SEPTEMBER
2016

An Assessment of Powertrain Technology Costs Associated with Meeting CAFE and GHG Standards

CAR
CENTER FOR AUTOMOTIVE RESEARCH

ACKNOWLEDGEMENTS

The Center for Automotive Research would like to thank the Alliance of Automobile Manufacturers for having the foresight to fund this project, and its members for providing critical momentum to keep this effort moving forward. CAR would also like to thank the members of the Global Automakers who participated in this study.

As with all studies, CAR's corporate and academic friends provided guidance, external reviews and commentary for this effort. Their input significantly contributed to the integrity of our research.

We would also like to thank the dozens of automotive industry engineers, strategic planners, and financial experts who contributed to this effort. CAR researchers are humbled by the commitment of these men and women. Their participation represents significant effort, analyses and contemplation. CAR is appreciative of the importance, honesty and sincerity these individuals placed on this task and their commitment to a collaborative and data-driven process. Their efforts cannot be overstated.

Brett Smith

Assistant Director, Manufacturing, Engineering and Technology

CAR
CENTER FOR AUTOMOTIVE RESEARCH

3005 Boardwalk, Suite 200
Ann Arbor, MI 48108
www.cargroup.org

CAR's mission is to conduct independent research and analysis to educate, inform and advise stakeholders, policy makers, and the general public on critical issu18,000es facing the automotive industry, and the industry's impact on the U.S. economy and society.

CONTENTS

LIST OF TABLES

I. EXECUTIVE SUMMARY

The Center for Automotive Research (CAR) was contracted by the Alliance of Automobile Manufacturers to conduct a survey to assess the cost and effectiveness of powertrain technologies that may be used to meet greenhouse gas (GHG) and fuel economy standards. This study is intended to offer critical insight and data for all stakeholders; and for consideration as regulators and policymakers deliberate the Midterm Evaluation (MTE). This project represents what the CAR research team believes is unprecedented participation from vehicle manufacturers. This report aggregates powertrain technology cost and efficiency data from nine global vehicle manufacturers. Members from the Alliance of Automobile Manufacturers and the Global Automakers contributed responses to both quantitative surveys and qualitative interviews.

With input from industry stakeholders, CAR developed two surveys: a quantitative survey to capture the incremental costs and efficiencies associated with technology pathways, and a qualitative interview assessment of opportunities and barriers to the implementation of new technologies. CAR's quantitative survey closely followed NHTSA's decision tree hierarchy for applying technologies to four technology categories (Turbocharging, Electrification, Diesel and Transmission). The NHTSA decision-tree was chosen due to clarity of pathway, and transparency of modeling inputs in previous generation models.

Survey results indicate differences between manufacturers and regulators with regard to current direct manufacturing cost DMC for many advanced powertrain technologies. For example, the manufacturers' aggregated average (DMC) estimate for starting with a I4 PFI DOHC fixed valve and concluding with I3 Turbo 24 bar with CEGR is **25.5 percent** higher than that of the regulators' 2012 final rule estimate for 2017 model year. And, the manufacturers' aggregated DMC estimate for starting with a V6 PFI DOHC fixed valve and concluding with I4 Turbo 24 bar with CEGR is **71.4 percent** higher than that of the regulators' 2012 final rule estimate for 2017 model year.

Importantly, the manufacturers' aggregated average cost estimates for plug-in vehicle technologies are currently near, or even below that of the regulators' 2012 final rule estimate for 2017 model year. This indicates important cost reductions for this technology have occurred, and will likely continue. However, vehicle electrification is still expensive.

During this project, it was clear that many manufacturers are concerned over the differences in the costs they experience for current programs vis-à-vis the estimates published by the regulators. However, it was also very clear that in many instances there was even more concern regarding the efficiencies of the technologies. The manufacturers indicate regulators over-estimate the potential efficiency gains from many advanced powertrain technologies. Each responding company indicated significant concern over the gap between regulator-modeled efficiencies for ICE technology, and the vehicle application experiences of the manufacturers. Accordingly, this difference between modeled and vehicle application as experienced by the manufacturers alters the electrification tipping point—that point when the internal combustion engine can no longer meet the standard, and the companies must shift to more expensive electrification at a significantly higher cost for the fleet.

II. INTRODUCTION

An important transition within the automotive industry is underway as fuel economy and carbon dioxide (CO_2) emissions regulations[1] quickly accelerate through the year 2025. The industry will be required by regulation to increase fuel efficiency of the U.S. fleet from 27.5 miles per gallon (MPG) for passenger cars and 23.4 MPG for light duty trucks in the 2010 model year to an originally estimated U.S. fleet average 54.5 MPG for all vehicles in model year (MY) 2025.[2] The goal of 54.5 MPG, the number originally used by the administration regulators and frequently reported by media, was an estimate of what the industry must meet in 2025. In reality, it is a representation of a complex set of measurements (e.g., manufacturer fleet average, vehicle footprint, car/truck mix, etc.). The actual fuel economy target required will depend on a variety of factors and will even differ from manufacturer to manufacturer.

