies, including BMW, Fiat-Chrysler, Jaguar-Land Rover, Mercedes, and Volkswagen, have higher costs for a variety of reasons. For luxury-focused automakers, the costs tend to be higher because these companies have already adopted many efficiency technologies, and automakers that have focused on offering larger engines, greater vehicle acceleration, and more consumer amenities that add weight need greater efficiency technology to compensate. Such companies will therefore require more advanced technology deployment—including hybrid and plug-in electric vehicle technology in particular—in the 2025–2030 fleet modeling, which will increase their average costs.

Figure 7 summarizes the relative increase in vehicle price due to vehicle efficiency technology adoption over time to achieve the lower CO_2 emission levels. As shown, the preceding analysis of efficiency technologies to achieve increased efficiency and lower CO_2 emissions would result in increasing vehicle prices by approximately 4%–6% in 2030. For context, the average price of a new 2016 vehicle was approximately $35,000, increasing 1.5% from the previous year (Kelley Blue Book, 2017). Based on this growing price trend, the increase in price from the efficiency technologies would only amount to about one-quarter of the total expected vehicle price increase over the time frame of this analysis. The approximate 5% increase in vehicle prices due to increased efficiency technology would be associated with increasing consumer fuel economy by about 65%–81%, from 26 mpg in 2016 to 42–46 mpg by 2030. The increased fuel economy would be associated with a 47%–53% reduction in CO_2 emissions per mile.

We also conducted a preliminary analysis of the fuel savings impact of these standards and the technology costs on an average vehicle. We apply U.S. EPA's benefits calculation methodology, including the U.S. Energy Information Administration's reference fuel costs and a 3% discount rate. These scenarios for 2030 would result in greatly decreased fuel costs. Fuel savings for the average 2030 vehicle buyer are two to three times greater than the technology costs over the lifetime of each affected vehicle for the three scenarios analyzed.

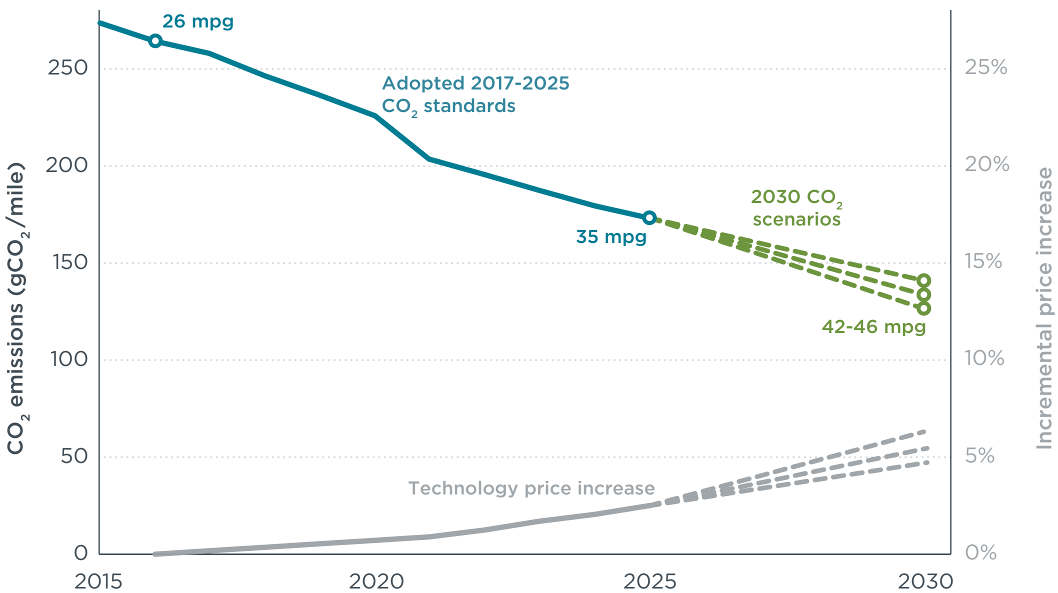

Figure 7. Vehicle price increases from using increased vehicle efficiency technology to achieve lower CO_2 emission levels.

IV. CONCLUSION

This work has numerous implications for future fuel efficiency and CO_2 standards, including insights related to technology availability and associated cost in the 2025–2030 time frame. The analysis builds on the extensive U.S. EPA technical inputs, state-of-the-art modeling, and underlying peer-reviewed reports. The analysis couples this U.S. EPA work with emerging efficiency technology developments to provide an update to the government's regulatory analysis for new vehicles in 2025, as well as estimate the technical potential and cost of continued fleet improvements for new vehicles through 2030.