An essential part of the 2012 regulation (2017 and later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards), is the requirement for a Midterm Evaluation (MTE) to be completed by April 2018. According to the U.S. Environmental Protection Agency (EPA):

“The MTE will be conducted through a collaborative, data-driven, and transparent process. To gather the most robust data and information to inform the MTE, EPA, in coordination with National Highway Transportation Safety Administration (NHTSA) and California Air Resources Board (CARB), is conducting extensive outreach with a wide range of stakeholders – including auto manufacturers, automotive suppliers, NGOs, consumer groups, labor unions, automobile dealers, states, and others.” [3]

The MTE will include three key elements: A Technical Assessment Report (TAR); a proposed Determination/Notice of Proposed Rule Making (NPRM); and, a Final Determination. The Final Determination is due no later than April 1, 2018. Both the TAR and NPRM include opportunity for public comment.

---

[1] Although this paper will mainly address CO2 emitted, it is useful to note the other greenhouse gases emitted by light vehicles are also considered by EPA. The EPA endangerment finding identified six greenhouse gases--carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) -- as a threat to public health and welfare of the current and future population. An internal combustion engine (ICE) equipped automobile emits four (CO2, methane, nitrous oxide, and hydrofluorocarbons) of the regulated pollutants. However, tailpipe CO2 represents approximately 88.7 percent of GHG emissions from light vehicles, and is directly related to fuel consumption. Clearly meaningful reductions in CO2 must be focused on tailpipe emissions. While the authors note this difference, for this paper, unless otherwise stated, CO2 and GHG will be considered interchangeable.

[2] Due to market shifts in vehicle segmentation, regulators now expect the 2025 fuel economy target to be between 50.0 and 52.5 MPG

[3] https://www3.epa.gov/otaq/climate/mte.htm

Diagram A below is representative of the expected timeline for the 3-step MTE process as defined by regulators:

Diagram A: Midterm Evaluation Schedule

The GHG emissions standards as determined by the EPA in 2012 are set in regulation through 2025. However, the fuel economy regulation as set by NHTSA is set only through 2021. NHTSA has a statutory obligation to conduct a comprehensive de novo rulemaking to establish final CAFE standards for MYs 2022–2025. Thus, technically, the MTE is, by law, only applicable to NHTSA in setting fuel economy standards for years 2022-2025. EPA will use the MTE to determine if GHG standards for those years should be refined. However, the EPA, NHTSA and California Air Resources Board (CARB) are strongly expected to harmonize any alterations to the existing regulations to achieve the goal of a one national program.

The MTE presents an important opportunity to assess trends in technology development. As noted above, the EPA has proclaimed the MTE will be a "collaborative, data-driven, and transparent process." To support this goal, it is critical to gather, in aggregate form, cost and efficiency estimates directly from the source—the vehicle manufacturers. Such data represents an important perspective on the opportunities and challenges of meeting future GHG and fuel economy regulations, and should be considered by all stakeholders.

III. PROJECT OVERVIEW

The Center for Automotive Research (CAR) was contracted by the Alliance of Automobile Manufacturers (the Alliance) to conduct a study to assess the cost and effectiveness of powertrain technologies that may be used to meet GHG and fuel economy standards. This study is intended to offer critical insight and data for all stakeholders; and for consideration as regulators and policymakers deliberate the MTE.

Cost estimates are possibly the most challenging of all studies to undertake. First, cost may be the most competitive, and thus most confidential of all strategic information. Revealing cost gives insight into the deepest of competitive secrets. Further difficulty arises from different accounting styles, variations in technology implementation, global labor rates, as well as a variety of other considerations. Great care was taken by CAR researchers and industry respondents to minimize differences, and assure the respondents were using similar parameters in their estimates. And, finally, it is difficult at best to project how costs may be reduced over time. Learnings from volume, refinement, innovation and invention are bound to occur. However, the rate of the cost reduction is often uncertain—especially for new technologies. For this study, only direct manufacturing costs for 2016 were gathered.

This project represents what the CAR research team believes is unprecedented participation from vehicle manufacturers. This report aggregates cost and efficiency data from nine global vehicle manufacturers. Members from the Alliance of Automobile Manufacturers and the Global Automakers participated. These companies contributed responses to both quantitative surveys and qualitative interviews. By leveraging experience from actual vehicle programs, data presented in this report relies on analysis of dozens of powertrain programs developed by key engineering, strategy, finance and planning personnel; and hundreds—if not thousands—of technology efficiency modeling runs performed by highly skilled manufacturer representatives.

Nine automakers participated in the survey responses out of the 14 invited to participate. The 14 invited automakers are listed below:

- BMW
- Fiat Chrysler Automobiles
- Ford
- General Motors
- Honda
- Hyundai/Kia
- Jaguar Land Rover
- Mazda
- Mercedes Benz
- Mitsubishi
- Nissan
- Subaru
- Toyota
- Volkswagen

For this project CAR researchers, and survey respondents, took the utmost care in assuring all cost data was handled in a secure and confidential manner. Non-Disclosure Agreements (NDA) were signed with all participating companies after careful vetting by legal staffs, and were followed to the letter. Only CAR researchers directly involved in the data gathering and assessment were given access to individual company survey results. The data was stored on a secure server, with access allowed only to those individuals directly involved in data analysis. No other CAR employees had access to the cost data. Further, data are presented only in aggregate form. CAR did not make public in any way which companies responded to this survey. CAR researchers did not present, nor did companies ever ask CAR to indicate in, anyway, cost comparisons between respondents, nor other differentiations. To the best of CAR researcher's knowledge, respondents do not know who else responded. It is essential to the CAR's mission that this effort was conducted in the most ethical way possible.

Considerable resources have been expended trying to estimate the costs associated with different powertrain technologies and pathways. However, due to the highly competitive factors mentioned above, the one source for the most accurate of information—the manufacturers—has not readily been aggregated. To this point, CAR researchers believe this project is the most quantifiable, real-world data driven estimate to date.

For the automotive industry, specifically with regard to powertrain technology cost, the two most influential studies are the 2011 Technical Assessment Report (TAR) and the 2015 National Research Council (NRC) report.[4] These reports do an outstanding job of describing powertrain technologies and pathways. The sections of the NRC report describing internal combustion engines (ICE), electrification and transmissions are especially thoughtful. This report does not attempt to add further to the description of technologies, instead it guides readers to those reports for a comprehensive discussion. This report focuses instead on gathering cost data for these technologies—from the source. The 2016 Technical Assessment Report (TAR) for the MTE was released late in the process of completing this project. Although late in the process, this report does attempt to address the 2016 TAR where possible. But, even with the inclusion of the 2016 TAR, it remains clear that these documents do not completely capture the costs of powertrain technologies as described by the vehicle manufacturers.

There have been previous attempts to gather the actual cost data for powertrain technologies and pathways directly from manufacturers. These efforts have meet with somewhat limited success. Realistically, any company is highly cautious when sharing cost data. This caution is amplified when the data offered may be misrepresented. It is understandable that any company would be greatly uncomfortable with sharing such mission critical data. CARs independence provides a mechanism for "blinding" and aggregating of such data. Further, the data as presented becomes a representation as an aggregate of manufacturers—but not any one manufacturer.

Survey Development

This effort began as a quantitative assessment of cost and efficiencies for powertrain technologies and pathways. That is, to define the costs and efficiencies associated with incremental and revolutionary technology implementation. After discussions with industry stakeholders, it became clear there was a need for qualitative analysis as well. Parallel to this project, CAR researchers conducted an assessment of technology and costs to lightweight vehicles.[5] Prior to that effort, CAR conducted a qualitative assessment of barriers to lightweighting.[6] The implementation of new technologies into the automotive industry is often far more complex than may initially appear. The CAR paper *Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs*, identified such challenges for materials implementation. In addition to identifying powertrain

---

[4] Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicle, Committee of the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2, National Research Council of the National Academies, The National Academies Press, Washington D.D., 2015

[5] Baron, Jay, Modi, Shashank, Assessing the Fleet-wide Technology and Costs to Lightweight Vehicles, Center for Automotive Research, September 2016

[6] Baron, Jay; Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs, Center for Automotive Research, January 2016

costs and efficiencies, this report will attempt to highlight critical barriers to implementation with regard to powertrain technology. However, due to limited time and resources, it should not be considered a comprehensive description of the barriers to implementing new powertrain technology. Clearly, there are many challenges (along with opportunities) when bringing new, unproven technology to market. And, it is essential that those challenges are not overlooked in the regulatory process.

With input from industry stakeholders, CAR developed two surveys: a quantitative survey to capture the incremental costs and efficiencies associated with technology pathways, and; a qualitative interview assessment of opportunities and barriers to the implementation of new technologies. The quantitative survey was distributed during the fourth quarter of 2015 and the first quarter of 2016. Interviews were conducted during the first and second quarters of 2016.

Through several iterations with expert reviewers and industry stakeholders, CAR developed a carefully crafted survey to gather costs and efficiency estimates from manufacturers of various powertrain technologies. The survey was based on the incremental technology pathways as defined NHTSA and was intended to emulate the steps used by the agencies in previous technical analyzes. CAR researchers' intent was to make the data as comparable as possible to previous agency work, thus enabling easier comparisons with agency estimates. The NHTSA pathways presented a clear and discernable means of achieving that goal. Care was also taken to consider how the aggregated data compares to that provided by the NRC study.

The quantitative survey was designed to capture the incremental costs of the most influential technologies, and included comprehensive instructions. Due to resource constraints, some technologies were left off the survey. Fourteen manufacturers were invited to complete the survey and 9 of them participated. CAR researchers held meetings with the companies (often several meetings) to assure clarity. Capturing cost data is far more complex than at first glance. Key elements of such data are often captured by different functions within a company, and not necessarily compiled in a manner that matched the CAR questionnaire. Generally, companies assigned an individual to guide the questionnaire through the company labyrinth; including purchasing, engineering, planning and, of course, legal counsel. Once the data was gathered internally, the surveys were turned over to the CAR researchers for aggregation.

Interviews were then conducted to confirm clarity on the quantitative data and to gather other more qualitative information. These interviews included representatives from several functions, and often included several separate meetings per company. Companies shared critical strategic planning documents, including technology pathways, implementation targets, and barriers to market penetration. The qualitative discussions proved critical in the research team's understanding of the topic.

Defining Cost Data

For this project, incremental Direct Manufacturing Cost (DMC) was captured. DMC is defined as the price a vehicle manufacturer would pay a supplier for a fully manufactured part ready for assembly in a vehicle, or the vehicle manufacturer's full cost of internally manufacturing the same part. All data is presented as DMC for manufacturing a component for the 2017 model year.

Respondents were asked to include all costs associated with the technology implementation, such as costs for installation requirements (wiring, connectors, plumbing, brackets, revised engine mounts, etc.); thermal management; possible addition of torsional vibration dampers to transmissions (for reduced number of cylinders); noise, vibration and harshness (NVH) control measures; and ignition system upgrades (possibly for high EGR rates). In addition to cost data, the manufacturers were also asked to provide fuel consumption reduction (efficiency) for each step.