The primary technology conclusion is that emerging efficiency technologies are expanding the frontier for internal combustion vehicles. Our analysis indicates that approximately 8%–10% greater efficiency improvement, compared to the latest regulatory agency analysis, is available and cost effective in advanced technology packages in the 2025 time frame. Continually improving technologies like cylinder deactivation, high compression Atkinson cycle engines, lightweighting, and mild hybrid technology will each allow several percent greater CO_2 emission reduction benefits than the 2022–2025 regulatory analysis indicated. These developments will allow internal combustion engine vehicles that are much more advanced than those in 2017 to continue to play the predominant role in most automakers' compliance strategies in the 2025 time frame.

Technology cost reduction among emerging technologies is indicating that previous government regulatory cost estimates have been too conservative. This follows a long-standing pattern whereby the auto industry innovates and finds less expensive paths to comply with standards once those standards have been in place for several years (e.g., see National Research Council, 2006). Updated technology cost studies, with input from leading technology suppliers, show direct injection, cooled exhaust gas recirculation, and lightweighting technology will cost hundreds of dollars less than federal analysis has indicated. Based primarily on rapid developments in battery packs, electric vehicle costs will be reduced by thousands of dollars per vehicle by 2025 compared to regulatory estimates. Including these latest technology developments and updated technology cost inputs, compliance costs for the U.S. 2025 standards will be 34%–40% lower than estimated in the latest regulatory agency analysis.

The impact of these findings on new consumer vehicle fuel economy is profound. Consumer fuel economy in model year 2015 was about 26 mpg. With the adopted 2025 standards, fuel economy is projected to reach 35 mpg. Based on this paper's technical assessment, scenarios for a progressively more efficient fleet at 4%–6% lower fuel use per mile annually would increase consumer fuel economy levels to 42–46 mpg in 2030, up 65%–81% from the 2016 average fuel economy. This translates directly into substantial consumer fuel savings. New vehicles in 2030 could consume at least 40% less fuel per mile than new 2016 vehicles. The three 2030 technology cases we analyzed resulted in consumer fuel savings that were two to three times the technology costs.

These greater efficiency levels by 2030 can be achieved cost-effectively, with the associated vehicle efficiency technology resulting in an approximate 4%–6% increase in vehicle prices. Although advanced combustion technologies could dominate most automakers' approaches to complying with the 2025 standards, greater electrification with hybrids and eventually plug-in electric vehicles is likely in the 2030 time frame.

Under the 2030 fleet scenarios analyzed, the launch of electric vehicles, including plug-in hybrids, would reach 13%–23% of the new vehicle fleet. This increased electrification trend is enabled by the battery industry's shift to higher production volume as the emerging suppliers compete and meet market demand globally. We emphasize that many automakers could deploy electric vehicle technology at greater levels than indicated by our minimum-compliance-cost scenarios, due to their plans to stake out technology leadership positions and be well positioned for the longer term. Other automakers may deploy fewer electric vehicles, choosing to exhaust advanced combustion efficiency options.

We note several additional implications of the results. Our updated technology assessment indicates that the average payback period will become even more advantageous to first vehicle owners than the regulatory agencies indicated. Further consumer fuel saving analysis would ideally investigate such implications, including the cost savings to consumers at various technology levels and the associated payback periods for given car buyers. There could also be much broader economic benefits from the increased sales of more attractive high-efficiency vehicles, increased fuel savings rippling through the economy, and employment benefits from the new technologies. Such impacts warrant further assessment to better understand the implications of shifting to a more efficient vehicle fleet.

A much broader investigation of the impacts of this work internationally would also be warranted. For example, major markets like Europe and China have similar questions regarding their automobile fleets' potential to help meet their climate and energy goals. Others, like Japan, Canada, India, Brazil, South Korea, and Mexico, have similar motivations and would also gain from a better understanding of the potential for 2025–2030 standards that go beyond their currently adopted policies. The expanding frontier of advanced combustion, hybridization, and plug-in electric vehicle technology affects all these markets. Adoption of progressive, harmonized, long-lead-time standards around the world would ensure that technology is widely deployed and would further reduce technology costs. This, in turn, would allow for greater and more cost-effective emission-reduction and oil-saving benefits.

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APPENDIX

This section provides additional details associated with the technology progressions for 2025 CO_2-reduction technologies. For the passenger cars and crossovers of vehicle type #6, Table A1 shows U.S. EPA's data for the final lowest cost technology progression (from Figure 2), and Table A2 shows ICCT's updated data (Figure 3). For the light trucks in vehicle type #21, Table A3 shows U.S. EPA's data for the final lowest cost technology progression (Figure 4) and Table A4 shows ICCT's updated data (Figure 5). Following the four tables is Table 5, which defines the technology packages abbreviations.