While this report captures the critical manufacturing costs, it does not consider the indirect costs (IC) associated with new technologies. Indirect costs include expenditures not directly required for manufacturing a component but which are necessary for the operation of the automobile manufacturing firm. These costs include such things as warranty; research and development; depreciation and appreciation; maintenance repair operation; general and administrative services; retirement; health; transportation; marketing; dealer selling; and profit. Due to time and resource constraints, the CAR team did not investigate indirect costs nor learning curves.

Many of the respondents to this survey indicated strong disagreement regarding the indirect costs multipliers (ICM) and learning curves (LC) used by regulators to forecast future technology costs. Several respondents indicated that to use those multipliers to generate a final 2025 cost estimate would provide tacit approval for their accuracy. And, therefore, these estimates would not be a valuable addition to the research. The data provided in this report illustrates the differences between the regulators' estimates for direct manufacturing costs and the aggregated average direct manufacturing costs of the manufacturers. As such, it presents an important contribution for any discussion on technology cost.

Technology Pathways: Decision Trees

CAR's survey closely followed NHTSA's decision tree hierarchy for applying technologies to four technology categories (Turbocharging, Electrification, Diesel and Transmission). The NHTSA decision-tree was chosen due to clarity of pathway, and transparency of modeling inputs in previous generation models. For Turbocharging, and Electrification, input was requested for I4, V6 and V8 engine applications. For all responses, it is assumed that the performance of each subsequent engine will match the performance of the baseline engine.[7] Each cost and efficiency estimate was measured from the previous decision point in the technology tree.

---

[7] The idea of equivalent performance led to important discussion. Market competition requires each iteration of a product is expected to be better and/or less expensive than the previous one. Whether defined as noise, vibration and harshness (NVH); durability; fuel economy; reliability; torque; horsepower; or any of many characteristics, the next product must be better—not merely as good as—the one it replaces. Customers decide on the importance of these performance characteristics, and make purchases accordingly.

Survey hierarchy technologies included the following baselines:

- I4 Port Fuel Injection (PFI) Dual Overhead Cam (DOHC) in a midsized passenger car
- Baseline V6 PFI DOHC in a large passenger car
- Baseline V8 PFI OHV in a large light duty truck
- Electrification: Baseline I4 PFI DOHC in a midsized passenger car
- Electrification: Baseline V6 PFI DOHC in a large passenger car
- Electrification: Baseline V8 PFI Overhead Valve (OHV) in a large pickup truck car (Insufficient data received from survey respondents)
- Diesel Engines (Insufficient data received from survey respondents)
- Transmission (Insufficient data received from survey respondents)

Further, to more completely match the 2012 NHTSA data, all responses were requested in 2010 dollars. For reference, the agencies' estimates of direct manufacturing cost for 2017 MY (in 2010 dollars) are provided.[8] Although data for Turbocharging, Electrification, Diesel, and Transmission were gathered, this report presents results for only Turbocharging, and Electrification. Data for V8 Truck Electrification, Diesel and Transmission are not presented in this report as there was very little data provided for diesel technology, and because of the multitude of transmission variations, very few technology strategies had sufficient data to meet the minimum required response rate.

Several caveats are worth noting. First, the 2012 Final Rule relied heavily on turbocharged boosted engines up to 27 bar BMEP and (with industry guidance) included little expectation for cylinder deactivation for I4 and V6 technology. During data collection for this project, there was great—even extreme—doubt indicated by the manufacturers for using 27 bar BMEP. For the 2016 TAR, the regulators appear to have come to a similar conclusion. The 2016 TAR does not appear to consider 27 bar BMEP as part of the 2025 solution. Conversely, cylinder deactivation has become a strong candidate for higher penetration—both in current market penetration and in regulator pathways. Also, some higher compression engines (e.g., Atkinson cycle) were not viewed by the regulators as a low cost pathway in the 2012 pathways, but now play a central role in the EPA's (but not NHTSA's) technology pathway for the 2016 TAR. Neither of these technology strategies were included in the CAR survey.

The aggregation of data for V8 engines provided some challenge, and highlights the importance of considering technology strategies and pathways in the regulatory process. Because there are two very distinct initial pathways (OHV and OHC) currently in the market, and a limited number of participants in certain segments, presenting data for the initial steps of the V8 decision tree may have uniquely identified individual companies. Therefore, the survey focuses on steps after the point where NHTSA's decision tree merges—the turbocharging and downsizing step.

The electrification alternatives, (Baseline I4 PFI DOHC in a midsized passenger car; Baseline V6 PFI DOHC in a large passenger car; and, Baseline V8 PFI OHV in a large pickup truck) provided numerous technology pathways for companies to compare. CAR did not seek to identify the percentage of cost the battery comprises for each of the electrification options. This is clearly an important element of the overall cost equation, but presented significant barriers for the survey. Finally, for each of the

---

[8] For reference data, CAR used the NRC 2015 report, Appendix S. pp, 409-419

Electrification pathways, development is happening rapidly. There are many variations and strategies. For example, the 2012 final rule did not emphasize 200-mile range electric vehicles—a target that by 2016 had become a likelihood. Such rapid development makes it difficult to predict the success or failure of any single electrification strategy and to identify current costs.

IV. DIRECT MANUFACTURING COSTS AND FUEL CONSUMPTION EFFICIENCY RESULTS

Baseline I4 PFI DOHC in a midsized passenger car

Table 1 presents the incremental technology steps starting from the baseline I4 PFI DOHC fixed valve, and concluding with I3 Turbo 24 bar with cooled exhaust gas recirculation (CEGR) (step 7). There are two steps from the pathway that are not included in the table. The step to I4 Turbo 24 Bar with level 2 downsizing is not part of the continuing pathway as presented in the hierarchy, and I3 Turbo 27 bar w/CEGR was not supported by a majority of manufacturers and therefore dropped from analysis. Both were presented in the survey, but are not considered likely pathways for future implementation.

The manufacturers' total aggregated average DMC estimate of $1,099 in 2010 dollars for steps 1 through 7 is **25.5 percent** ($223 in 2010 dollars) higher than that of the regulators' 2012 final rule estimate ($876 in 2010 dollars). It is also valuable to consider moving from gasoline direct injection (step 5) through I3 turbo 24 bar (step 7), the manufacturers' aggregate cost estimate is **30.1 percent** higher ($123 in 2010 dollars) than regulators' estimate.

Table 1: Technology Hierarchy Baseline I4 PFI DOHC in a Midsized Passenger Car
(Industry Aggregated Average Cost ($2010) and Efficiencies compared to NHTSA Final Rule 2012)

Step	**Base Engine Technology**	**Incremental Engine Technology**	**NHTSA Estimate of Direct Manufacturing Cost in MY 2017**	**Industry Average Direct Manufacturing Cost for MY 2017**	**NHTSA Estimate Fuel Consumption Reduction (%)**	**Industry Average Estimate Fuel Consumption Reduction (%)**
	Column (A)	Column (B)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B)	Incremental from (A) to (B)
1	I4 PFI DOHC Fixed Valve	I4 PFI DOHC Fixed Valve with Engine Friction Reduction (w/improved lubricants) (EFR-LUB)	$102	$112	4.6%	2.1%
2	I4 PFI DOHC Fixed Valve with EFR-LUB	I4 PFI Variable Valve Timing (DCP)	$68	$85	5.1%	3.2%
3	I4 PFI Variable Valve Timing	I4 PFI Variable Valve Lift (Discrete)	$116	$164	3.6%	1.6%
4	I4 PFI Variable Valve Lift	I4 Gasoline Direct Injection	$182	$207	1.5%	2.1%
5	I4 GDI	I4 Turbo 18 bar with w/*33%* downsizing (Level 1)	$288	$378	8.3%	8.7%
6	I4 Turbo 18 bar with downsizing (Level 1)	I3 Turbo 24 bar with cylinder reduction and SOHC	-$92	$-70	3.5%	2.5%
7	I3 Turbo 24 bar w/cylinder reduction	I3 Turbo 24 bar with CEGR	$212	$223	3.5%	1.0%
	Total additional cost (Steps 1-7)		$876	$1,099		

The aggregated averages for efficiencies also indicate differences between manufacturers' experience and the regulators' 2012 estimates. The manufacturers indicate a much smaller efficiency gain when implementing the technologies than expected by the regulators for 5 of the 7 steps. For example, the regulators' estimate a 3.5 percent improvement for adding CEGR, while the manufacturers only expect a 1.0 percent improvement (step 7). Thus, even with a what appears to be a *relatively small* (5.2 percent) difference in cost, the difference in efficiency estimates may greatly affect the value of adding CEGR. The manufacturers do indicate a greater efficiency gain than that of the regulators for moving to gasoline direct injection (step 4) where the aggregated average manufacturers' response is 2.1 percent compared to 1.5 percent for the regulators.

Baseline V6 PFI DOHC in a Large Passenger Car

Table 2 presents the incremental technology steps starting from the baseline V6 PFI DOHC fixed valve, and concluding with I4 Turbo 24 bar with CEGR (step 7). As with the I4 pathway, there are two steps from the pathway that are not included in the table. The step to V6 Turbo with Level 1 downsizing is not part of the continuing pathway as presented in the hierarchy, and I4 Turbo 27 bar with CEGR was not supported by a majority of manufacturers. Both were presented in the survey, but are not considered likely pathways for future implementation.

The manufacturers' total aggregated average DMC estimate of $1,186 in 2010 dollars for steps 1 through 7 is **71.4 percent** ($494 in 2010 dollars) higher than that of the regulators' 2012 final rule estimate. The manufacturers' aggregated average costs for moving from gasoline direct injection (step 5) through I3 turbo 24 bar (step 7) are worth noting. While the manufacturers' aggregate cost estimate is **much** higher ($437 in 2010 dollars) than regulators, that differential is entirely driven by a substantially higher ($487 in 2010 dollars) estimate moving from GDI to I4 Turbo 18 bar with cylinder reduction. As shown in the table, the industry aggregated average costs for steps 6 and 7 are actually lower than the regulators.