Table A1. Technology packages, CO_2 emissions, and 2025 cost for U.S. EPA passenger car and crossover (vehicle type #6)

Technology Package	Percent CO_2 reduction	Test cycle CO_2 (g/mi)	Incremental vehicle price in 2025 (2015 $)
Baseline (inline 4-cylinder dual overhead cam, 4-speed automatic transmission)	0%	248	$0
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR5, TRX11	20%	197	$362
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR5, TRX21	26%	183	$499
EFR2, LRR2, IACC1, EPS, Aero1, LDB, DCP, WR5, TRX21	28%	177	$610
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, WR5, TRX21	32%	169	$811
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, WR10, TRX21	34%	163	$929
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, WR10, TRX22	37%	156	$1,150
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, WR10, TRX22	38%	153	$1,255
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, ATK, EGR, WR10, TRX22	45%	135	$1,932
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, ATK, EGR, OC1, WR10, TRX22	46%	134	$2,006
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, ATK, EGR, OC1, WR15, TRX22	48%	129	$2,259
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, SS, ATK, EGR, OC1, WR15, TRX22	49%	126	$2,591
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, SS, ATK, EGR, OC2, WR15, TRX22	50%	125	$2,697
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, SS, ATK, EGR, OC2, WR20, TRX22	51%	120	$3,058
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, SS, ATK, TURBM, EGR, OC2, WR20, TRX22	54%	115	$3,861
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, MHEV, ATK, TURBM, EGR, OC2, WR20, TRX22	56%	110	$4,343
LRR2, IACC1, EPS, Aero2, LDB, EV75 mile, WR20	100%	0	$8,591
LRR2, IACC1, EPS, Aero2, LDB, EV100 mile, WR20	100%	0	$9,382
LRR2, IACC1, EPS, Aero2, LDB, EV200 mile, WR20	100%	0	$12,301

Table A2. Technology packages, CO_2 emissions, and 2025 cost for ICCT updated passenger car and crossover (vehicle type #6)

Technology Package	Percent CO_2 reduction	Test cycle CO_2 (g/mi)	Incremental vehicle price in 2025 (2015 $)
Baseline (inline 4-cylinder dual overhead cam, 4-speed automatic transmission)	0%	248	$0
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR10, TRX11	23%	191	$378
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR10, TRX21	29%	177	$515
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, GDI, ATK, EGR, WR10, TRX21	40%	150	$901
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR10, TRX21	44%	139	$1,085
EFR2, LRR2, IACC1, EPS, Aero1, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR10, TRX21	46%	135	$1,196
EFR2, LRR2, IACC1, EPS, Aero1, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR15, TRX21	48%	130	$1,322
EFR2, LRR2, IACC1, EPS, Aero1, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR15, TRX22	51%	123	$1,544
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR15, TRX22	53%	117	$1,744
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR20, TRX22	55%	112	$1,928
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, SS, ATK, EGR, OC1, WR20, TRX22	56%	109	$2,333
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, SS, ATK, EGR, OC2, WR20, TRX22	57%	107	$2,439
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, MHEV, ATK, EGR, OC2, WR20, TRX22	59%	103	$2,921
LRR2, IACC1, EPS, Aero2, LDB, EV100 mile, WR20	100%	0	$4,151
LRR2, IACC1, EPS, Aero2, LDB, EV125 mile, WR20	100%	0	$5,122
LRR2, IACC1, EPS, Aero2, LDB, EV200 mile, WR20	100%	0	$6,963

Table A3. Technology packages, CO_2 emissions, and 2025 cost for U.S. EPA light truck (vehicle type #21)