Table 2: Technology Hierarchy: Baseline V6 PFI DOHC in a Large Passenger Car
(Industry Aggregated Average Cost ($2010) and Efficiencies compared to NHTSA Final Rule 2012)

Step	**Base Engine Technology**	**Incremental Engine Technology**	**NHTSA Estimate of Direct Manufacturing Cost in MY 2017**	**Industry Average Direct Manufacturing Cost for MY 2017**	**NHTSA Estimate Fuel Consumption Reduction (%)**	**Industry Average Estimate Fuel Consumption Reduction (%)**
	Column (A)	Column (B)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B)	Incremental from (A) to (B)
1	V6 PFI DOHC Fixed Valve	V6 PFI DOHC Fixed Valve with EFR-LUB	$149	$152	4.8%	2.2%
2	V6 PFI DOHC Fixed Valve with EFR-LUB	V6 PFI Variable Valve Timing (DCP)	$146	$161	5.4%	5.4%
3	V6 PFI Variable Valve Timing	V6 PFI Variable Valve Lift (Discrete)	$168	$240	3.9%	1.5%
4	V6 PFI Variable Valve Lift (w'/ Cylinder Deact)	V6 Gasoline Direct Injection	$290	$257	1.5%	2.3%
5	V6 GDI	I4 Turbo 18 bar with cylinder reduction and DOHC	-$455	$32	7.8%	4.9%
6	I4 Turbo 18 bar w/cylinder reduction	I4 Turbo I4 Turbo 24 bar w/*50%* downsizing (Level 2)	$182	$153	3.7%	1.8%
7	I4 Turbo 24 bar	I4 Turbo 24 bar with CEGR	$212	$191	3.5%	1.4%
	Total additional cost (Steps 1-7)		$692	$1,186		

The data from the V6 pathway points to a valuable difference between the manufacturers' appraisal of the challenge and that of the regulators. While the aggregated costs are higher (at least over the entire process), there are steps which manufacturers estimate a lower cost. While the differences for some steps may appear to be inconsequential, the manufacturers' data clearly indicates they experience higher costs overall. Further, there are important differences between the manufacturers' aggregated averages and the regulators' 2012 estimates for the pathway efficiencies. The manufacturers again indicate that GDI may offer slightly more efficiency, and CEGR may offer less than the regulators expect. The industry reports lower efficiencies in 5 of the 7 steps considered. The combination of somewhat higher costs, and *much lower* efficiencies makes an important difference—one that can redefine overall technology portfolio and strategy.

Baseline V8 PFI OHV in a Large Light Duty Truck

The average direct manufacturing costs and efficiency estimates as aggregated from the manufacturers' responses for the V8 technology pathway are presented below (Table 3). Because there are at least two very distinct initial pathways (OHV and OHC) currently in the market, and a limited number of participants in certain segments, presenting data for the initial steps of the V8 decision-tree may have uniquely identified individual companies. Therefore, the survey focuses on steps after the point where NHTSA's decision tree merges—the turbocharging and downsizing step.

The manufacturers' aggregated average cost for step 1 (V8 GDI to V6 Turbo 18 bar) is 16.2 percent lower than that of the regulators (Table 3). While the results are important, it is valuable to point out it represents the first step for bringing two technologies (OHC and OHV) into the same pathway. Respondents may not have been considering the same base technology when responding to the question. For step 2, the manufacturers are somewhat higher (3.2 percent) than the regulators' estimate, and for step 3, they are *much* higher (38.2 percent). With regard to efficiency estimates, the manufacturers only differ in step 3. For each of the gasoline engine pathways (I4, V6 and V8) the manufacturers consistently estimate lower efficiencies for adding CEGR than did the regulators—this is especially interesting given the shift by EPA away from turbocharged engines in the 2016 TAR.

Table 3: Baseline V8 PFI OHV in a Large Light Duty Truck
(Industry Aggregated Average Cost ($2010) and Efficiencies compared to NHTSA Final Rule 2012)

Step	**Base Engine Technology**	**Incremental Engine Technology**	**NHTSA Estimate of Direct Manufacturing Cost in MY 2017**	**Industry Average Direct Manufacturing Cost for MY 2017**	**NHTSA Estimate Fuel Consumption Reduction (%)**	**Industry Average Estimate Fuel Consumption Reduction (%)**
	Column (A)	Column (B)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B)	Incremental from (A) to (B)
1	V8 GDI	V6 Turbo 18 bar w/cylinder reduction	$841	$704	7.3%	7.0%
2	V6 Turbo 18 bar w/cylinder reduction	V6 Turbo 24 bar with Level 2 downsizing	$308	$318	3.4%	3.5%
3	V6 Turbo 24 bar	V6 Turbo 24 bar with CEGR	$212	$293	3.6%	1.7%

Electrification: Baseline I4 PFI DOHC in a Midsized Passenger Car and Baseline V6 PFI DOHC in a Large Passenger Car

While the manufacturers' average cost for adding stop-start technology is higher for both I4 and V6, they also had higher efficiency estimates than the 2012 regulation (Table 4 and Table 5). For both I4 and V6 applications, the manufacturers reported a much lower efficiency for P2 hybrid technology than was presented by the regulators in 2012. Several respondents indicated concern over the disparity of the aggregated average cost for P2 with that of the regulators. Importantly, the 2016 TAR updated P2 hybrid effectiveness to 19.9% for a large car.[9] The 2016 TAR includes some discussion about more accurately accounting for efficiencies due to P2 technology and for other fuel consumption reduction technologies applied to the P2 HEV vehicles. They appear to apply this to efficiency estimate to all strong HEVs. While this adjustment was important, there remains great concern over how the regulators may be treating the differences between power split and P2 cost, efficiency and performance in the midterm review.

The data for the power split hybrid highlighted the importance of each company's implementation strategy. It also highlighted how these differing strategies influence cost and efficiency. Although the aggregated average cost estimate for power split technology was nearly 60 percent higher than the regulators' 2012 estimate, there was a wide range among the respondents. There was a similarly wide range of efficiency estimates. A simple review of the products suggests divergent product strategies and

---

[9] Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025 Technical Assessment Report, EPA-420-D-16-900, July 2016; p 5-203

corporate capabilities. As noted several times in this report, it can be very risky to define a best-in-class cost or efficiency (or any of a number of performance attributes) and assume it may apply to the entire fleet across manufacturers. Different market segments require different performance characteristics—those can drive cost and efficiency differences.

For plug-in technology, the manufacturers' estimates were closely aligned with the regulators in three of the four technologies where comparison was possible. In fact, the manufacturers' estimates for V6 Plug-in Hybrid – 40-mile range and Electric Vehicle – 100-mile range were below those of the regulators' 2012 estimates. The companies also provided some data for Electric Vehicle – 200-mile range, something not considered by the regulators in 2012.

Table 4: Electrification: Baseline I4 PFI DOHC in a Midsized Passenger Car
(Industry Average Cost ($2010) and Efficiencies compared to NHTSA Final Rule 2012)

Base Engine Technology	**Incremental Engine Technology**	**NHTSA Estimate of Direct Manufacturing Cost in MY 2017**	**Industry Average Direct Manufacturing Cost for MY 2017**	**NHTSA Estimate Fuel Consumption Reduction (%)**	**Industry Average Estimate Fuel Consumption Reduction (%)**
Column (A)	Column (B)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B)	Incremental from (A) to (B)
I4 PFI DOHC Fixed Valve	Stop-Start (12V Micro-Hybrid)	$287	$337	2.1%	3.6%
I4 PFI DOHC Fixed Valve	Integrated Starter Generator (ISG) 48V Mild Hybrid	Not Calculated	$1,388	Not Calculated	8.8%
I4 PFI DOHC Fixed Valve	Strong Hybrid - P2	$2,463	Insufficient Data	33.6%	21.8%
I4 PFI DOHC Fixed Valve	Strong Hybrid - PS	$3,139	$4,995	33.0%	33.2%
I4 PFI DOHC Fixed Valve	Plug-in Hybrid - 20 mile range	Not Calculated	$10,250	Not Calculated	Insufficient Data
I4 PFI DOHC Fixed Valve	Plug-in Hybrid - 40 mile range	$13,193	$13,236	65.1%	Insufficient Data
I4 PFI DOHC Fixed Valve	Electric Vehicle - 100 mile	$16,831	$14,577	Not Calculated	Not Calculated
I4 PFI DOHC Fixed Valve	Electric Vehicle - 200 mile	Not Calculated	$16,000	Not Calculated	Not Calculated

Table 5: Electrification: Baseline V6 PFI DOHC in a Large Passenger Car
(Industry Aggregated Average Cost ($2010) and Efficiencies compared to NHTSA Final Rule 2012)

Base Engine Technology	**Incremental Engine Technology**	**NHTSA Estimate of Direct Manufacturing Cost in MY 2017**	**Industry Average Direct Manufacturing Cost for MY 2017**	**NHTSA Estimate Fuel Consumption Reduction (%)**	**Industry Average Estimate Fuel Consumption Reduction (%)**
Column (A)	Column (B)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B) ($2010)	Incremental from (A) to (B)	Incremental from (A) to (B)
V6 PFI DOHC Fixed Valve	Stop-Start (12V Micro-Hybrid)	$325	$366	2.2%	4.5%
V6 PFI DOHC Fixed Valve	ISG 48V Mild Hybrid	Not Calculated	$1,613	Not Calculated	10.5%
V6 PFI DOHC Fixed Valve	Strong Hybrid - P2	$2,908	Insufficient Data	34.5%	19.5%
V6 PFI DOHC Fixed Valve	Strong Hybrid - PS	$3,396	$5,275	32%	34.5%
V6 PFI DOHC Fixed Valve	Plug-in Hybrid - 20 mile range	Not Calculated	$12,167	Not Calculated	66.3%
V6 PFI DOHC Fixed Valve	Plug-in Hybrid - 40 mile range	$17,854	$15,500	69.5%	67.0%
V6 PFI DOHC Fixed Valve	Electric Vehicle - 100 mile	$21,123	$16,050	87%	Not Calculated
V6 PFI DOHC Fixed Valve	Electric Vehicle - 200 mile	Not Calculated	$20,000	87%	Not Calculated

V. OBSERVATIONS AND CONCLUSIONS

The following observations and conclusions are based on the quantitative survey results and the qualitative interviews. The importance of the in-depth interviews cannot be overstated. While compiling cost data is essential, it is also necessary to put this data into the context of real-world decision-making. Through an extensive and iterative interview process, the CAR research team was able to better capture not only the costs, but the operational barriers to rapid technology implementation.

Survey Results Indicate Differences Between Manufacturers and Regulators with Regard to Direct Cost of Manufacturing for Many Advanced Powertrain Technologies.

The aggregate industry direct manufacturing costs for many of technologies are higher than those presented by the regulators. An observer may look at any one data point and surmise that they are “not that far apart.” On an operational level, such a conclusion may be very dangerous. One program engineer said upon review of the data, “My program gets raked over the coals for a few pennies. These differences are in the tens, or even hundreds, of dollars. It is a big deal.”