Technology Package	Percent CO_2 reduction	Test cycle CO_2 (g/mi)	Incremental vehicle price in 2025 (2015 $)
Baseline (V-6 engine dual overhead cam, 4-speed automatic transmission)	0%	349	$0
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR5, TRX21	28%	250	$586
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR5, TRX22	32%	236	$807
LUB, EFR1, LRR1, IACC2, EPS, Aero2, LDB, DCP, WR5, TRX22	35%	226	$1,008
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, WR5, TRX22	38%	218	$1,150
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, WR10, TRX22	40%	210	$1,303
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, GDI, TDS18, WR10, TRX22	43%	198	$1,581
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, TDS18, WR10, TRX22	44%	194	$1,729
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, SS, TDS18, WR10, TRX22	46%	190	$2,061
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, MHEV, TDS18, WR10, TRX22	48%	180	$2,542
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, MHEV, TDS18, OC1, WR10, TRX22	49%	178	$2,616
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, MHEV, TDS24, EGR, OC1, WR10, TRX22	52%	167	$3,208
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, MHEV, TDS24, EGR, OC1, WR15, TRX22	53%	162	$3,537
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, MHEV, TDS24, EGR, OC2, WR15, TRX22	54%	161	$3,643
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, MHEV, TDS24, EGR, OC2, WR20, TRX22	55%	156	$4,112
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, GDI, MHEV, SA, TDS24, EGR, OC2, WR20, TRX22	56%	155	$4,203
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, MHEV, ATK, TURBM, EGR, OC2, WR20, TRX22	58%	146	$5,511
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, Deac, GDI, MHEV, SA, ATK, TURBM, EGR, OC2, WR20, TRX22	58%	145	$5,602
LRR2, IACC1, EPS, Aero2, LDB, EV75 mile, WR20	100%	0	$10,877
LRR2, IACC1, EPS, Aero2, LDB, EV100 mile, WR20	100%	0	$11,477
LRR2, IACC1, EPS, Aero2, LDB, EV200 mile, WR20	100%	0	$14,888

Table A4. Technology packages, CO_2 emissions, and 2025 cost for ICCT updated light truck (vehicle type #21)

Technology Package	Percent CO_2 reduction	Test cycle CO_2 (g/mi)	Incremental vehicle price in 2025 (2015 $)
Baseline (V-6 engine dual overhead cam, 4-speed automatic transmission)	0%	349	$0
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR5, TRX11	22%	273	$416
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR5, TRX21	28%	250	$553
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, WR10, TRX21	31%	241	$607
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, GDI, TDS18, WR10, TRX21	35%	227	$788
EFR2, LRR2, IACC1, EPS, Aero1, LDB, DCP, GDI, TDS18, WR10, TRX21	37%	219	$900
LUB, EFR1, LRR1, IACC1, EPS, Aero1, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR10, TRX22	49%	179	$1,621
LUB, EFR1, LRR1, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR10, TRX22	51%	171	$1,822
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR10, TRX22	53%	165	$1,963
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR15, TRX22	55%	159	$2,127
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, ATK, EGR, WR20, TRX22	56%	152	$2,365
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, SS, ATK, EGR, WR20, TRX22	57%	149	$2,697
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, SS, ATK, EGR, OC1, WR20, TRX22	58%	148	$2,770
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, SS, ATK, EGR, OC2, WR20, TRX22	58%	146	$2,876
EFR2, LRR2, IACC2, EPS, Aero2, LDB, DCP, DVVL, DyDeac, GDI, MHEV, ATK, EGR, OC2, WR20, TRX22	60%	140	$3,358
LRR2, IACC1, EPS, Aero2, LDB, EV100 mile, WR20	100%	0	$5,931
LRR2, IACC1, EPS, Aero2, LDB, EV125 mile, WR20	100%	0	$7,095
LRR2, IACC1, EPS, Aero2, LDB, EV200 mile, WR20	100%	0	$9,527

Table A5. Technology abbreviations

Abbreviation	Technology
Aero1	Aerodynamic drag reduction, level 1 (passive)
Aero2	Aerodynamic drag reduction, level 2 (active)
ATK	Atkinson cycle
DCP	Dual cam phasing
Deac	Cylinder deactivation
DVVL	Discrete variable valve lift
DyDeac	Dynamic deactivation
EFR1	Engine friction reduction, level 1
EFR2	Engine friction reduction, level 2
EGR	Cooled exhaust gas recirculation
EPS	Electric power steering
EV75	Electric vehicle, 75-mile electric range
EV100	Electric vehicle, 100-mile electric range
EV125	Electric vehicle, 125-mile electric range
EV200	Electric vehicle, 200-mile electric range
GDI	Gasoline direct injection
IACC1	Improved accessories, level 1
IACC2	Improved accessories, level 2
LDB	Low drag brakes
LRR1	Low rolling resistance tires, level 1
LRR2	Low rolling resistance tires, level 2
LUB	Engine changes to accommodate low friction lubrication
MHEV	Mild hybrid (48-volt)
OC1	Off cycle credit, level 1
OC2	Off cycle credit, level 2
SA	Secondary axle disconnect
SS	Stop-start
TDS18	Turbocharging with downsizing, 18-bar
TDS24	Turbocharging with downsizing, 24-bar
TRX11	Transmission improvement, current/step 1
TRX21	Transmission improvement, step 2 with additional gear-ratio spread
TRX22	Transmission improvement, TRX21 with improved efficiency
TURBM	Miller cycle (Atkinson with turbocharging)
WR5	Weight reduction, 5%
WR10	Weight reduction, 10%
WR15	Weight reduction, 15%
WR20	Weight reduction, 20%