Although the manufacturers’ aggregated average costs for many technology steps are higher than the regulators’ 2012 cost estimates, there are areas the manufacturers’ aggregated averages were near, or even lower than that of the of regulators. It is important to note that the manufacturers’ estimates for plug-in technology (OPHEV and BEV) were closely aligned with the regulators in several of the technologies where comparison was possible. Many of the respondents identified important advancements in battery technology and cost reduction. Vehicle electrification presents many hurdles—cost being a critical one. There appears to consensus that the costs challenges, while still significant, continue to show development progress, and should be closely monitored.

During this project, it was clear that many manufacturers were concerned over the differences in the costs they experienced for current programs vis-à-vis the estimates published by the regulators. However, it was also very clear that in many instances there was even more concern regarding the real-world efficiencies of the technologies.

Survey Results Indicate Fundamental Differences Between Manufacturers and Regulators with Regard to Expectation for Efficiencies of Advanced Powertrain Technologies—This May be Even More Important Than the Cost Differences.

The manufacturers indicate regulators over-estimate the potential efficiency gains from many advanced powertrain technologies. While the quantitative results define these differences, the qualitative interviews gave depth to the reasons why there may be differing expectations. Manufacturer representatives stated that modeling often tends to exaggerate the synergies of adding technologies, and may not reflect real-world vehicle implementation. Clearly great effort and care has been given to create useful mathematical models for simulating in-use performance. However, given the differences between regulator-modeled results, and manufacturer reported real-world experience, there appears to be opportunity for all stakeholders to further refine the discussion.

Just as there are learning curves for manufacturing, there are also learning curves for implementation. Many new technologies recently introduced to the market will see improvement in overall effectiveness as manufacturers learn how to better execute them. However, industry and regulators appear to have differing views on the slope of the refinement curve. Regulators appear to be more optimistic than industry regarding the ability to increase the efficiency of some technologies. It is generally agreed that, over time, vehicle manufacturers will develop strategies to enable these technologies to become more efficient than at introduction. There is great concern however, that creating regulation based on uncertain—or overly aggressive refinement expectations—could be damaging.

The Ability to Accurately Model Efficiencies is Critical—It Defines the Viable Technology Mix.

If, as the manufacturers indicate, the efficiencies of new technology do not reach levels predicted by regulators, the technology mix required to meet 2025 standards may be very different than forecasted by regulators. The consistency among manufacturer was remarkable. Each responding company indicated significant concern over the gap between regulator-modeled efficiencies for ICE technology, and the vehicle application experiences of the manufacturers. Accordingly, this difference between modeled and vehicle application as experienced by the manufacturers alters the electrification tipping point.

Possibly no other topic caused more discussion among those interviewed than the point where manufacturers would need to increase the use of vehicle electrification to meet the standards. Clearly, manufacturers believe it will take a much higher level of electrification to meet the standard than do the regulators. If, as the manufactures indicate, the efficiencies presented by the regulators do not materialize, it no longer is a comparison of costs associated with the step function of the ICE pathways. Instead, it becomes a comparison about the costs of adding electrification. And, that cost is far greater than merely taking additional steps on the ICE pathway. Manufacturers believe such a shift would lead to a significantly higher cost to the consumer—markedly impacting the overall vehicle market. And, while not considered for this report, California Zero Emission Vehicle (ZEV) mandates will likely further accentuate this cost differential.

Regulators Assume Performance Characteristic Maintain a Baseline Measure Going Forward. In a Competitive Market, This Can Mean Ruin.

The regulators' idea of equivalent performance—or "holding performance constant" led to important discussions during the interviews. Each iteration of a product is expected to be better than the previous one. Whether described as noise, vibration and harshness (NVH), durability, fuel economy, reliability, torque, horsepower, or any other vehicle attribute, the next product must be better—not merely as good as—the one it replaces. Customers decide on the importance of these performance characteristics, and make purchases accordingly. Fuel economy itself is a performance characteristic—albeit one that may not have high priority for many customers, especially given current low gas prices.

In discussions with manufacturers, the phrase often heard was "we would go out of business if we held performance constant." It is possible that the differences in expectations for efficiency data may have some root in the challenges of competing in a hyper-competitive market.

No Two Manufacturers have the Same Cost and Technology Pathways, And This Matters.

Although not provided in this report due to confidentiality constraints, there was a range of costs reported for each technology. While these ranges were in part due to the difficulty of exact comparisons, CAR researchers believe much of the differences were driven by other factors. The TAR identifies potential low cost solutions. The reality is each of those solutions is not applicable to any one manufacturer. Each manufacturer is pursuing many technology pathways. No two manufacturers have the same product and technology portfolio; nor fuel economy strategy and technology costs. Therefore, suggesting a lowest cost for a technology or implementation strategy may be misleading. Depending on market position, customer expectations, and product mix, some manufacturers will bear a much greater burden than others.

Flexibilities (Credits) will be a Critical Part of Achieving GHG Reduction. However, any Technology Considered for Off-Cycle Credit Must Deliver Real and Meaningful Reduction.

Throughout the interview process, manufacturers strongly supported the need to account for technologies that reduce GHG, but may not be captured on the 2-cycle test. Certainly manufacturers (and suppliers) have technology solutions that can make a difference but may have to be captured off-cycle. However, it is essential that industry present solutions that bring real and meaningful reductions. It is equally essential for regulators to consider each technology with openness and a willingness to include solutions that reduce GHG.